FGD Sludge Disposal Manual, Second Edition

Keywords:
Disposal Alternatives
Disposal Costs
Leachate Control
Site Selection
Sludge Disposal
Waste Composition
Gypsum Stacking

Prepared by
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EPRI

EPRI CS-1515
Project 1685-1
Final Report
September 1980

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EPRI-CS-1515

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Research Project 1685-1

Final Report, September 1980
Work Completed, June 1980

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Prepared by
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ABSTRACT

This Manual is an update of the one published in January, 1979. It incorporates the effects of the New Source Performance Standards (NSPS) of June, 1979, and those of the Resource Conservation and Recovery Act (RCRA), to the extent that details are known, as of May 19, 1980. Suggestions and guidance are provided to electric utility operators of lime, limestone, alkaline flyash and double-alkali wet scrubbers in the processing and disposal of the waste product. A decision path diagram illustrates the options available to the operators, and explains the steps necessary to select a disposal system. Current practices in the U. S. and other countries are briefly covered to illustrate trends and to supply possible sources of information for the utility industry.

Major and trace components of the sludge are discussed along with their effects on processing and disposal. Methods are presented for estimating the quantity of waste which will be produced under a set of assumed conditions. Both wet (ponding) and dry (landfill) disposal alternatives are described and illustrated, along with site selection and design recommendations for both types. The problem of leachate from such areas is considered and means of prevention or control are evaluated.

Options available for processing and disposal and the question of fixation/stabilization are considered in view of the existing regulations and the possible requirements of RCRA. The important subject of processing/disposal cost and the prospects for utilization are considered.

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

This document is an update of one of the series of manuals published by the Solid-Waste By-Products Disposal Subprogram on the storage and disposal of utility-waste by-products. This second edition of the FGD Sludge Disposal Manual replaces the earlier version published in January 1979 as EPRI Final Report FP-977. This revised edition, developed under RP1685-1, provides the utility industry with a sound methodology that will permit confident selection of the methods and facilities for the disposal of flue gas desulfurization (FGD) sludges.

The material covered in this manual encompasses four principal categories: (1) updated information on the chemical and physical properties of FGD sludges and a description of current practices in the United States and other countries; (2) information on site-selection methods, environmental monitoring, and site reclamation; (3) incorporation of the effects of the New Source Performance Standards of June 1979 on waste quantities and a review of proposed and final federal regulations on solid-waste disposal, including the May 19, 1980, hazardous-waste regulations; and (4) computational methods for estimating waste quantities, waste characteristics, leachate production rates, and new plant system and transportation costs. A completely new section has been added to this second edition on gypsum stacking.

PROJECT OBJECTIVE

The objective of this updated version of the FGD Sludge Disposal Manual is to provide the industry with detailed information about design features, equipment selection, and specific procedures for evaluating factors necessary for selecting optimal sludge disposal systems. It is intended for use by utility designers and managers in the preliminary identification, cost analysis, ranking of candidate disposal sites, and system selection. This manual has met one of the continuing objectives of the EPRI Solid-Waste By-Products Disposal Subprogram to update the manual series to incorporate changing regulatory requirements, advances in waste

disposal technology, and changing costs or economic factors. It is expected that future updated material will not require a completely revised third edition, but will be issued in the form of insertable supplements.

PROJECT RESULTS

This manual presents a systematic and objective methodology for evaluating candidate sludge disposal sites and methods. It provides background information and references on existing practices, regulatory constraints and trends, as well as FGD sludge properties and disposal system costs. The cost-estimating procedures in Section 14 are illustrated in a carefully described base case in conformance with the EPRI Technical Assessment Guide (EPRI PS-1201-SR). Adjusting factors from the base case for site-specific considerations are included in graphs.

In preparing for an EPRI seminar, a prominent engineering firm did an economic evaluation of the cost benefits of the sludge manual. This A-E firm concluded that the manual, if properly used, could save a utility $1,500,000 per year for a 500-MW(e) coal plant.

During 1979, a questionnaire was sent out to the users of the sludge manual. The results were quite useful in preparing this second edition. This manual contains a questionnaire to provide EPRI with a feedback mechanism so that subsequent editions will also be responsive to immediate needs. The questionnaire return date is given as December 1, 1980. Your comments and suggestions will be incorporated to the extent possible.

Dean M. Golden, Project Manager
Coal Combustion Systems Division

ACKNOWLEDGMENTS

This report represents the combined efforts of a number of individuals. The authors wish to acknowledge the assistance of Mr. A. V. Slack, who provided the details on current scrubber practices in Europe, of Ardaman Associates who prepared the section on gypsum stacking and of Radian, Inc., who contributed material on sludge properties and leachate. The authors also wish to express their appreciation to the various scrubber operators for their cooperation in providing information concerning their systems and practices. Finally, the authors thank Dean M. Golden of EPRI and the EPRI review committee for their many helpful suggestions in the preparation of this Manual.

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QUESTIONNAIRE ON 2nd EDITION OF
FGD SLUDGE DISPOSAL MANUAL, EPRI RP1685-1

To users of the FGD Sludge Disposal Manual:

The answers to this questionnaire will be used for future updates and improvements to the Manual. There are two sections to the questionnaire:

I Overall Comments

II Comments on Specific Sections

Your cooperation in answering all or any part of the questionnaire will be appreciated. Use additional sheets, if necessary.

Please return by December 1, 1980.

Dean M. Golden
Electric Power Research Institute
3412 Hillview Drive
Palo Alto, CA 94303

If you have any questions, please contact Dean Golden at (415)855-2516.

Note: If you receive your manual after December 1, 1980, please complete the questionnaire anyway. Your suggestions can be included in subsequent revisions.

I. Overall Comments

Format _____

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Appearance _____

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Contents _____

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Ease of Reference _____

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Other _____

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Answered By:

Name _____ Title _____

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II. COMMENTS ON SPECIFIC SECTIONS

Section 1 - INTRODUCTION

Was information helpful? _____ Factual? _____

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Suggestions for improvements (deletions, additions, method of presentation, other): _____

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Section 2 - CURRENT DISPOSAL PRACTICES

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Section 3 - WASTE PROPERTIES

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Section 4 - SOLID WASTE QUANTITIES

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Suggestions for improvements (deletions, additions, method of presentation, other): _____

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Section 5 - DISPOSAL ALTERNATIVES

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Section 6 - SITE SELECTION

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Section 7 - LEACHATE

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Section 8 - DESIGN OF DISPOSAL AREAS

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Suggestions for improvements (deletions, additions, method of presentation, other): _____

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Section 9 - PROCESSING ALTERNATIVES

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Section 10 - FORCED OXIDATION

Was information helpful? _____ Factual? _____

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Suggestions for improvements (deletions, additions, method of presentation, other): _____

Section 11 - THICKENING/DEWATERING

Was information helpful? _____ Factual? _____

Comments: _____

Suggestions for improvements (deletions, additions, method of presentation, other): _____

Section 12 - FIXATION/STABILIZATION

Was information helpful? _____ Factual? _____

Comments: _____

Suggestions for improvements (deletions, additions, method of presentation, other): _____

Section 13 - TRANSPORTATION

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Suggestions for improvements (deletions, additions, method of presentation, other): _____

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Section 14 - SYSTEM COSTS

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Suggestions for improvements (deletions, additions, method of presentation, other): _____

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Section 15 - UTILIZATION

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Section 16 - GYPSUM STACKING

Was information helpful? _____ Factual? _____

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Suggestions for improvements (deletions, additions, method of presentation, other): _____

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CONTENTS

Section		Page
1	INTRODUCTION	1-1
	Purpose	1-1
	Background	1-2
	Scope	1-2
	Definitions	1-3
	System Overview	1-4
	Selecting a System	1-9
	Fundamental Constraints	1-9
	Pertinent Regulations	1-11
2	CURRENT DISPOSAL PRACTICES	2-1
	Purpose	2-1
	Existing U. S. Disposal Practice	2-1
	Planned U. S. Practices	2-4
	Trends	2-7
	Utility Contacts	2-7
	European Practice	2-9
	Japanese Practice	2-14
	References	2-14
3	WASTE PROPERTIES	3-1
	Purpose	3-1
	Sources	3-1
	Sludge Composition	3-4
	Factors Affecting Composition	3-25
	Predicting Sludge Composition	3-31
	Sludge Physical Properties	3-33
	Factors Affecting Physical Properties	3-39
	Predicting Physical Properties	3-43
	Environmental Concerns	3-44
	References	3-51

CONTENTS (Cont.)

Section		Page
4	SOLID WASTE QUANTITY	4-1
	Purpose	4-1
	Introduction	4-1
	Factors Affecting Waste Quantity	4-1
	Numerical Method	4-2
	Tabular Method	4-12
	Graphical Method	4-16
	References	4-22
5	DISPOSAL ALTERNATIVES	5-1
	Purpose	5-1
	Introduction	5-1
	Wet Disposal	5-1
	Dry Disposal	5-5
	Operational Systems	5-7
6	SITE SELECTION	6-1
	Purpose	6-1
	Fundamentals	6-1
	Site Selection Process	6-3
	Siting Criteria	6-4
	Mine/Quarry Disposal	6-13
	Ocean Disposal	6-16
	References	6-18
7	LEACHATE	7-1
	Purpose	7-1
	Introduction	7-1
	Regulatory Requirements	7-2
	Leachate Quality	7-5
	Predicting Leachate Quality	7-11
	Leachate Quantity	7-25
	Predicting Leachate Quantity	7-35
	Methods of Leachate Control	7-49
	Liners	7-57
	References	7-66

CONTENTS (Cont.)

Section		Page
8	DESIGN OF DISPOSAL AREAS	8-1
	Purpose	8-1
	Background	8-1
	Alternative Disposal Configurations	8-1
	Geotechnical Considerations	8-15
	Geologic Site Investigations	8-20
	Pond Design	8-33
	Pond Operation	8-90
	Landfill Design	8-93
	Landfill Operation	8-117
	Monitoring	8-122
	Final Land Use	8-138
	References	8-145
9	PROCESSING ALTERNATIVES	9-1
	Purpose	9-1
	Primary Alternatives	9-1
	Selecting Appropriate Processing	9-5
	Conclusions	9-14
10	FORCED OXIDATION	10-1
	Purpose	10-1
	Background	10-1
	EPA/TVA Tests	10-5
	State-of-the-Art	10-9
	Advantages	10-11
	Disadvantages	10-17
	Costs	10-18
	Summary	10-19
	References	10-22
11	THICKENING/DEWATERING	11-1
	Purpose	11-1
	Fundamentals	11-1
	Settling Ponds	11-6
	Lamina-Type Clarifier/Thickener	11-8

CONTENTS (Cont.)

Section		Page
	Thickeners	11-10
	Cyclone-Hydroclone	11-29
	Vacuum Filters	11-33
	Centrifuges	11-48
	Dewatering Aids	11-57
	Process Cost	11-59
	References	11-64
12	FIXATION/STABILIZATION	12-1
	Purpose	12-1
	Definitions	12-1
	Is Stabilization/Fixation Necessary?	12-1
	Primary Alternative	12-4
	Proprietary Processes	12-5
	Fixation/Stabilization Mechanisms	12-6
	Mixing with Non-Alkaline Flyash or Soil	12-10
	Mixing with Alkaline Flyash	12-13
	Mixing with Lime and Flyash	12-16
	Mixing with Calcilox^{R}	12-23
	Design Procedures	12-30
	References	12-36
13	TRANSPORTATION	13-1
	Purpose	13-1
	Introduction	13-1
	Overview of Alternatives	13-1
	Design Factors for Transportation Systems	13-5
	Transportation Systems for Dry Disposal	13-8
	Transportation Systems for Wet Disposal	13-27
	References	13-38
14	SYSTEM COSTS	14-1
	Purpose	14-1
	Economic Basis	14-1
	Fundamentals	14-3
	Reported Total Disposal Costs	14-5
	Simplified Cost Estimating	14-7
	Detailed Cost Estimates	14-29

CONTENTS (Cont.)

Section		Page
	Further Information	14-54
	References	14-55
15	UTILIZATION	15-1
	Purpose	15-1
	Background	15-1
	Current Practices with Gypsum Market	15-2
	Utilization of Oxidized Sludge	15-3
	Utilization of Fixated Sludge	15-9
	Market Potential Evaluation	15-14
	Summary and Conclusions	15-15
	References	15-17
16	GYPSUM STACKING	16-1
	Introduction	16-1
	Design Considerations	16-3
	Operation of Gypsum Stacks	16-17
	Plant Scholz Prototype FGD Gypsum Stack	16-19
	Engineering Properties of FGD Waste Gypsum	16-26
	Summary and Conclusions	16-37
Appendix A	Regulatory Requirements - New Source Performance Standards	A-1
Appendix B	Disposal Regulations	B-1
Appendix C	Case Histories - Site Selection and Permitting	C-1

Blank Page

ILLUSTRATIONS

Figure		Page
1-1	Sludge Disposal Alternatives	1-7
1-2	Wet Disposal of Sludge after Thickening	1-8
1-3	Dry Disposal of Dewatered Sludge after Blending with Lime and Flyash	1-10
3-1	Typical Lime/Limestone Scrubber Flow Scheme	3-3
3-2	Typical Lime-Regenerated Double-Alkali Scrubber Flow Scheme	3-5
3-3	Calcium Sulfite Sludge	3-11
3-4	Calcium Sulfate Sludge	3-12
3-5	Phillips Power Station Flyash	3-22
3-6	Correlation of Unconfined Compressive Strength with Leachable Alkalinity	3-41
3-7	Correlation of Permeability with the Unconfined Compressive Strength	3-45
4-1	SO_2 Removal Required to Meet 1979 NSPS Standards	4-4
4-2	SO_2 Removal Required to Meet 1979 NSPS Standards	4-5
4-3	Estimated Dry SO_x Solids Weight per Million Tons of Fuel	4-17
4-4	Estimated Dry SO_x Solids Weight per Million Tons of Fuel with 70% SO_2 Removal	4-18
4-5	Volume of Waste Containing 1000 Tons of SO_2 Sludge Solids of 2.4 Specific Gravity	4-20
4-6	Total Weight of Waste Containing 1000 Tons of Dry SO_x Sludge Solids	4-21
5-1	Flow Diagram for Wet Disposal Option 1	5-12
5-2	Sludge Disposal Pond, Green River Plant	5-13
5-3	Sludge Disposal Pond, LaCygne Plant	5-15
5-4	Flow Diagram for Wet Disposal Option 2 with Oxidation, Sherburne County Plant	5-17
5-5	Sludge Disposal Pond, Sherburne County Plant	5-18
5-6	Flow Diagram for Wet Disposal Option 2, Colstrip Plant	5-20
5-7	Flyash/Sludge Settling Ponds, Colstrip Plant	5-21
5-8	Evaporation Pond, Colstrip Plant	5-22
5-9	Flow Diagram for Wet Disposal Option 3, Bruce Mansfield Plant	5-24
5-10	Sludge Fixation Plant, Bruce Mansfield Plant	5-25
5-11	Sludge Impoundment, Bruce Mansfield Plant	5-26
5-12	Flow Diagram for Dry Disposal Option 2, Cherokee Plant	5-28
5-13	Sludge/Bottom Ash Pond Being Excavated, Cherokee Plant	5-29

Figure		Page
5-14	Flow Diagram for Dry Disposal Option 3, Milton R. Young Plant	5-31
5-15	Vacuum Filters, Milton R. Young Plant	5-32
5-16	Active Disposal Area, Milton R. Young Plant	5-33
5-17	Reclaimed Portion of Mine Disposal Area, Milton R. Young Plant	5-34
5-18	Flow Diagram for Dry Disposal Option 4, Southwest Plant	5-36
5-19	Sludge Processing Area, Southwest Plant	5-37
5-20	Sludge Landfill, Southwest Plant	5-38
5-21	Flow Diagram for Dry Disposal Option 5, Conesville Plant	5-40
5-22	Sludge Processing Plant, Conesville Plant	5-41
5-23	Sludge Disposal Area, Conesville Plant	5-42
5-24	Simplified Flow Diagram for Dry Disposal Option 6, Scholz Plant	5-44
5-25	Gypsum from Chiyoda 101 Scrubber, Scholz Plant	5-45
5-26	Close-up of Chiyoda Gypsum, Scholz Plant	5-46
5-27	Flow Diagram for Dry Disposal Option 7, Scholz Plant	5-48
5-28	Gypsum Stacking Pond, Scholz Plant	5-49
5-29	Exterior of Gypsum Stack, Scholz Plant	5-50
5-30	Drainage Ditch for Gypsum Stack, Scholz Plant	5-51
5-31	View of Drained Phosphogypsum Pond, USS Agri-Chemical Plant	5-53
5-32	Vertical Cut Through Phosphogypsum Stack, USS Agri-Chemical Plant	5-54
5-33	Side of Completed Phosphogypsum Stack, USS Agri-Chemical Plant	5-55
7-1	Mass Loading of TDS to Subsoil for Various Disposal Modes of Treated and Untreated FGC Wastes	7-16
7-2	Concentration of Major Species in Leachate	7-24
7-3	Coefficient of Permeability for Different Soil Types at Unit Gradients	7-27
7-4	Effect of Fine Fraction on Soil Permeability	7-28
7-5	Falling Head Permeability Apparatus	7-29
7-6	Constant Head Permeameter	7-31
7-7	Field Permeability Tests Conducted in Boreholes	7-33
7-8	Average Net Precipitation in the United States	7-34
7-9	Water Balance for Landfill	7-37
7-10	Quantity of Leachate from a Landfill	7-38
7-11	Water Balance for Disposal Pond	7-41
7-12	Effect of Sludge Permeability on the Volume of Leachate from a Pond	7-42
7-13	Factors in Predicting Seepage Rates	7-44
7-14	Length of Flow Regime for Difference in Hydraulic Head of 10 Feet	7-45

Figure		Page
7-15	Dissolved Solids from Calcilox-Treated Material at TVA Field Test	7-52
7-16	Leachate Dissolved Solids from Poz-O-Tec at TVA Field Test	7-53
7-17	Installed Liner Costs	7-59
8-1	Typical Diked Pond Installation	8-3
8-2	Diked Pond Partially Excavated Below Grade	8-4
8-3	Diked Pond Constructed Above Grade	8-5
8-4	An Incised Disposal Pond	8-6
8-5	A Side-Hill Disposal Pond	8-7
8-6	A Cross-Valley Pond Configuration	8-9
8-7	Cross-Valley Sludge Disposal Pond, Bruce Mansfield Plant, Pennsylvania Company	8-10
8-8	A Heaped Landfill Configuration	8-11
8-9	Examples of Heaped and Valley-Fill Construction	8-12
8-10	A Side-Hill Landfill	8-13
8-11	A Valley-Fill Disposal Configuration	8-14
8-12	Homogeneous Pond Embankments	8-37
8-13	Typical Zoned Embankment Section	8-38
8-14	Example Calculation of Seepage Underflow	8-42
8-15	Cutoff and Partial Cutoff Trenches	8-45
8-16	Typical Sheet Piling Cutoff	8-46
8-17	Upstream Impervious Blankets and Downstream Filter Blankets	8-48
8-18	Example of Typical Filter Design	8-51
8-19	Flattened Embankment Slopes for Stabilization of Fine-Grained Foundations	8-56
8-20	Range of Impervious Core Sizes for Zoned Embankments	8-64
8-21	Staged Ponding, Upstream Method	8-69
8-22	Staged Ponding, Downstream Method	8-70
8-23	Typical Section Through a Valley-Fill or Side-Hill Fill	8-98
8-24	Schematic Example of Heaped Landfill	8-99
8-25	Examples of Methods of Development of Heaped Fills	8-100
8-26	Schematic Examples of Side-Hill Landfills	8-102
8-27	Schematic Examples of Valley-Fill Landfills	8-103
8-28	Underdrain Schemes for Landfills without Impoundments	8-106
8-29	Typical Spring Collection Device	8-107
8-30	Typical Design Details for Drainage Facilities	8-109
8-31	Typical Access Road	8-114

ILLUSTRATIONS (Cont.)

Figure		Page
8-32	Alternative Site Entry Configurations	8-116
8-33	Typical Plan for Determining Magnitude and Direction of the Hydraulic Gradient	8-126
8-34	Typical Plan for Determining Aquifer Permeability by Well Pumping	8-127
8-35	Typical Monitoring Network	8-129
8-36	Monitoring Network for Aquifers with Intergranular Porosity	8-130
8-37	Example of Monitoring Well	8-132
8-38	Piezometer Modified for Collection of Water Samples	8-135
9-1	Percent Solids in Mixes of Flyash with Sludge of Various Solids Content	9-15
10-1	Arrangement of the Venturi/Spray Tower Oxidation Tank with Sparger	10-3
10-2	Jet Bubbling Reactor	10-4
10-3	Flow Diagram for Two-Scrubber-Loop Forced Oxidation	10-6
10-4	Flow Diagram for One-Scrubber-Loop Forced Oxidation	10-8
10-5	Flow Diagram for Bleed Stream Oxidation	10-10
10-6	Sherburne County Wet Scrubber System	10-12
10-7	Kellogg Scrubbing System	10-13
10-8	Oxidation and Its Sludge Thickening Characteristics	10-14
10-9	Effect of Oxidation on Initial Settling Rate	10-16
11-1	Relationship Between Sludge Volume and Solids Content	11-2
11-2	Sludge Processing Flow Sheet	11-4
11-3	Removing Settled Sludge from Settling Pond	11-7
11-4	Lamella Clarifier Thickener	11-9
11-5	Cross-Section of a Conventional Gravity Thickener	11-11
11-6	Typical Gravity Thickener	11-12
11-7	Thickener Flow Pattern and Concentration Zones	11-14
11-8	Thickener Plow Blade Designs	11-17
11-9	Hinged Rake Arm Designs for Thickeners	11-18
11-10	Thickener Cross-Section Showing Tunnel	11-20
11-11	Results of a Thickener Settling Test	11-23
11-12	Solid Flux Curve for Continuous Gravity Thickener	11-27
11-13	Typical Gravity Thickener Section Showing Pickets	11-30
11-14	Cyclone Cross-Section	11-31
11-15	Typical Rotary Drum Vacuum Filter	11-35
11-16	Cutaway View of a Rotary Drum Vacuum Filter	11-36
11-17	Cross-Section of a Belt Filter	11-37

ILLUSTRATIONS (Cont.)

Figure		Page
11-18	Difference in Drying Times of Belt Discharge and Scraper Discharge	11-38
11-19	Flow Sheet for Continuous Rotary-Drum Vacuum Filtration	11-40
11-20	Filter Leaf Test Apparatus	11-45
11-21	Typical Solid Bowl Centrifuge	11-49
11-22	Cross-Section of Solid Bowl Centrifuge	11-50
11-23	Beta Concept for Sizing Centrifuges - Definition of Terms	11-56
11-24	System for Preparation and Feed of Dry Polymer	11-58
11-25	Thickener Area and Capital Cost	11-60
11-26	Capital Costs for Vacuum Filters	11-61
11-27	Centrifuge Capital Cost as a Function of Centrifuge Capacity	11-62
12-1	Alternatives for Blending Non-Alkaline Flyash	12-11
12-2	Alternatives for Blending Alkaline Flyash	12-14
12-3	Alternatives for Blending Flyash and Lime	12-17
12-4	Dravo Treatment Processes	12-24
12-5	Top View of Double-Shaft Mixer	12-34
12-6	Top View of Muller Mixer	12-35
13-1	Belt Conveyor Components	13-13
13-2	Belt Conveyor Arrangements	13-15
13-3	Nomograph for Determining the Volume of Conical Surge Piles	13-23
13-4	Windrow Formed by a Radial Stacker	13-24
13-5	Conveyor Belt Placement of FGD Sludge in Surge Piles	13-26
13-6	Radial Stacker, Conesville Station, Columbus and Southern Ohio Electric Company	13-28
13-7	Viscosity of Typical Sludges	13-30
14-1a	All Processes - Effect of Power Plant Size and Age on Total Capital Investment	14-14
14-1b	All Processes - Effect of Power Plant Size and Age on Total Annual Revenue Requirements	14-15
14-2	All Alternatives. Correction Factors for % S in Coal	14-19
14-3	Ponding Without Fixation. Correction Factors for % Ash in Coal	14-20
14-4	Landfill Alternatives. Correction Factors for % Ash in Coal	14-21
14-5	Ponding Without Fixation. Correction Factors for Distance to Disposal Site	14-22
14-6	Landfill Alternatives. Correction Factors for Distance to Disposal Site	14-23
14-7a	Landfill Alternatives. Correction Factors for Long Distances to Disposal Site - Capital Investment	14-24

Figure		Page
14-7b	Landfill Alternatives. Correction Factors for Long Distance to Disposal Site - Annual Revenue Requirement	14-25
14-8	Ponding without Fixation. Correction Factors for Land Availability	14-26
14-9	Ponding without Fixation. Correction Factors for Synthetic Liner Costs	14-27
14-10	All Alternatives. Correction Factors for Levelized Annual Revenue Requirements	14-28
14-11	Limestone Slurry Process Dike Construction	14-36
14-12	IUCS Process. Flow Diagram and Material Balance	14-37
14-13	IUCS Process. Overall Plot Plan	14-38
14-14	IUCS Process. Elevation Plot Plan	14-39
15-1	Samples of Wallboard Made from FGD Gypsum and Natural Gypsum	15-5
15-2	Using Poz-O-Tec as a Base Material in Construction of a Parking Area	15-12
15-3	Placing Poz-O-Tec as a Base for an Ash Haul Road	15-13
16-1	Phosphate Fertilizer Gypsum Stack	16-2
16-2	Upstream Method of Gypsum Stack Construction	16-4
16-3	Typical Gypsum Stack Design	16-6
16-4	Bearing Capacity Type Foundation Failure	16-8
16-5	Progressive Type Slope Failure	16-8
16-6	Seepage Pattern Through a Gypsum Stack on a Pervious Foundation	16-10
16-7	Seepage Pattern Through a Gypsum Stack on an Impervious Foundation	16-10
16-8	Effect of Internal Drain on Seepage Pattern Through a Gypsum Stack on an Impervious Foundation	16-10
16-9	Fixed Vertical Riser Decant System	16-13
16-10	Stage Decant System	16-13
16-11	Perimeter Seepage Collection Ditch for Gypsum Stack on a Deep Sand Deposit Overlying an Impervious Foundation	16-15
16-12	Perimeter Seepage Collection Ditch for Gypsum Stack on a Shallow Sand Foundation Overlying a Thick Clay Deposit	16-15
16-13	Use of a Cut-Off Trench to Control Seepage from a Gypsum Stack	16-16
16-14	Use of an Impervious Liner and Underdrain to Control Seepage from a Gypsum Stack	16-16
16-15	Use of Elevated Ditch to Sediment Coarse Gypsum Around Perimeter of Stack	16-18
16-16	Flattening Gypsum Stack Slopes by Benching	16-20
16-17	Stacking Area Prior to Initial Dike Raising	16-22
16-18	Raising North Wall of Cast Gypsum Dike	16-23
16-19	Dragline Operation from Crest of Cast Gypsum Dike	16-24

ILLUSTRATIONS (Cont.)

Figure		Page
16-20	Completed Gypsum Stack	16-25
16-21	Scanning Electron Photomicrographs of Chiyoda FGD Gypsum	16-27
16-22	Grain Size Distribution	16-28
16-23	Drying Curve Characteristics	16-30
16-24	Sedimentation - Consolidation Behavior	16-31
16-25	Void Ratio versus Coefficient of Permeability	16-33
16-26	Typical Undrained Stress-Strain-Strength Behavior of FGD Gypsum	16-35
16-27	Void Ratio versus Effective Friction Angle	16-36

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TABLES

Table		Page
2-1	Sludge Processing and Disposal Practices for Utility Scrubbers in Operation - November 1, 1979	2-2
2-2	Planned Sludge Processing and Disposal Practices for Utility Scrubbers under Contract, Letter of Intent or Construction - November 1, 1979	2-5
2-3	Utility Scrubber Contacts	2-8
2-4	Japanese Electric Utility Scrubbers in Operation as of October 1, 1978	2-15
3-1	Identification of Chemical Phases of FGD Sludge Solids	3-6
3-2	Trace Element Composition of FGC Solids	3-7
3-3	Range of Concentration of Major Species in FGD Sludge, Liquors and Elutriates	3-8
3-4	Range of Concentration of Trace Elements in FGD Sludge, Liquors and Elutriates	3-9
3-5	Typical Analyses of Lime	3-17
3-6	Trace Element Analyses of Lime and Limestone Samples	3-18
3-7	Typical Analyses of Limestone	3-19
3-8	Results of Chemical Analyses of Flyashes	3-21
3-9	Precipitator Ash Trace Element Analyses	3-23
3-10	Chemical Analyses of Lime Process Sludges	3-26
3-11	Trace Element Content of Coal Samples	3-28
3-12	Typical Ash Composition from Western Coals	3-30
3-13	Typical Engineering Properties of FGD Sludges	3-34
3-14	Percent Solids Achieved by Various Laboratory Dewatering Techniques	3-35
3-15	Trace Element Concentration in Scrubber Liquor	3-47
3-16	Representative Trace Element Concentrations in Coal Ash Leachate	3-48
4-1	Estimation of Scrubber Waste Quantities - Assumptions	4-6
4-2	Estimation of Waste Quantities - Calculations	4-8
4-3	Estimation of Waste Quantities - Summary	4-11
4-4	Weight of Dry SO_x Sludge Resulting from Scrubbing Emissions from One Million Tons of Fuel to Meet 1979 NSPS Standards	4-13
4-5	Weight of Dry SO_x - Flyash Solids Resulting from Scrubbing Emissions from Lignite or Sub-bituminous Coal	4-14
4-6	Quantity of Wet Scrubber Solids Containing One Thousand Tons of Dry Solids	4-15

TABLES (Cont.)

Table		Page
5-1	Examples of Processing/Disposal Options	5-8
6-1	Site Evaluation Criteria	6-6
7-1	EPA Interim Primary and Proposed Secondary Drinking Water Standards	7-3
7-2	EPA Draft Extraction Procedure	7-4
7-3	Range of Concentration of Major Species in FGD Sludge, Liquors and Elutriates	7-7
7-4	Range of Concentration of Trace Elements in FGD Sludge, Liquors and Elutriates	7-8
7-5	Comparison of Constituents in FGD Sludge, Liquors and Elutriates to Drinking Water Standards	7-9
7-6	Comparison of Constituents in FGD Sludge, Liquors and Elutriates to Irrigation Water Standards	7-10
7-7	Tendencies for Various Elements to be Preferentially Concentrated in Coal Combustion Residue	7-14
7-8	Chemical Constituents in Leachate from Untreated and Chemically Treated FGD Waste After 1 and 50 Pore Volume Displacements	7-17
7-9	Example Calculation of Pond Seepage Rate	7-46
7-10	Procedure for Determining Cation Exchange Capacity	7-55
7-11	Reference Conditions for Liner Cost Estimates	7-64
7-12	Estimated Costs for Disposal of Untreated FGD Waste in Ponds with Indigenous Clay Soil	7-65
7-13	Estimated Costs for Ponding Untreated Wastes with Flexible 20-Mil PVC Liner	7-65
8-1	Relative Density of Sands According to Results of Standard Penetration Test	8-28
8-2	Relation of Consistency of Clay, Number of Blows on Sampling Spoon and Unconfined Compressive Strength	8-29
8-3	Summary of Typical Laboratory Soil Tests for Various Materials	8-31
8-4	Unified Soil Classification System	8-32
8-5	Dam Size Classifications	8-33
8-6	Treatment of Coarse-Grained Foundations	8-53
8-7	Recommended Slopes of Stabilizing Fills for Dams on Saturated Silt and Clay Foundations	8-57
8-8	Recommended Slopes for Small Homogeneous Earthfill Dams on Stable Foundations	8-62
8-9	Recommended Slopes for Small Zoned Embankments on Stable Foundations	8-65
8-10	Minimum Design Storm Criteria for Long-Term Disposal Impoundments	8-76
8-11	Minimum Design Criteria for Short-Term Hydraulic Structures	8-77
8-12	References for Hydraulic Design	8-84
8-13	Suggested Haul Road Design Criteria	8-115

TABLES (Cont.)

Table		Page
8-14	Suggested Analytical Parameters for Water Samples	8-136
8-15	Typical Dry Bulk Density Values of Landfilled FGC Wastes	8-136
8-16	Pond Inspection Check List	8-139
8-17	Landfill Inspection Check List	8-140
8-18	Some Recreational Features Suitable for Landfill Areas	8-144
9-1	Estimation of Waste Quantities	9-7
9-2	Disposal Site Volumes at 45% Capacity Factor	9-8
9-3	Volume of Scrubber Sludge Pumped to Disposal Pond	9-10
9-4	Volume of Supernatant Return	9-11
10-1	Capital Investment for Base-Case Waste Disposal Processes	10-21
10-2	Annual Revenue Requirements for Base-Case Waste Disposal Processes	10-21
11-1	Summary of FGD Sludge-Dewatering Practices	11-3
11-2	Typical Solids Concentrations of FGD Sludges	11-5
11-3	Typical Sludge-Filtration Rates for Vacuum Filters	11-44
11-4	Effects of Centrifuge Variables on Performance	11-53
12-1	Composition of Blast Furnace Slag	12-8
12-2	Blast Furnace Slag Reactions	12-8
12-3	Sulfate and Sulfite Reactions	12-9
12-4	Present and Planned IUCS Installations	12-22
13-1	Typical Test Data on FGD Sludges	13-9
13-2	Alternative Transportation Modes	13-12
13-3	Belt Conveyor Capacities and Load Cross-Sectional Areas	13-14
14-1	Typical Assumptions Used to Determine the 30-Year Levelized Fixed Charge Rate	14-2
14-2	Economic Factors	14-2
14-3	Design and Cost Estimate Classifications	14-6
14-4a	Reported FGD Disposal Costs from Operating Systems	14-5
14-4b	Summary of Estimates of Sludge Disposal Costs Reported in the Literature	14-8
14-5	Index of Figures to be Used to Obtain Correction Factors for Estimating System Costs	14-16
14-6	Power Unit Operating Schedules for TVA Facilities	14-30
14-7	Typical System Description - Untreated Disposal	14-32
14-8	Material Balance - Untreated Process	14-33
14-9	Untreated Disposal - Base Case Equipment List	14-33
14-10	Typical System Description - IUCS Process	14-34
14-11	IUCS Process - Base Case Equipment List	14-35
14-12	Untreated Disposal. Total Capital Investment - Equipment and Installation	14-41

TABLES (Cont.)

Table		Page
14-13	IUCS Process. Total Capital Investment - Equipment and Installation	14-42
14-14	Guidelines for Assigning Process Contingency Allowances	14-44
14-15	Example of AFDC Calculation from the Construction Period Cash Flow .	14-46
14-16	Untreated Disposal. Total Annual Revenue Requirements	14-48
14-17	IUCS Process. Total Annual Revenue Requirements	14-49
14-18	Cost Indexes and Projections	14-50
14-19	Levelized Annual Revenue Requirements - Both Cases	14-53

SUMMARY

Requirements of regulatory agencies at various levels of government for the clean up of stack emissions will result in ever-increasing quantities of solid waste from the combustion of solid fossil fuels. Compounding the problem will be the increased use of solid fossil fuels resulting from conversions from oil or gas as utility boiler fuels. Bottom ash and flyash are solid wastes that have required disposal for many years. However, the requirements for reduced particulate emissions will result in greater quantities of flyash to be disposed. Furthermore, with the requirement for the removal of sulfur oxides from stack emissions, the overall quantity of waste can be more than doubled in some cases.

Presently, the most-used type of sulfur oxide removal is the wet scrubber, and this type is expected to be predominant into the 1990's. The waste produced by wet scrubbing is a sludge composed of the scrubbing liquor, calcium sulfite/sulfate solids and varying quantities of flyash. It is necessary to dispose of this sludge either alone or in combination with flyash and/or bottom ash. Since the combustion wastes of today may be a natural resource of the future, consideration should be given to the fact that the presently disposed material may be reclaimed at a future date.

The chosen disposal method must be economical and result in a properly placed, structurally stable material. Furthermore, the process must be environmentally acceptable, and, with the present and near-future provisions of the Resource Conservation and Recovery Act (RCRA), this aspect is expected to have growing importance.

Guidance is provided for the designers and operators of electric utilities in providing for the disposal of scrubber sludge. The disposal of flyash and bottom ash is considered only in the case of co-disposal of one or both with the sludge. Present and proposed scrubber disposal systems are listed along with pertinent factors to indicate current practices and trends. Operating companies with scrubbers possess a wealth of information gained from experience and can be of great assistance in pointing out pitfalls to be avoided. In many cases, the trends indicated for planned waste management are illustrative of practices developed from the earlier disposal systems.

All sludge disposal systems can be categorized as wet or dry, or as ponding or landfilling. Wet disposal has been used for years as the method of choice for bottom ash and flyash. It was only natural that many utility operators would choose this familiar method for sludge disposal because of ease and economy of operation. However, practice is trending toward dry disposal because of lower capital costs and environmental pressures. Decision paths lead the designer and operator through the three steps which are required for all systems, wet or dry. The steps are processing, transportation and disposal. Alternative procedures exist in each of the steps and require consideration and evaluation.

An important preliminary step in any sludge disposal system is consideration of the chemical/physical characteristics of the material. The predominant solid components are calcium sulfite, calcium sulfate and flyash. Each of these can have an important effect on sludge characteristics and on the procedures to be followed in planning for and designing disposal systems. Flyash can vary considerably in quantity, depending on the presence and efficiency of upstream flyash removal devices and, in the case of alkaline flyash, the use of the flyash as all or a part of the scrubber reagent. The proportions of calcium sulfite and calcium sulfate depend on the type of reagent, air inleakage to the gas system, presence of an oxidation catalyst or inhibitor and the utilization of forced oxidation. Predictions or estimates of relative quantities of the components can be made from a knowledge of the boiler system, upstream particulate removal equipment, fuel and reagent analyses and the liquid cycle of the scrubber/disposal system. These data can be obtained from pilot or prototype operation, from similar full-scale systems, or from equipment/material specifications.

Of equal importance with sludge characteristics is the quantity to be processed, transported and disposed. The predictions and estimates developed above can be used to estimate sludge quantities by a series of assumptions and calculations. This is further developed by consideration of various water contents in the sludge to be disposed.

With the information developed to this point and with other pertinent influences, a decision can probably be made as to whether wet or dry disposal is favored. Consideration should then be given to disposal site selection and design. Although the types of sites for the two methods may be completely different, many aspects of selection and design are the same. It is not a simple process. Many steps must be considered and are explained in detail. Not the least of these is the thorough exploration of environmental requirements. Current regulatory requirements at federal

and selected-state levels are given, including the regulations for leachate control and monitoring wells. Liner materials and well location and construction details are discussed.

The first step in designing the disposal system is the choice of processing steps. Processing includes the options of whether to (1) change the sludge characteristics by forced oxidation to the calcium sulfate or gypsum form, (2) dewater by gravity or mechanical means, or (3) stabilize by the addition of flyash or fixate by the addition of a fixating agent with or without flyash. Each of these options has disadvantages ranging from added cost of equipment or operation to increased solubility of calcium sulfate over calcium sulfite. Advantages may include better water separation, less volume of waste to handle and better structural properties. Information is given on experimental, prototype and commercial methods for the forced oxidation option, with typical results and costs where available. The pros and cons of the option are discussed. Various means of dewatering include gravity settling in ponds, thickeners, and lamina-type settlers. Cyclones, vacuum filters and centrifuges are described. The dewatering equipment is classified as to first- and second-stage devices, advantages and disadvantages discussed, and design details provided. The final option in processing, stabilization or fixation, can be as simple as on-site mixing of alternate loads of flyash and dewatered sludge or as elaborate as the dewatering/blending plants designed and, in some cases, operated by the two commercial fixation companies whose processes are described.

Transportation is the next step in the decision path. There is no choice to be exercised when wet disposal is used. The only practical method is by pipeline, although specially-equipped trucks or rail cars could conceivably be used but appear impractical. Design and equipment details are discussed. Suggestions for operation and inspection are provided for both wet and dry systems. For dry transportation, a variety of earth-moving equipment and rail cars is available and in use. Design and equipment choices are covered.

Disposal/utilization is the final step in the system, and much of this is considered early in the decision process in order to make the primary choice of wet or dry disposal. A very important factor in the decision is system cost. Examples of cost data are discussed, curves provided for estimating typical costs, and a sample calculation given for one processing-transportation-disposal system.

Utilization, to this point, has not developed as a viable alternative to disposal. With more interest in and use of forced oxidation, the potential for utilization should increase. Calcium sulfate or abatement gypsum has found limited experimental use in agricultural application, use in wallboard and as a set-retarding agent in cement. These and other experimental applications are listed, and references for obtaining additional information are given.

A method of storage/disposal which is new for abatement gypsum has been used in a prototype scrubber test under EPRI sponsorship. The method is termed "stacking" and has been used for over 20 years by the phosphate fertilizer industry in Florida. As described, the gypsum is transported as a slurry to the stack where gravity dewatering takes place, so disposal/storage is actually a dry method.

Section 1

INTRODUCTION

PURPOSE

The current trend in selecting flue gas desulfurization (FGD) equipment is toward throwaway scrubbing systems, primarily lime and limestone, with alkaline flyash double-alkali and dry scrubbers to a lesser extent. A significant quantity of waste is generated by these systems. At present, there are no prospects for large-scale utilization of the by-product. As a result, the waste product must be disposed of in an environmentally-acceptable manner.

It is impossible to emphasize too strongly the necessity for early consideration of the important problem of scrubber sludge handling and disposal. This decision should accompany the choice of a scrubber system. Some utilities are finding it advisable to have one contract cover both the scrubber system and waste disposal. In this connection, it might be advisable to make the two aspects complementary but also separable. At any rate an early decision on the important question of FGD waste disposal is highly advisable. To delay on the decision will reduce the number of options available.

In devising disposal schemes, consideration should be given to the strong possibility that today's waste may be a natural resource of the future. Ash can be a source of metals, fill material or aggregate for road or building materials. Sulfur-based wastes can be a source of gypsum for building materials or soil amendments, or of elemental sulfur or sulfuric acid. Consequently, it may be advisable to stockpile the ash and sludge separately and to record the areas where each can be found.

The purpose of this Manual is to provide information and direction to utilities so that they can select and design FGD by-product disposal systems and components with confidence. The Manual is intended as a useful summary tool for evaluating alternative approaches and making practical planning and design decisions about a solid waste disposal system.

The Manual will be periodically updated in order to keep abreast of changes in regulatory requirements, the changing technology and the experience of operating utilities

with FGD waste disposal. The up-dates will be made as often as is warranted by changes in the state-of-the-art. Future up-dates will cover the emerging technology of dry scrubbing and the wastes which are produced.

BACKGROUND

The Manual represents one end-product of an R & D program relating to the problems of scrubber waste disposal which was discussed in October, 1975, at a workshop of the EPRI By-Product/Waste Disposal Working Group. One result of the workshop was RP 786. Four of the major tasks in the project were:

Task 1 - Evaluate Existing Data Base

Task 2 - Define and Quantify Leachate Variables

Task 3 - Evaluate State-of-the-Art of Sludge Fixation

Task 4 - Develop FGC Waste Disposal Guidelines. This was later changed to FGD Sludge Disposal Manual with an enlarged scope.

The first two tasks were contracted to Radian Corporation as RP 786-2 and Tasks 3 and 4 to Michael Baker, Jr., Inc., as RP 786-1 in November, 1976. Reports on the first three tasks are identified as FP 671, Volumes 1, 2 and 3, the volume numbers corresponding to the task numbers. The scopes of the first three tasks were structured so that they would provide information and data for preparation of the Manual.

A third contract, RP 786-3, was later awarded to Envirotech under the title "Sludge Dewatering Methods for FGD Products". The report of this project has been published as EPRI FP-937 (May, 1979).

SCOPE

The Manual considers wastes from lime, limestone, alkaline-flyash, and double-alkali wet scrubbing systems designed for flue gas desulfurization of flue gas from utility boilers. The discussion also includes disposal of flyash, when the flyash is collected in the scrubber and becomes part of the sludge, or when flyash relates to sludge disposal. The Manual does not address collection and disposal of flyash as a separate by-product; this is included in the scope of EPRI RP 1404, Coal Ash Disposal Manual, FP-1257, December 1979.

The Manual also does not cover dry-scrubbing wastes because no full-scale system is yet in operation. These processes use either sodium- or calcium-based reagents. They will result in dry solid wastes which will be easier to handle than wet wastes but may give problems in disposal. Sodium compounds will be extremely soluble, and

leachate can affect ground water. The disposal of calcium compounds can cause the same problems as experienced with the dry disposal of wastes from lime/limestone wet scrubbers. Protection of ground/surface water, prevention of dusting and the possible restrictions of upcoming regulations must all be met. As these systems go into service and operating experience is gained, the Manual up-dates will reflect the state-of-the-art. No coverage is included regarding surface water discharges from storm-water runoff which are regulated under the National Pollutant Discharge Elimination System (NPDES).

The Manual is intended to provide guidance and direction in determining the optimum disposal system for a particular situation. While intended to be as comprehensive as possible, the Manual is necessarily restricted because some factors which influence selection decisions are specific to a certain region or even to an individual utility or station. Also, the relative importance of some decision-making factors varies from situation to situation. It is sufficient to state that each case is somewhat different, and the ultimate selection of a disposal system must be made by the individual utility, based on the site-specific conditions facing that utility.

DEFINITIONS

A new set of terms has grown along with the development of flue gas desulfurization. The purpose of this section is to define these terms, explain some of the subtle differences in meaning which are consistent with general usage, and to explain how these terms are used in this Manual.

Flue Gas Cleaning (FGC)

Flue gas cleaning is a general term which refers to scrubbers, electrostatic precipitators, mechanical collectors, and other collection equipment designed to remove particulate matter and/or sulfur oxide gaseous constituents from flue gases. Therefore, FGC by-products can include both scrubber sludge and flyash, collected either separately or together.

Flue Gas Desulfurization (FGD)

Flue gas desulfurization systems refer to scrubbers designed primarily for removal of the sulfur oxide gaseous constituents of flue gases. The central focus in this Manual is on problems associated with throwaway FGC by-products from electric utility installations employing wet scrubbers in the FGD system.

Scrubber Sludge

The term scrubber sludge means the liquid/solids bleed stream from the scrubber which carries away the reaction products and contains water, dissolved solids and suspended solids (predominantly calcium sulfite, calcium sulfate, and sometimes flyash). These sludges are the waste products from lime, limestone, alkaline fly-ash and double-alkali wet scrubbers. In this Manual, the terms scrubber sludge, FGD scrubber sludge and FGD sludge are all used synonymously and interchangeably.

Fixation/Stabilization

There is no clearcut difference between the terms stabilization and fixation as used in the industry. They are often used interchangeably and the terminology is somewhat confusing. Stabilization in a broad sense is any chemical and/or physical treatment designed to improve the chemical and/or physical properties of the sludge. Strictly speaking, this definition could include thickening/dewatering. However, stabilization is generally understood to mean addition of dry flyash, soil, or other dry additive to reduce the moisture content and improve handling characteristics without a chemical interaction between the sludge components and the additive. It is used in this context throughout this Manual.

Fixation or chemical treatment is defined as a type of stabilization which involves the addition of lime or other reactive material, such as blast furnace slag, alkaline flyash, or portland cement, to result in cementitious-type reactions in the sludge. These reactions bind the sludge particles together, thus increasing shear strength and reducing permeability. The structural stability and environmental characteristics of the waste product are thereby improved.

SYSTEM OVERVIEW

Nearly all existing FGD sludge disposal systems consist of three principal operations:

- Processing
- Transportation
- Disposal

Processing (discussed in Section 9 - PROCESSING ALTERNATIVES) includes various methods for changing the characteristics of the raw scrubber waste to make more alternatives available for transportation and disposal. The practical processing alternatives include:

- Forced Oxidation (see Section 10)
- Thickening/Dewatering by (see Section 11)
  - -- Settling pond
  - -- Mechanical thickener
  - -- Vacuum filtration
  - -- Centrifuge
- Fixation/Stabilization by mixing with (see Section 12)
  - -- Flyash
  - -- Soil
  - -- Flyash and lime
  - -- Proprietary materials

In all systems, some type of transportation must be utilized to convey the scrubber waste to the processing facility and/or to the disposal site. Transportation alternatives include:

- Rail
- Barge
- Pipeline
- Earthmoving (e.g., truck, dozer)
- Conveyor

The selection of the appropriate alternative is a function of a number of system variables which are discussed in Section 13 - TRANSPORTATION.

Disposal is defined as the final placement of the sludge. The principal, practical disposal alternatives are:

- Wet Disposal (Ponding)
  - -- Diked construction
  - -- Watershed construction
  - -- Tiered ponds
  - -- Mine/quarry disposal
- Dry Disposal (Landfill)
  - -- Valley fill
  - -- Mounded fill
  - -- Surface mine/quarry disposal
  - -- Stacking

Other disposal alternatives are available in selected cases. These and the principal alternatives are discussed in an overview manner in Section 5 - DISPOSAL ALTERNATIVES and more details are provided in Section 8 - DESIGN OF DISPOSAL AREAS.

There is a large number of choices available from the array of alternatives. Figure 1-1 shows schematically the range of alternatives and some of the more important decision variables which should be considered in developing a workable disposal system. For the most part, Figure 1-1 follows the sequence of unit operations from scrubber bleed stream to ultimate disposal, in the order in which these operations normally occur.

Figure 1-1 can be used as a decision path, starting at the left with the scrubber bleed, and working to the right. For example, in starting with the scrubber bleed, a utility can choose either to oxidize or not oxidize the waste. Having made that decision, there is a choice of thickening/dewatering methods. Following that, there is the choice of whether or not to provide fixation or stabilization. If fixation is selected, then it is determined which method should be used. This selection process continues until the entire system has been selected.

Similarly, if site conditions or utility preference dictates a particular type of disposal, the diagram can be entered at the far right. The decision path may then be followed in reverse order to choose, in succession, the type of transportation, wet or dry alternative, fixation/stabilization, thickening/dewatering and finally whether or not to oxidize.

It should be noted that the processing, transportation, and disposal alternatives are strongly interdependent. That is, making a decision at one point, reduces the number of remaining alternatives available elsewhere in the system. Some of the alternatives are also mutually exclusive; that is, you cannot have one without the other. For example: If an FGD waste is not fully oxidized or is not fixed or stabilized, then landfilling is ordinarily ruled out. On the other hand, if forced oxidation is utilized, fixation/stabilization is not necessary and the sludge can be landfilled, if properly dewatered.

Virtually all existing or planned scrubber sludge disposal systems can be described as being a combination of the alternatives shown in Figure 1-1. For example, a ponding disposal system is illustrated conceptually in Figure 1-2 in the context of Figure 1-1. This shows no forced oxidation, mechanical thickening, pipeline transport, and ponding in a diked pond having a natural liner.

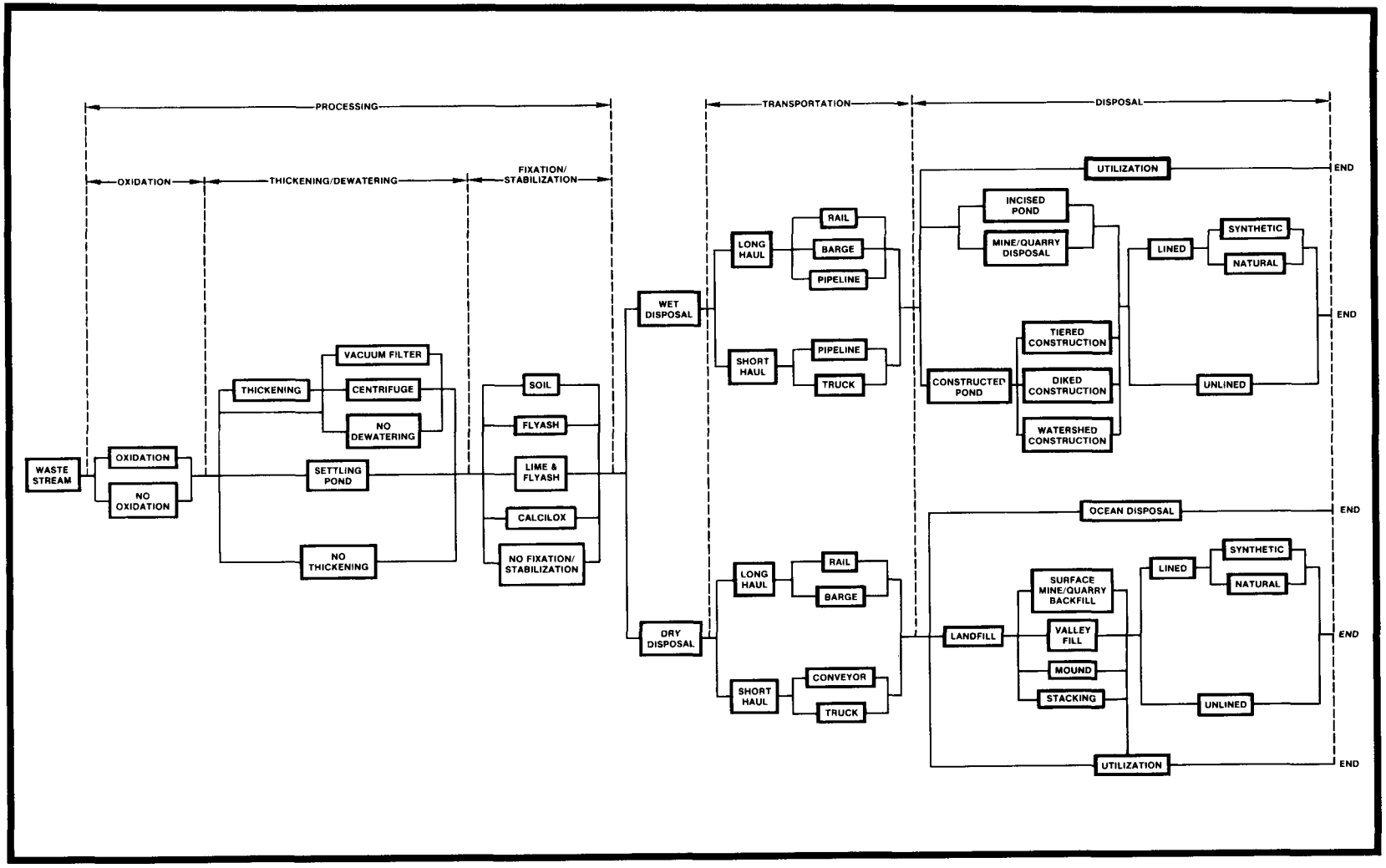


Figure 1-1. FGD Sludge Disposal Alternatives.

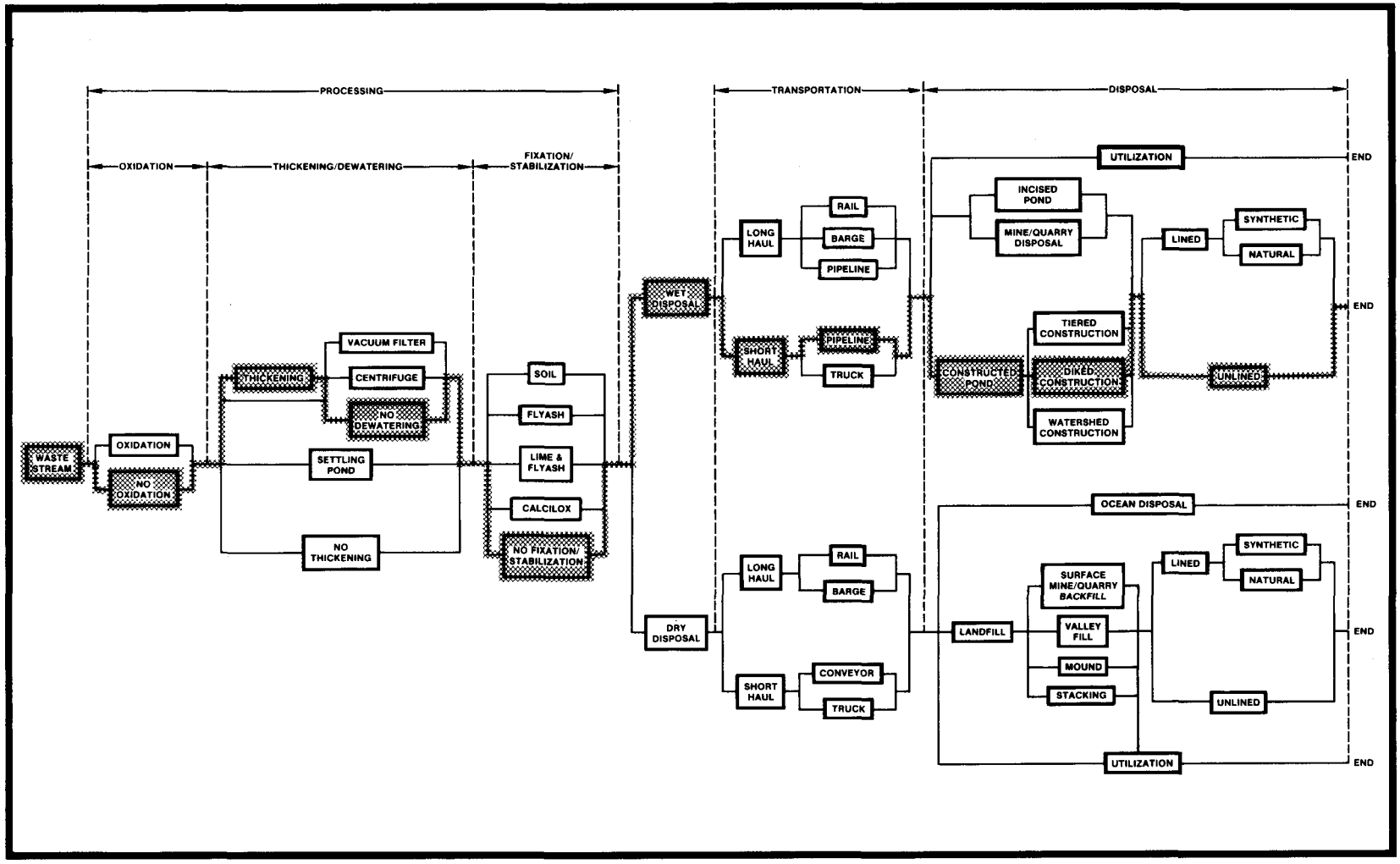


Figure 1-2. Wet Disposal of Sludge After Thickening.

In a like manner, Figure 1-3 illustrates the flow of waste through a plant such as that of the IU Conversion Systems at the Conesville Plant of the Columbus & Southern Ohio Electric Company. The sludge is not oxidized; it is dewatered by thickeners and vacuum filters, mixed with lime and flyash, and sent to dry disposal via conveyor to a mounded landfill for final disposal.

Other existing or planned facilities can be described in a similar manner. Figure 1-1, therefore, represents a general display of the principal, practical alternatives available in the processing/disposal sequence.

SELECTING A SYSTEM

The flow of operations, shown in Figure 1-1, is useful for describing the disposal system and for gaining perspective on the overall issue. However, it does not explain the sequence of events necessary to arrive at a final decision. There is a series of eight intermediate determinations which must be made to arrive at a decision. These steps are:

1. Characterize the waste - quality and quantity
2. Select a disposal option - wet or dry
3. Determine available disposal sites
4. Determine if a liner is necessary
5. Determine the processing requirements for the chosen option
6. Determine the transportation method
7. Evaluate systems on the bases of feasibility and cost.
8. Select a disposal system based on regulatory requirements, cost and company preference.

It is evident that these steps are something of an oversimplification of the decision-making process, because there are subquestions to be answered, and there is feedback from one step to another. Nevertheless, these are the critical questions, and this is primarily the order in which they must be answered. Consequently, this Manual is organized in the same sequence. Each section is devoted to a principal topic in which the options are explained, important factors highlighted, and guidance offered.

FUNDAMENTAL CONSTRAINTS

In the choice of a disposal system, there are two overriding factors which must be considered. These concepts are of paramount importance, and should continuously guide a utility's thinking in considering alternatives. The factors are:

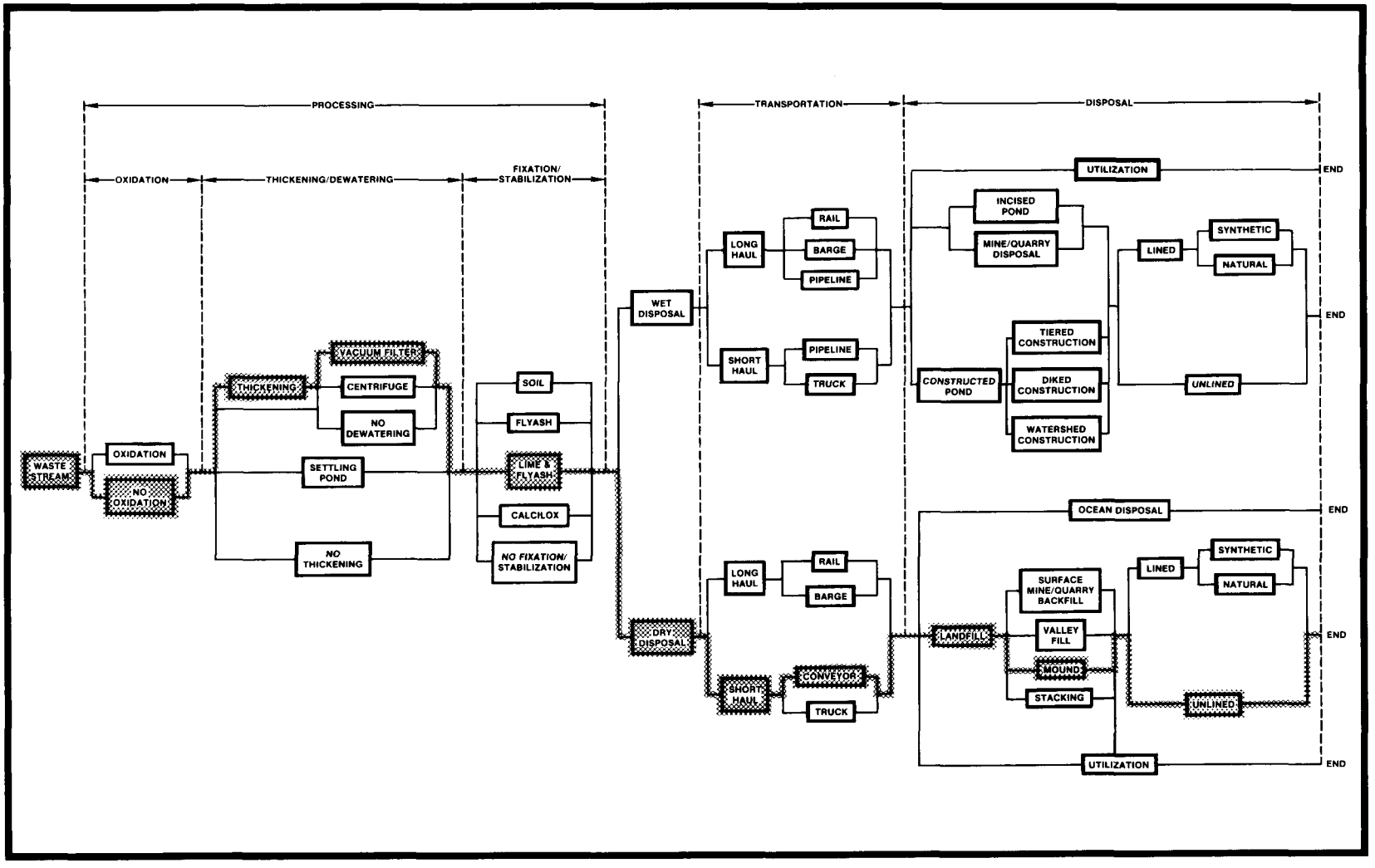


Figure 1-3. Dry Disposal of Sludge After Dewatering and Blending with Lime and Flyash.

1. THE DISPOSAL SYSTEM MUST NOT INTERFERE WITH THE OPERATION OF THE STATION OR THE SCRUBBER.

Several corollaries of this basic premise are:

- Sufficient equipment redundancy, emergency bypass, or contingency storage must be provided to insure that the disposal system can accept waste whenever the scrubber is operating. In this regard, the size must be such that peak waste production can be accommodated. Maximum power generation, worst coal conditions and foreseeable upsets should be considered.
- The system must be sufficiently flexible to accept waste under varying scrubber load and conditions. Ordinarily, this means surge capacity and equalization must be built into the system.
- The system must be able to operate year round in all types of weather. If an all-weather disposal operation is not possible, then sufficient storage must be provided to hold the waste until such time as the disposal operation can continue.
- The disposal area should be large enough to accommodate all the waste produced. It is not always desirable to fully develop a disposal site at one time to accommodate the service life of the scrubber. However, it is important to have a plan for a disposal area, even if only a portion of the waste will go there, or only a portion will be developed.

2. THE DISPOSAL AREA MUST BE STRUCTURALLY SOUND, ENVIRONMENTALLY ACCEPTABLE, AND PERMANENT.

- Structurally sound and permanent means the sludge or its containment must have sufficient physical and mechanical integrity that it will remain where it is placed and not be subject to displacement by flooding, overflow, slumping, sliding, slope failure, erosion or similar phenomena.
- Environmentally acceptable means that the area and its operation will not cause water, air or noise pollution or endanger public health, and it must meet all regulatory requirements.

PERTINENT REGULATIONS

It should be recognized that FGD sludge is a relatively new material and, as a result, regulatory agencies do not have a great deal of familiarity with its properties and characteristics, nor are they familiar with the technologies which are available to deal with potential problems. As a result, few regulations which specifically pertain to the disposal of FGD sludges have been issued at this time. In the absence of specific Federal guidance, state and local agencies have, for the most part, relied on standards and regulations developed around the disposal of other types of waste. Many of these other regulations are inappropriate or irrelevant in relation to FGD sludges. As discussed below, however, this situation is rapidly changing.

Federal Regulations

Prior to 1976, there were no Federal regulations which specifically related to FGD sludges. The two major pieces of Federal legislation addressing solid wastes, the Solid Waste Disposal Act of 1965 and the Resource Recovery Act of 1970, were aimed primarily at municipal solid waste and had no direct applicability to FGD sludges. Furthermore, there was little regulatory authority centered in these laws. The Federal government issued general guidelines and provided technical assistance, but had little power to regulate operations. This situation has now changed.

The Resource Conservation and Recovery Act of 1976 (RCRA) greatly expanded the role of the Federal government in regulating solid waste handling and disposal. Subtitle C of RCRA addresses hazardous wastes, while Subtitle D focuses on non-hazardous wastes. As required by the Act, the EPA is developing a detailed program for the regulation of hazardous wastes. Wastes defined as hazardous are subject to "cradle to grave" considerations.

In EPA's regulations of May 19, 1980 for identifying hazardous wastes, large volume utility wastes, including FGD sludge, were specifically excluded from regulation under Subtitle C. With this exclusion, FGD sludge will be primarily regulated as a non-hazardous waste under Subtitle D. However, the non-hazardous waste regulations are quite general and not specifically oriented toward FGD wastes. This generalized approach to the regulation of utility wastes may change in the near future as a result of an EPA program for developing standards which are specifically applicable to large volume utility wastes. The regulations evolving from this program will probably not be promulgated for four or five years. Therefore, while non-hazardous waste regulations will govern current FGD disposal activities, compliance with more detailed standards will likely be required in the future.

As previously mentioned, FGD sludge will be subject to the requirements for non-hazardous wastes which are to be implemented by the states under Subtitle D. This subtitle of RCRA prohibits open dumping and requires that environmentally acceptable practices be utilized. As provided for in the Act, the EPA has developed criteria for classifying solid waste disposal sites. Facilities which cannot meet the criteria standards will be considered "open dumps" which are illegal. The EPA has also proposed guidelines for landfill disposal of solid waste. These guidelines describe waste disposal practices which are recommended by the EPA for attaining compliance

with the aforementioned criteria. While the EPA has issued criteria and guidelines for non-hazardous waste management, the primary authority for implementing non-hazardous waste regulatory programs will continue to be with State agencies. A more detailed discussion of RCRA and associated Federal and State regulations is contained in Appendix B.

State Regulations

Current state regulations applicable to FGD sludges vary widely across the country. Most states have sufficiently broad legislative authority to regulate FGD sludge disposal in some degree. Some states have laws which allow direct control of solid wastes. Other states have indirect control through implementation of regulations designed to protect the ground water or limit activities in floodplains. Because there are no generally accepted criteria for FGD sludge disposal, and the material is relatively new, many states have imposed regulations developed for other materials. Requirements have been derived from regulations such as those for municipal-waste landfills, sewage lagoons, phosphate slime disposal, acid mine drainage sludges, and ore mine and smelter tailings. Some of these requirements are applicable but many are irrelevant or unnecessary. Because of these requirements, with FGD material most states proceed cautiously, issuing permits on a case-by-case basis.

The primary concern with pond disposal has been the integrity of dikes and impoundments. Regulations pertaining to such structures have been concerned with physical damage to persons or property and effects on ground or surface waters. Primary concerns with landfilled wastes have been those of structural stability and leachate/runoff effects on ground and surface water.

As a result of RCRA, many state programs are currently being revised. With EPA's encouragement and financial support, numerous state agencies are developing new regulations and the framework to implement them. Most state programs are being modeled after the Federal program in order to minimize complications in obtaining authorization from the EPA. Therefore, delays in finalizing EPA's regulations are, in turn, postponing the promulgation of state regulations.

In carrying out this new Federal program, the state agencies will continue to play an important role in permitting FGD sludge disposal sites. In spite of the increased Federal role, state requirements and procedures may differ substantially from state to state. In this light, utilities are advised to contact the appropriate state agencies to determine the prevailing permitting requirements.

Section 2

CURRENT DISPOSAL PRACTICES

PURPOSE

The purposes of this section are to:

- Summarize the activities of U.S. utilities in operating scrubber sludge disposal systems.
- Present examples of the various disposal options open to scrubber operators.
- List contacts which may be made to obtain first-hand planning and operating information.

This section provides a summary of FGD sludge disposal systems in operation in the U.S. as of November 1, 1979, a summary of the processing and disposal plans for plants in the U.S. which are scheduled for near-term start-up, and a summary of European and Japanese practices.

EXISTING U.S. DISPOSAL PRACTICES

The data in Table 2-1 show a total of 33 utilities using scrubbers on 62 units or groups of units, equivalent to 20,630 MW of scrubbed capacity as of November 1, 1979. Of these, 2590 MW represents scrubbers intended for particulate removal; however, there is incidental SO_2 removal, and sludge is produced.

Sludge from 37 of the 62 installations is being ponded, with that from 18 receiving no processing before ponding. One company uses forced oxidation on sludge from two units before disposal. Sludge from 19 units receives some dewatering by settling ponds or thickeners, with that from three being treated by commercial processes after dewatering by thickeners.

Sludge from the remaining 25 installations is disposed of in landfills. One plant uses an interim pond on sludge from a particulate scrubber before excavating for disposal. Sludge from eight units is thickened before ponding, then excavated. Flyash is added after two dewatering steps on the sludge from 10 units. Commercial fixation is used after a thickening stage for six units, with another four under contract.

Table 2-1

SLUDGE PROCESSING AND DISPOSAL PRACTICES FOR UTILITY SCRUBBERS IN OPERATION
November 1, 1979

OPERATING UTILITY	STATION NAME & UNIT NO.	MW ON SCRUBBER (s)	PARTICULATE REMOVAL	SO_2 REMOVAL		YEAR IN SERVICE	REAGENT [3]	FORCED OXIDATION	FLOCCULANT	THICKENER	DEWATERING [4]	MIX WITH FLYASH	COMMERCIAL FIXATION	TRANSPORTATION [5]	FINAL DISPOSAL	
				MFR [1]	TYPE [2]										POND	LANDFILL
Alabama Electric Coop	Tombigbee 2,3	360 [6]	ESP	P	ST	1979	LS							P	●	
Arizona Electric Power Coop	Apache 2	190	ESP	RC		1978	LS							P	●	
Arizona Public Service	Four Corners 1,2,3	580	Venturi	C	V	1979 [8]	FA-L			●				P	●	
	Cholla 1,2	470	Mech	RC	Flooded Disc + Absorber	1973,78	LS				SP			P	●	
Central Illinois Light	Duck Creek 1	415	ESP	R	VRA	1978	LS							P	●	
Columbus & So. Ohio Electric	Conesville 5,6	800	ESP	UOP	TCA	1977,78	L		●	●			IUCS	C		●
Commonwealth Edison	Will County 1	140	ESP + Venturi	(7)			LS			●	SP	●		T		●
	Powerton 51	450	ESP	UOP	TCA	1979	LS			●			IUCS	T		●
Cooperative Power Assn. - United Power Assn.	Coal Creek 1	335 [6]	ESP	CE	ST	1979	FA-L							P	●	
Detroit Edison	St. Clair 6	160	Mech + ESP + Venturi	(7)		1975	LS							P	●	
Duquesne Light	Elrama Station	500	Mech + ESP	C	V	1975	L		●	●			IUCS	T		●
	Philips Station	400	Mech + ESP	C	V	1973	L		●	●			IUCS	T		●
Indianapolis Power & Light	Petersburg 3	530	ESP	UOP	TCA	1977	LS			●			IUCS	T		●
Kansas City Power & Light	Hawthorn 3,4	360	CE Marble Bed	(7)		1977 [8]	L			●				P	●	
	LaCygne 1	875	Venturi	B&W	Perforated Plate	1973	LS							P	●	
Kansas Power & Light	Jeffrey 1	500 [6]	ESP	CE	ST	1978	FA-LS							P	●	
	Lawrence 4	125	Rod Venturi	CE	ST	1976 [8]	FA-LS	● [9]		●				P	●	
	Lawrence 5	420	Rod Venturi	CE	ST	1978 [8]	FA-LS							P	●	
Kentucky Utilities	Green River 1-3	65	Mech + Venturi	AAF	Mobile Bed	1976	L							P	●	
Louisville Gas & Electric	Cane Run 4	190	ESP	AAF	Mobile Bed	1977	CL		●	●			IUCS [10]	P	●	
	Cane Run 5	190	ESP	CE	ST	1977	CL			●				P	●	
	Cane Run 6	290	ESP	CEA/ADL	ST	1979	DA			●	DVF			T		●
	Mill Creek 3	425	ESP	AAF	Mobile Bed ST	1979	CL		●	●				P	●	
	Paddy's Run 6	70	ESP	CE	Marble Bed	1973	CL			●	DVF			T		●

Table 2-1 (Cont.)

OPERATING UTILITY	STATION NAME & UNIT NO.	MW ON SCRUBBER (s)	PARTICULATE REMOVAL	SO_2 REMOVAL		YEAR IN SERVICE	REAGENT [3]	FORCED OXIDATION	FLOCCULANT	THICKENER	DEWATERING [4]	MIX WITH FLYASH	COMMERCIAL FIXATION	TRANSPORTATION [5]	FINAL DISPOSAL	
				MFR [1]	TYPE [2]										POND	LANDFILL
Minnesota Power & Light	Aurora 1,2	115	Elbair Spray	(7)			FA							P	●	
	Clay Boswell 3	350	Elbair Spray	(7)			FA			●				P	●	
Minnkota Power Coop	Milton R. Young 2	405 [6]	ESP	CEA/ADL	ST	1978	FA-L			●	DVF			T		●
Monongahela Power	Pleasants 1	690	ESP	B&W	V + ST	1979	L			●			DRAVO	P	●	
Montana Dakota Utilities	Lewis & Clark	50	Mech	RC	Flooded Disc	1975	LS							P	●	
Montana Power	Colstrip 1,2	720	Venturi	CEA/ADL	ST	1975,76	FA-L							P	●	
Northern States Power	Sherburne 1,2	1480	Rod Venturi	CE	Marble Bed	1976,77	FA-LS	●		●				P	●	
Pacific Power & Light	Dave Johnston 4	330	Venturi	(7)			FA-L				SP			T		●
Pennsylvania Power	Bruce Mansfield 1,2	1840	Venturi	C	V	1976,77	L		●	●			DRAVO	P	●	
Potomac Electric Power	Dickerson 3	95 [6]	ESP + Venturi	(7)		1962	L		●	●	DVF			T		●
Public Service of Colorado	Cherokee 1, 4	490	MECH + ESP + UOP TCA	(7)			FA			●	SP			T		●
	Arapahoe 4	110					FA			●	SP			T		●
	Valmont 5	80					FA			●				P	●	
South Carolina Public Serv. Auth.	Winyah 2	140 [6]	ESP	B&W	V + ST	1977	LS			●				P	●	
Southern Illinois Power	Marion 4	185	ESP	B&W	V + ST	1979	LS			●	C	●		C		●
Southern Indiana Gas & Electric	A. B. Brown 1	265	ESP	FMC	ST	1979	DA			●	DVF			T		●
So. Mississippi Electric Power	R. D. Morrow 1,2	250[6]	ESP	R	VRA	1978,79	LS			●	BVF	●		C		●
Southwestern Public Service	Harrington 1	360	ESP + Marble Bed	(7)		WS								P	●	
Springfield City Utilities	Southwest 1	195	ESP	UOP	TCA	1977	LS		●	●	BVF	●		T		●
TVA	Widows Creek 8	575	ESP	TVA	V + Tray	1978	LS							P	●	
Texas Utilities	Martin Lake 1,2,3	1575 [6]	ESP	RC	DL	1977,79	LS			●	C	●		R		●
	Monticello 3	800	ESP	C	ST	1978	LS							P	●	
Utah Power & Light	Huntington 1	345 [8]	ESP	C	ST	1978	L		●	●	DVF	●		T		●
	Hunter 1	345 [8]	ESP	C	ST	1979	L		●	●	DVF	●		T		●

(1) Scrubber Manufacturer: AAF-American Air Filter; B&W-Babcock & Wilcox; CEA/ADL-Combustion Equipment Associates/Arthur D. Little; CE-Combustion Engineering; FMC-FMC Corporation; P-Peabody; RC-Research Cottrell; R-Riley; UOP-Universal Oil Products; C-Chemico.

(2) Scrubber Type: DL-Double Loop™; ST-Spray Tower; TCA-Turbulent Contact Absorber®; V-Venturi; VRA-Ventri Rod Absorber.

(3) Reagent: CL-Carbide Lime; DA-Double Alkali; FA-Flyash; L-Lime; LS-Limestone; WS-Waste $CaCO_3$ Slurry.

(4) Dewatering: BVF-Belt Vacuum Filter; DVF-Drum Vacuum Filter; C-Centrifuge; SP-Settling Pond.

(5) Transportation: C-Conveyor; P-Pipeline; R-Railroad; T-Truck.

(6) Some gas by-passed.

(7) Where no SO_2 removal equipment is indicated, there is some SO_2 removal by the particulate scrubber.

(8) This is service date for modified scrubber.

(9) Equipment installed but not used.

(10) Under contract. Process shown is currently in use.

It is of interest to note that drum vacuum filters are used for the second dewatering stage for seven units, belt vacuum filters for three and centrifuges for four. All six of the commercial dry fixation applications also use vacuum filters as a second dewatering step. Also of interest is the use of a flocculant by seven companies (12 units) to aid settling in thickeners. Forced oxidation facilities are installed by two companies on three units but is used by only one of the companies on two scrubbers.

To a certain extent, the data on existing systems reflect the use of early-generation scrubbers, many of which are retrofit systems, in which utilities were beginning to learn about full-scale disposal operations. In many cases, the disposal systems were designed so that sludge would be handled in the same manner (i.e., wet or dry) as the flyash has been traditionally handled. In some retrofit situations, there was no other choice. More recently, however, some newer trends have been developing and are discussed in the next section.

PLANNED U.S. PRACTICES

Table 2-2 shows the planned sludge processing and disposal practices for utility scrubbers under construction, contract or letter of intent as of November 1, 1979. A total of 51 additional units in 35 utilities will be provided with scrubbers, totalling an additional 24,385 equivalent MW scrubbed. These installations include new stations, addition of new units to existing facilities, and retrofit of scrubbers to existing plants. The closing date of this summary is such as to show little, if any, impact of the New Source Performance Standards of June, 1979.

The data are of interest in showing developments in scrubber systems and in the processing and disposition of scrubber sludge. The trend in scrubber construction is toward the use of spray towers with a minimum of internals to avoid the tendency toward plugging and scaling. All but one of the new wet scrubbers will include upstream particulate removal, and most (45 units out of 47) will use electrostatic precipitators; two will be using venturis. For the first time, dry scrubbing systems appear in the tabulation, with three installations totalling 1410 MW. Two of these will use lime as the reagent, the other, soda ash. Two will collect the waste in baghouses, one in an ESP. Waste disposal will be in landfills, one a mine. In relation to sludge disposal, there is a trend toward an increase in dry landfill disposal as opposed to ponding. Thirty-three of the new systems, amounting to 15,450 MW, will use landfill disposal, while 17 (8320 MW) will utilize ponding. A decision has not been made on one installation.

Table 2-2

PLANNED SLUDGE PROCESSING AND DISPOSAL PRACTICES FOR UTILITY SCRUBBERS UNDER CONTRACT, LETTER OF INTENT OR CONSTRUCTION AS OF November 1, 1979

OPERATING UTILITY	STATION NAME & UNIT NO.	MW ON SCRUBBER(s)	PARTICULATE REMOVAL	SO_2 REMOVAL		SCHEDULED-IN-SERVICE	REAGENT [3]	FORCED OXIDATION	THICKENER	DEWATERING [4]	MIX WITH FLYASH	COMMERCIAL FIXATION	TRANSPORTATION [5]	FINAL DISPOSAL	
				MFR [1]	TYPE [2]									POND	LANDFILL
Arizona Electric Power Coop	Apache 3	195	ESP	RC	DL	1979	LS						P	●	
Arizona Public Service	Cholla 4	220 [6]	ESP	RC	ST	1981	LS						P	●	
	Four Corners 4,5	1500	ESP	UE	HSA	1982	L						P	●	
Associated Electric Coop	Thomas Hill 3	730	ESP	PK	HSA	1982	LS	●	●	C	●		T		●
Basin Electric Power Coop	Laramie River 1,2	1140	ESP	RC	DL	1980	LS	●	●	C	●		C		●
	Laramie River 3	570	ESP	B&W	Dry	1982	L						C		●
	Antelope Valley 1	440	Bag House	Joy	Dry	1982	L						C or T		●
Big Rivers Electric Coop	Green 1,2	480	ESP	AAF	ST	1980	L		●			IUCS	T		●
Central Illinois Public Service	Newton 1	615	ESP	B	ST	1979	DA		●			IUCS	C & T		●
Cincinnati Gas & Electric	East Bend 2	600	ESP	B&W	V + ST	1981	L		●			IUCS	T		●
Colorado Ute Electric	Craig 1,2	900	ESP	P	ST	1979,80	LS		●	C	●		T		●
Columbus & Southern Ohio Electric	Poston 5,6	800	ESP	UOP	TCA	1987,90	L		●			IUCS	C or T		●
Cooperative Power Ass'n United Power Ass'n	Coal Creek 2	335 [6]	ESP	CE	ST	1980	FA-L						P	●	
East Kentucky Power Coop	Spurlock 2	500	ESP	CEA/AOL	ST	1980	L		●			IUCS	R		●
Hoosier Energy	Merom 1,2	980	ESP	M	ST	1981,82	LS		●			IUCS	T		●
Indianaopolis Power & Light	Petersburg 4	530	ESP	RC	DL	1983	LS		●			IUCS			●
Kansas Power & Light	Jeffrey 2	540	ESP	CE	ST	1980	LS						P	●	
Lakeland Utilities	McIntosh 3	350	ESP	B&W	ST	1981	LS		●			IUCS	C or T		●
Louisville Gas & Electric	Mill Creek 1,2	660	ESP	CE	ST	1981,82	CL/LS		●			IUCS	T		●
	Mill Creek 4	495	ESP	AAF	ST	1981	CL		●			IUCS	T		●
Minnesota Power & Light	Clay Boswell 4	555 [6]		P	ST	1980	FA-L						P	●	
Monongahela Power	Pleasants 2	690	ESP	B&W	V+ST	1980	L		●			DRAVO	P	●	
Montana Power	Colstrip 3,4	1560	Venturi	CEA/ADL	ST	1980,81	FA-L			SP			P	●	

Table 2-2 (Cont.)

OPERATING UTILITY	STATION NAME & UNIT NO.	MW ON SCRUBBER (s)	PARTICULATE REMOVAL	SO_2 REMOVAL		SCHEDULED-IN-SERVICE	REAGENT [3]	FORCED OXIDATION	THICKENER	DEWATERING [4]	MIX WITH FLYASH	COMMERCIAL FIXATION	TRANSPORTATION [5]	FINAL DISPOSAL	
				MFR [1]	TYPE [2]									POND	LANDFILL
Otter Tail Power	Coyote 1	400	Bag House	WF	Dry	1981	SA								●
Pennsylvania Power	Mansfield 3	920	ESP	PK	HSA	1980	L		●		●	DRAVO	P	●	
Public Service of Indiana	Gibson 5	650	ESP	PK	HSA	1982	LS		●			IUCS			●
Salt River Project	Coronado 1,2	640 [6]	ESP	PK	HSA	1979,80	LS		●				P	●	
San Miguel Electric Coop	San Miguel 1	435	ESP	B&W	V+ST	1980	LS		●	DVF	●		T		●
Sikeston Municipal Utilities	Sikeston 1	235	ESP	B&W	V+ST	1981	LS						P	●	
South Carolina Public	Winyah 3	280	ESP	B&W	V	1980	LS		●				P	●	
Service	Winyah 4	280	ESP	AAF	ST	1981	LS		●				P	●	
Southwestern Electric Power	Henry W. Pirkey 1	720	ESP	UOP	ST	1985	WS		●			IUCS	T		●
Springfield Water, Light & Power	Dallman 33	200	ESP	RC	DL	1980	LS	●		CY			T		●
TVA	Paradise 1,2	1400	ESP	C	V+ST	1982	LS	●	●	DVF			T		●
	Widows Creek 7	575	ESP	CE	ST	1980	LS	●	●	DVF			T		●
Texas Municipal Power	Gibbons Creek 1	410	ESP	CE	ST	1982	LS		●			IUCS	T		●
Texas Power & Light	Sandow 4	370 [6]	ESP	CE	ST	1980	LS	●					P	●	
Texas Utilities	Martin Lake 4	525 [6]	ESP	RC	DL	1985	LS		●	C	●		R		●
Utah Power & Light	Hunter 2	345 [6]	ESP	C	ST	1980	L		●	DVF	●		T		●
West Penn Power	Mitchell 3	300	ESP	C	ST	1982	L		●						
Wisconsin Power & Light	Columbia 2	315 [6]	ESP	C	ST	1983	FA-L		●		●				●

(1) Scrubber Manufacturer: AAF-American Air Filter; B-Buell; B&W-Babcock & Wilcox; CEA/ADL-Combustion Equipment Associates/Arthur D. Little; CE-Combustion Engineering; P-Peabody; PK-Pullman Kellogg; RC-Research Cottrell; UE-United Engineers; UOP-Universal Oil Products; WF-Wheelabrator-Frye; C-Chemico; M-Mitsubishi

(2) Scrubber Type: DL-Double Loop ™; HSA-Horizontal Spray Absorber; ST-Spray Tower; TCA-Turbulent Contact Absorber ®; V-Venturi.

(3) Reagent: CL-Carbide Lime; FA-Flyash; L-Lime; LS-Limestone; SA-Soda Ash; WS-Waste $CaCO_3$, Slurry.

(4) Dewatering: BVF-Belt Vacuum Filter; C-Centrifuge; DVF-Drum Vacuum Filter; CY-Cyclone; SP-Settling Pond.

(5) Transportation: C-Conveyor; P-Pipeline; R-Railroad; T-Truck.

(6) Some gas by-passed.

Seven of the 17 ponding systems will do no processing of the sludge before disposal. The remainder, except two using interim settling ponds, will utilize mechanical thickeners for dewatering prior to pond disposal. One installation will use forced oxidation and ponding without thickening. Two new installations will utilize Dravo's proprietary method of fixation.

With the landfilling operations, 26 of the 33 new installations will utilize some form of stabilization/fixation. Seventeen of the installations will utilize the IUCS process for fixation. Nine installations plan to mix the sludge with flyash: six after dewatering by centrifuge, two after dewatering by vacuum filter and one after mechanical thickening. Four of the installations that will not use stabilization/fixation plan to landfill sludge that has been dewatered by vacuum filtration; three of these will be force-oxidized sludge. One will utilize cyclone dewatering of oxidized sludge. As previously noted, three installations using dry scrubbers are included in the total of those using dry disposal.

TRENDS

Trends and developments in sludge processing and disposal as shown in the tabulations can be observed:

- While the sludge from 60% of operating scrubber systems is being ponded, future installations will employ wet disposal for only 35%.
- Of those installations using dry disposal, 81% will stabilize the sludge by mixing with flyash (28%) or fixate by use of the IUCS system (53%).
- With the growing use of dry disposal, the wider application of vacuum filters also is evident. They will be used at 43% of the total planned installations, including those using the IUCS process. Centrifuges will be used by 12% of the total.
- Forced oxidation shows an increase from three current installations to an additional eight in those planned or under construction.
- Upstream particulate removal will be employed in 98% of the new installations; practically all will use electrostatic precipitators.
- The advent of dry scrubbing is an interesting development. The three planned installations will, of course, employ dry disposal of the combined flyash-SO_x waste. No fixation/stabilization is planned.

UTILITY CONTACTS

Names and phone numbers of personnel at the various utilities which are either operating or planning for scrubbers are listed in Table 2-3.

Table 2-3
Utility Scrubber Contacts

Company	Name	Phone
Alabama Electric Coop., Inc.	Royce Hutchenson	(205) 246-4507
Arizona Electric Power Coop., Inc.	T.L. Adams	(602) 586-3631
Associated Electric Coop., Inc.	Lance Granger	(417) 881-1204
Basin Electric Power Coop.	Bob Erikson	(701) 223-0441
Big Rivers Electric Coop.	Sam Haddan	(502) 827-2561
Central Illinois Light Co.	Larry Haynes	(303) 672-5477
Central Illinois Public Service	R.J. Grant	(217) 523-3600
Cincinnati Gas & Electric Co.	R.L. Dirr	(513) 632-3462
Colorado Ute Electric Assn., Inc.	N.R. Cates	(303) 824-4411
Columbus & Southern Ohio Electric Co.	Harl Todd	(614) 829-2378
Commonwealth Edison Co.	W.G. Stober	(312) 294-8448
Cooperative Power Assn./United Power Assn.	James Rivard	(612) 441-3121
Detroit Edison Co.	Dennis Leonard	(313) 897-1178
Duquesne Light Co.	J.A. Rocco	(412) 456-6181
East Kentucky Power Coop., Inc.	R.E. Hughes	(606) 744-4812
Indianapolis Power & Light Co.	Charles Martin	(317) 261-8672
Kansas City Power & Light	C.F. McDaniel	(816) 556-1421
Kansas Power & Light	Kelly Green	(913) 296-6412
Kentucky Utilities Co.	J.B. Beard	(606) 255-1461
Lakeland Utilities	J.A. Libey	(813) 682-1121
Louisville Gas & Electric Co.	R.P. Van Ness	(502) 566-4216
Minnesota Power & Light Co.	E.R. Kilpatrick	(218) 722-2641
Minnkota Power Coop., Inc.	P.F. Richmond	(701) 794-8711
Monongahela Power Co.	W.R. Cress	(412) 837-3000
Montana Dakota Utilities Co.	Earl Backhus	(701) 222-7900
Montana Power Co.	Carlton Grimm	(406) 723-5421
Northern States Power Co.	Carl Sannes	(612) 330-5857
Pacific Power & Light Co.	H.G. Sanders	(503) 243-4036
Pennsylvania Power Co.	W.P. Horrocks	(412) 643-5000
Potomac Electric Power Co.	Conrad Shirley	(301) 428-8987
Public Service Co. of Colorado	A.B. Albrandt	(303) 571-6739
Public Service Co. of Indiana	T.W. McCafferty	(317) 838-1482
Salt River Project	Larry Bethell	(602) 273-2250
San Miguel Electric Coop.	R.L. Magel	(512) 784-3411
Sikeston Board of Public Utilities	Maurice Hixon	(314) 471-5000
South Carolina Public Service Auth.	Richard Le May	(803) 899-2121
Southern Illinois Power Coop.	Carl Stafford	(618) 964-1448
Southern Indiana Gas & Electric Co.	B.J. Reynolds	(812) 985-2226
South Mississippi Electric Power Assn.	Roger Smith	(601) 583-4315
Southwestern Electric Power Co.	B.T. Whetstone	(318) 425-3046
Southwestern Public Services Co.	K.L. Ladd	(806) 378-2192
Springfield (MO) City Utilities	Gary Pendergrass	(417) 831-8575
Springfield (IL) Power Dept.	Steve Bolser	(217) 789-2141
TVA	J.W. Barrier	(205) 383-4631 X2814
Texas Municipal Power Agency	James Shoults	(817) 461-4400
Texas Power & Light Co.	J.E. Sockwell	(214) 748-5411
Texas Utilities Co.	H.B. Coffman	(214) 653-4793
Utah Power & Light Co.	J.N. Lacey	(801) 535-2310
West Penn Power Co.	W.R. Cress	(412) 837-3000
Wisconsin Power & Light Co.	M.E. Horn	(608) 252-3081

EUROPEAN PRACTICE

European activity in the flue gas cleaning field is not as significant as that in the U.S. and Japan, but is growing in importance. One of the factors is the European Economic Community (EEC), which has been trying to set emission standards for the member countries as a means of avoiding situations in which one country would have a competitive advantage over another because of more lenient pollution regulations. Although some progress has been made in this direction, there is still a wide disparity among the various countries in regard to air pollution regulations. The EEC has been able to establish a limit of 1% sulfur in the fuel in some of the member countries. In most cases, however, there are no set emission standards. The most stringent regulations are in West Germany, particularly in the state of Nordrhein-Westfalen where air pollution is severe because of the industrial Ruhr area.

The North Atlantic Treaty Organization (NATO) also has an interest in SO_2 control and through its Committee on the Challenges of Modern Society has sponsored a paper study of FGD processes. Cooperating countries were Denmark, Germany, Greece, Italy, Netherlands, Norway, and the U.K.; Canada and the U.S. also took part in the project.

It can be expected that there will be more emphasis on flue gas desulfurization in the future because of a shift away from oil to coal as power plant fuel. The native coals are generally lower in sulfur content than the bulk of U.S. coals, but because of the high cost, there may be a trend to importing coal from other parts of the world.

England

Although English coal runs about 1.6% sulfur, there are no emission or ambient SO_2 standards but rather a sort of informal BACT agreement between the government agencies involved (CEGB for power production and the Alkali Inspector for environmental protection). CEGB claims, on the basis of extensive ambient concentration data, that power plant contribution to ambient levels, through virtue of the tall stacks used, is too small to warrant the large expenditure that would be required for SO_2 emission control. In any event, the average ambient concentration over the country is said to be much below the minimum for adverse health effects.

France

Electricite de France (EDF), the government-owned utility corresponding to CEGB in England, some years back funded a fair amount of research and development on FGD processes. This appears to have been a public gesture, however, rather than a real effort to develop a commercial process. The effort has died out and EDF apparently has no further interest in FGD development. As indicated by the high ambient standard, the government is not greatly concerned about SO_2. There is little coal of acceptable quality. The main reliance is on nuclear power.

Scandinavia

The EEC 1% sulfur limitation has been adopted, but there is little in the way of commercial FGD. The main new development is a small sea water scrubbing system on the coast of Norway. Although this is a very economical process, resistance by environmental groups has kept it from being used widely.

Four scrubbers, using sea water as the absorbent and totalling about 70 MW, have been installed on oil-fired boilers at a plant in Norway. At an L/G of 67 gal/mcf and an inlet SO_2 concentration of 1400 ppm, removal was over 99%. The scrubber effluent (once-through basis) is oxidized, diluted with raw sea water, and discharged back into the sea.

The process is quite economical but subject to criticism by environmental groups. The main concern seems to be heavy metal particles collected in the scrubber rather than the sulfate resulting from SO_2 scrubbing. A NATO-sponsored study has indicated, however, that the process is acceptable if there is adequate dilution before discharge.

USSR

The Russian situation is difficult to assess. Although the ambient standard for SO_2 is the most stringent in the world, there is very little in the way of FGD (none on power plants). Two 300 MW demonstration plants are "planned," but the plans have been under consideration so long that there is some question as to whether the plants will ever be built. No data seems to be available on the actual ambient concentrations over the country and on attainment of the 50 g/m^3 standard (daily average).

It is reported that Russia is in the final stages of purchasing an FGD system in Germany for installation on a Moscow power plant. If this works out, it will be the first power plant FGD system, commercial or otherwise, in the country. This will be a lime system with gypsum as the product.

West Germany

Large amounts of coal are burned to make power in Germany, but unlike England, FGD is required by the federal "Clean Air Act." The rules are not very clear, but generally involve, for a new boiler, starting out with about 20% of the gas scrubbed and going later to 50%--or in some cases, to full scrubbing. The general aim seems to be reducing emission to a level equivalent to burning coal containing about 0.5% sulfur.

There are now two systems operating and about five in some stage of design or construction. The trend for the future is not clear. Coal is expensive and generally not of very good quality. One station (NWK at Wilhelmshafen) has been built as a seaside plant to burn imported coal.

In the Ruhr area, RWE, one of the larger power producers, burns lignite and has escaped the scrubber requirement so far because of the low-sulfur content. There is environmental and government pressure to use scrubbers, however, and the trend may be in this direction in the future. Those who have escaped the regulation so far are known to be studying the various processes and making contingency plans.

All the systems, operating or planned, use lime as the absorbent (with Mg^{++} in one plant). There is not enough cost differential between lime and limestone to give limestone an edge as there is in the U.S. All the new installations will also oxidize sulfite to gypsum. As in England and Scandanavia, there is a general consensus that sludge disposal is to be avoided if possible. The sludge is discarded at Wilhelmshafen, but there was so much environmental uproar that utilities in the Ruhr and Saar areas, where much of the power is produced, are apparently dubious about getting disposal permits. It appears that for all the systems planned, there will be an effort to sell the gypsum to the wallboard and construction industries and to landfill as a last resort. It is not clear how much gypsum the market can absorb.

STEAG. Located in the Ruhr area in West Germany, STEAG is the main utility burning bituminous coal. Since the coal contains more sulfur (about 1.5%) than the lignite also burned in the area, the company has been the main recipient of pressure to install FGD. Several large stations are planned, but siting problems have caused several delays.

The first of the new stations was to be Voerde (1400 MW), planned to go on line in 1977, but the various permits and hearings have so delayed the project that it is not clear when or if the plant will be built. The station will be jointly owned by RWE, who owns the distribution system. As compared to the regulatory situation when the plans were started, it will now be necessary to scrub more gas. The current state standard is 2.75 grams SO_2/kWh (about 0.67 lb/10^6 Btu) as compared to the earlier one of 3.75 grams. This will require scrubbing about 80% of the gas, whereas only 50% was required before. The 3.75 grams/kWh comes from the federal regulation that coal containing not more than 1% sulfur must be burned (attained by washing) and that 50% of the gas must be scrubbed to remove 80% of the SO_2 (the 80% is an arbitrary ruling). The states can have more stringent rules, however, and Nordrhein-Westfalen recently lowered the standard to 2.75 grams/kWh.

The next station planned after Voerde was Bergkamen (two units, each 750 MW). Plans are moving ahead and a construction permit has been obtained, which will probably result in Bergkamen coming on line before Voerde. The station will be a joint venture with VEW. The coal to be burned will contain 1.0 to 1.3% sulfur. The 1.0% S is local washed coal allowed by the regulation, but the 1.3% coal must be brought in from outside the area; a special permit was required. The local regulation requires that an emission reduction to 2.75 grams SO_2/kWh be attained within 3.5 years after startup of the boiler, which will require scrubbing 81.6% of the gas (at the standard 80% removal level). In accordance with the stepwise procedure allowed by the environmental agency, only 44.6% will be scrubbed to begin with. The slurry will be oxidized to give gypsum that hopefully can be sold. Sulfuric acid will be added to facilitate the oxidation, which admittedly is not necessary, but is used in keeping with the design philosophy of being conservative and doing everything possible to ensure that the system will work reliably.

STEAG thinks that the gypsum can be sold from both Voerde and Bergkamen, but contract arrangements have not yet been worked out. A 20-year contract with a

stable buyer is needed, but this is difficult to arrange. One of the problems is insistence by the buyers on very rigorous quality specifications. For the Ruhr area, it is considered that discarding the gypsum is not possible and, therefore, selling it is essential. It is expected that much of the market will be in the mining industry where calcined gypsum is used. The FGD gypsum would likely be sold to companies that specialize in calcining gypsum for this purpose.

Saarberg Corporation. This company, with headquarters in Saarbrucken (Saar area of West Germany), is a major power producer (government-owned) and operator of coal mines and coke ovens. The company is also active in research and development in the energy field. Saarbergwerke, the power company, has joined with Hoelter, a gas cleaning equipment company, to form Saarberg-Hoelter Umwelttechnik GMBH to further develop and promote the Hoelter lime-scrubbing process.

The Hoelter method was tested earlier in a 40 MW demonstration unit at Saarbergwerke's Weiher station near Saarbrucken. The process has recently been installed on one-fourth of the gas flow from a new 700 MW boiler at the Weiher station (to be expanded to one-half the flow later); startup was in February-March, 1979. Saarbergwerke will also use the process in two other power plants.

Saarberg-Hoelter has been successful in selling the process outside Germany:

- A 700 MW plant is being constructed in Nigeria as a government project to supply power for a resettlement project planned to eventually involve some three million people. The station will be fired with coal (1.5 to 3% S) since Nigeria wants to export its oil. Because of temperature inversions in the area, it is considered necessary to scrub all the gas. The Hoelter process is to be used, with Saarbergwerke planning the project and STEAG managing it.
- A 375 MW FGD system has been sold to Russia, to be installed at a power station in or near Moscow. This appears to be a joint venture. A similar joint venture is being worked out in Bulgaria.
- A 40 MW demonstration unit of the Hoelter process is being negotiated for installation in Poland.

The system involves use of lime as the absorbent in a downflow scrubber of the spray tower type. The scrubber effluent solution all goes to the dewatering equipment, rather than the bulk being recirculated directly to the scrubber as is usual in scrubber systems. The effluent goes to an oxidizer, lime is added, and the product gypsum is separated in a thickener. The thickener overflow, a

clear solution, is recirculated to the scrubber. Formic acid is carried in the solution to promote SO_2 absorption. A recent paper gives details of the system (1).

The process has been licensed to Davy Powergas in the U.S., where it is being promoted under the name of "Davy S-H."

JAPANESE PRACTICE

Information for this section was obtained from a recent paper by Jumpei Ando (2). Up to this time, the practice of the Japanese in disposing of scrubber sludge has been almost completely that of oxidation to salable gypsum. There have been several reasons for this:

- There was a ready market for by-product gypsum in the manufacture of wallboard and cement.
- The lack of available land in the vicinity of scrubber plants made land disposal difficult, if not impossible.
- Most of the scrubbed gas is from oil-fired boilers and is consequently very low in particulate content, thus yielding a high-grade gypsum.
- Governmental and public pressure has discouraged the disposal of calcium sulfite because of the oxygen demand.

Scrubber construction in Japan is expected to proceed at a slower rate in the future because the ambient SO_2 has almost declined to the level required by regulations and because the production of by-products has saturated the market. Currently, the gases from about 15,000 MW of utility boiler capacity are being processed in FGD plants. Including both utility and industrial plants, gas from a total equivalent of 29,000 MW is being processed. Of that total, about 50% scrub with lime or limestone, and the waste product is oxidized to gypsum; another 16% utilize a double-alkali process, with gypsum being the end product. Only one industrial generating plant, at Mitsui Aluminum, produces a throwaway sludge.

Table 4-3 is a tabulation of utility scrubbers operating in Japan as of the end of 1978, all of which produce by-product gypsum.

REFERENCES

1. Flamser, J.H., et al., "A Lime Based FGD Process Utilizing Forced Oxidation to Produce Stable Gypsum By-Product," EPA Symposium on Flue Gas Desulfurization," March, 1979, EPA-600/7-79-167.

2. Ando, J., "Status of SO_2 and NO_x Removal Systems in Japan," EPA Symposium on Flue Gas Desulfurization, March, 1979, EPA-600/7-79-167.

Table 2-4

JAPANESE ELECTRIC UTILITY SCRUBBERS IN OPERATION - ALL PRODUCING BY-PRODUCT GYPSUM
October 1, 1978

Operating Utility	Station Name & Unit No.	MW		Process Developer	Reagent[1]
		Unit	Scrubber		
		OIL FIRED			
Chubu	Owase 1, 2	750	750	Mitsubishi H.I.	L
Chugoku	Mizushima 2	156	100	Babcock-Hitachi	LS
Tamashima	Tamashima 2, 3	850	850	Babcock-Hitachi	LS
	Shimonoseki 2	400	400	Mitsubishi H.I.	LS
Fukui	Fukui 1	250	250	---	LS
Hokuriku	Toyama 1	500	250	Chiyoda	H_2SO_4, LS
	Fukui 1	350	350	Chiyoda	H_2SO_4, LS
	Nanao 1	500	500	---	---
Kansai	Amagasaki 1, 2	312	312	Mitsubishi H.I.	L
	Osaka 2, 3, 4	468	468	Babcock-Hitachi	LS
	Kainan 4	600	150	Mitsubishi H.I.	L
Kyushu	Karita 2	375	188	Mitsubishi H.I.	L
	Karatsu 2, 3	875	438	Mitsubishi H.I.	LS
	Ainoura 1, 2	875	500	Mitsubishi H.I.	LS
	Buzen 1, 2	1000	500	Kureha-Kawasaki	Na_2SO_3, LS
Mizushima	Mizushima 5	156	156	Mitsubishi H.I.	L
Nugata	Nugata 1	350	175	MHI	LS
Sakata	Sakata 1, 2	700	700	Mitsubishi H.I.	LS
Shikoku	Anan 3	450	450	Kureha, Kawasaki	Na_2SO_3, LS
	Sakaide 3	450	450	Kureha, Kawasaki	Na_2SO_3, LS
Sumitomo	Niihama 3	156	156	IHI	LS
Showa	Ichihara 1	150	150	Showa Denko	Na_2SO_3, LS
	Ichihara 5	250	250	Babcock-Hitachi	LS
Tohoku	Shinsendai 2	600	150	Kureha-Kawasaki	Na_2SO_3, LS
	Hachinohe 4	250	125	Mitsubishi H.I.	L
	Niigata H. 1	600	150	Mitsubishi H.I.	LS
	Akita 3	350	350	Kureha-Kawasaki	Na_2SO_3, LS
Tokyo	Kashima 3	600	150	Hitachi-Tokyo	Carbon, LS
	Yokosuka 1	265	133	Mitsubishi H.I.	LS
Toyama	Toyama 1	250	250	Chiyoda	H_2SO_4, LS
Operating Utility	Station Name & Unit No.	MW		Process Developer	Reagent[1]
		Unit	Scrubber		
		COAL FIRED			
Electric Power Development Co.	Takasago 1, 2	500	500	Mitsui-Chemico	LS
	Isogo 1, 2	530	530	Chemico-IHI	LS
	Takehara 1	250	250	Babcock-Hitachi	LS

(1) Reagent Identification: L-Lime, LS-Limestone.

Source: Ando, Jumpei, "SO_2 and NO_x Removal Technology-Japan," EPA Symposium on Flue Gas Desulfurization, March, 1979.

Section 3

WASTE PROPERTIES

PURPOSE

The purpose of this section is to describe the origin of flue gas desulfurization (FGD) sludge, its principal chemical characteristics, and the physical properties which arise from those characteristics. Environmental concern associated with FGD sludge are described as are methods for predicting sludge composition and physical properties.

SOURCES

Scrubber sludge, as considered in this manual, is composed primarily of calcium-based reaction products, excess scrubbing reagent, flyash, and scrubbing liquor. The relative amounts of each of these components can vary over a wide range. At the present state of the scrubbing art, most of the sludge is generated in the U.S. from throwaway-type FGD scrubbers. Lime, limestone or alkaline flyash, either separately or in various combinations, may be used as the scrubbing reagent.

Calcium-based scrubber sludge typically has undesirable properties when it is disposed of without stabilization or fixation. The sludge generally has little or no cohesive strength and is difficult to dewater. However, these undesirable physical properties can be improved through various stabilization/fixation or oxidation techniques and disposal methodologies.

As defined in Section 1 - INTRODUCTION, stabilization involves the additon of dry flyash, soil, or other dry additive to reduce the moisture content and improve handling characteristics without a chemical interaction between the sludge components and the additive. Fixation or chemical treatment is defined as a type of stabilization which involves the addition of lime or other reactive material, such as blast furnace slag, alkaline flyash, or portland cement, to result in cementitious-type reactions in the sludge.

The two major scrubber systems currently used to remove SO_2 from flue gases are throwaway lime/limestone/alkaline flyash scrubbers and double-alkali scrubbers. These two systems are discussed in this section. Other scrubbers are available which produce usable by-products such as sulfur and sulfuric acid. These systems will not be discussed here because they do not generate large volumes of waste product. They do, however, generate a high dissolved solids sludge from their chloride pre-scrubbers. Similarly, the Reid Gardner scrubbers, using a throwaway sodium salt will not be discussed because they represent an atypical situation.

Throwaway Lime/Limestone Systems

Throwaway lime/limestone/alkaline flyash scrubber systems can be represented by the flow diagram shown in Figure 3-1. Flue gas from the boiler is directed either through a flyash removal device or directly to the scrubber. The flyash removal device may be a mechanical collector (cyclones), an electrostatic precipitator, or a baghouse. Recent developments (see Table 2-2) indicate that most new scrubber systems will include an upstream electrostatic precipitator.

Sulfur dioxide is removed by intimately contacting the alkaline sorbent with the gas. The method used varies with the particular system and has included venturis, spray towers or chambers, impingement plates, packed towers or turbulent contactors. The trend appears to be toward simple spray devices. The reagent used is added as a slurry to the reaction tank or scrubber basin where it is mixed with recycled slurry from the scrubber. The slurry is then returned to the scrubber. Within this recycle loop, a surge tank may be used to control slurry flows and a thickener or pond is used to remove solids. The slurry may be purged with oxygen to oxidize the calcium sulfite solids to calcium sulfate thus producing a more manageable solid waste. The solids from the settling pond or thickener are then ready for disposal or, if ponded, they may be left permanently in the pond.

The sorption of SO_2 in the scrubber takes place by dissolving gaseous SO_2 in the alkaline scrubber slurry liquor to form the soluble species sulfite and bisulfite:

$$2H_2O + 2\ SO_2(g) \rightleftarrows SO_3^{2-} + HSO_3^- + 3H^+$$

The alkalinity required to drive this reaction toward the product species is supplied by the reagent, either lime/limestone/or alkaline-flyash. The extent of oxidation will determine whether the solids are predominately calcium sulfite ($CaSO_3 \cdot \frac{1}{2}H_2O$) a calcium sulfite-sulfate coprecipitate ($CaSO_3 \cdot CaSO_4 \cdot \frac{1}{2}H_2O$) or calcium sulfate (gypsum - $CaSO_4 \cdot 2H_2O$).

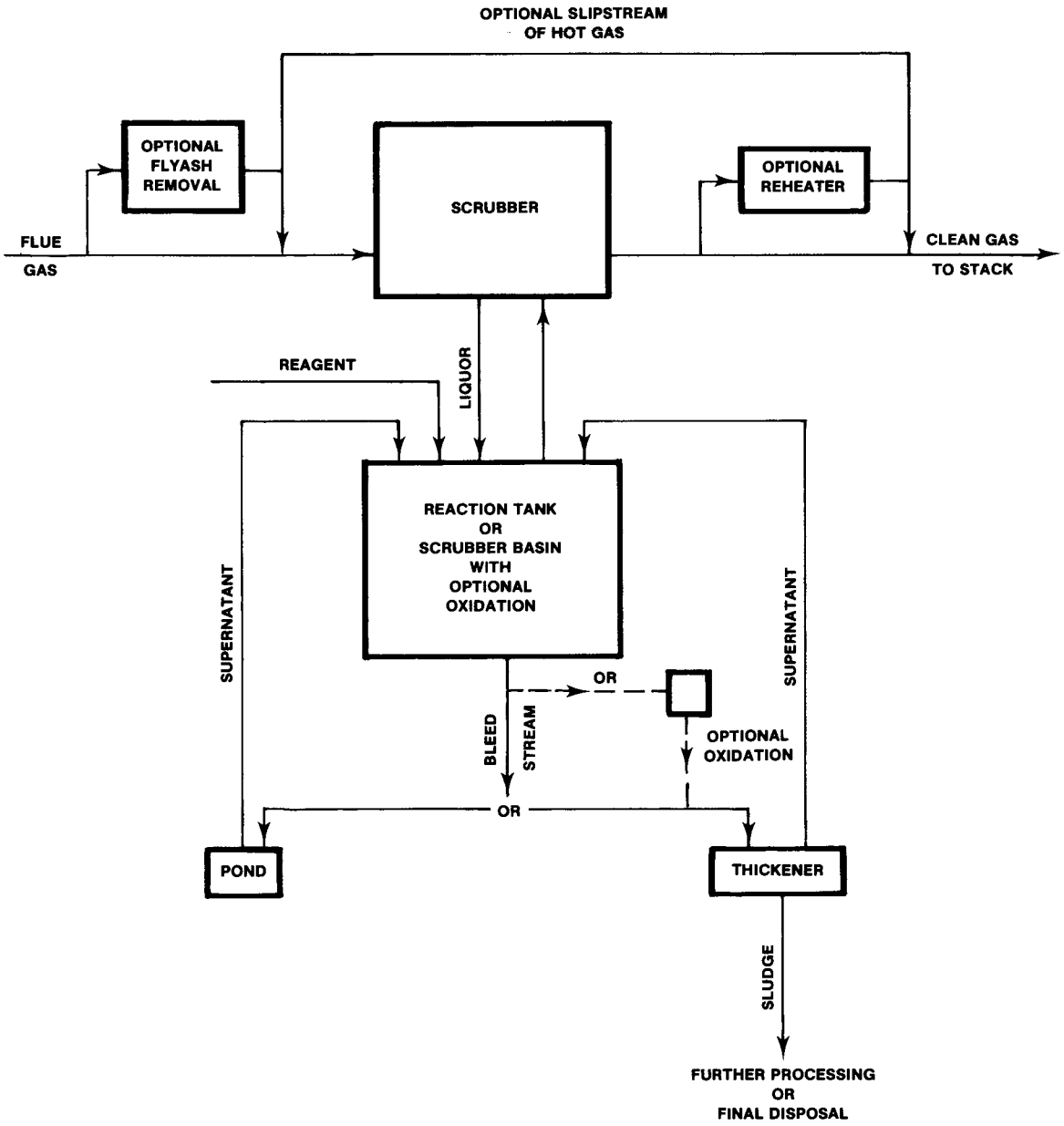


Figure 3-1. Typical Lime/Limestone Scrubber Flow Scheme.

Double Alkali Systems

Double alkali type systems, shown in Figure 3-2, differ from the other throwaway systems in one primary way. A soluble sodium salt, such as sodium hydroxide or carbonate, is used as the reagent, rather than lime or limestone. The systems are very much the same, except that the soluble sodium bisulfite in the bleed system is contacted with lime to regenerate sodium sulfite, for additional absorption, and to form the insoluble calcium sulfite. The latter is settled out of the slurry, while the regenerated, soluble sodium salts are recycled to the scrubber system. This system avoids the precipitation of calcium salts in the scrubber system. However, as disadvantages, the regeneration step is added, and there could be a release of appreciable quantities of dissolved salts to the ground or surface water if a malfunction occurs or a system blowdown is required. In addition, complete separation of soluble sodium salts from the sludge is impossible, leading to loss of reagent and leaching from the disposed waste upon contact with water.

SLUDGE COMPOSITION

The bleed from the scrubber system is a low solids content water slurry containing from 5 to 15 percent solids and a variety of materials in solution. Major and trace analyses of some scrubber liquors and sludge solids are shown in Tables 3-1, 3-2, 3-3, and 3-4. These data show the large number and wide range of constituents present in both the aqueous and solid phases of the scrubber sludge. The actual constituents at any given time are highly variable and site-specific. Not only is there variability in sludge composition from station to station, but there is hour-to-hour variation within a single facility. This continuous variability complicates an already difficult processing and disposal task and precludes any simple, all-inclusive solutions to handling and disposal.

Calcium Sulfite/Sulfate - Solid Phase

Operation of calcium-based throwaway scrubbers results in reaction products containing a mixture of calcium sulfate and calcium sulfite (see Table 3-3). The calcium sulfate normally occurs as gypsum ($CaSO_4 \cdot \frac{1}{2}H_2O$). With low oxidizing conditions, calcium sulfite hemihydrate ($CaSO_3 \cdot \frac{1}{2}H_2O$) is the principle solid phase product. Small quantities of calcium sulfate will be coprecipitated with the sulfite. The calcium sulfite/sulfate coprecipitate has the general formula,

$$Ca\ \{(1-x)SO_3 + (x)SO_4\} \cdot \tfrac{1}{2}H_2O \qquad (3\text{-}1)$$

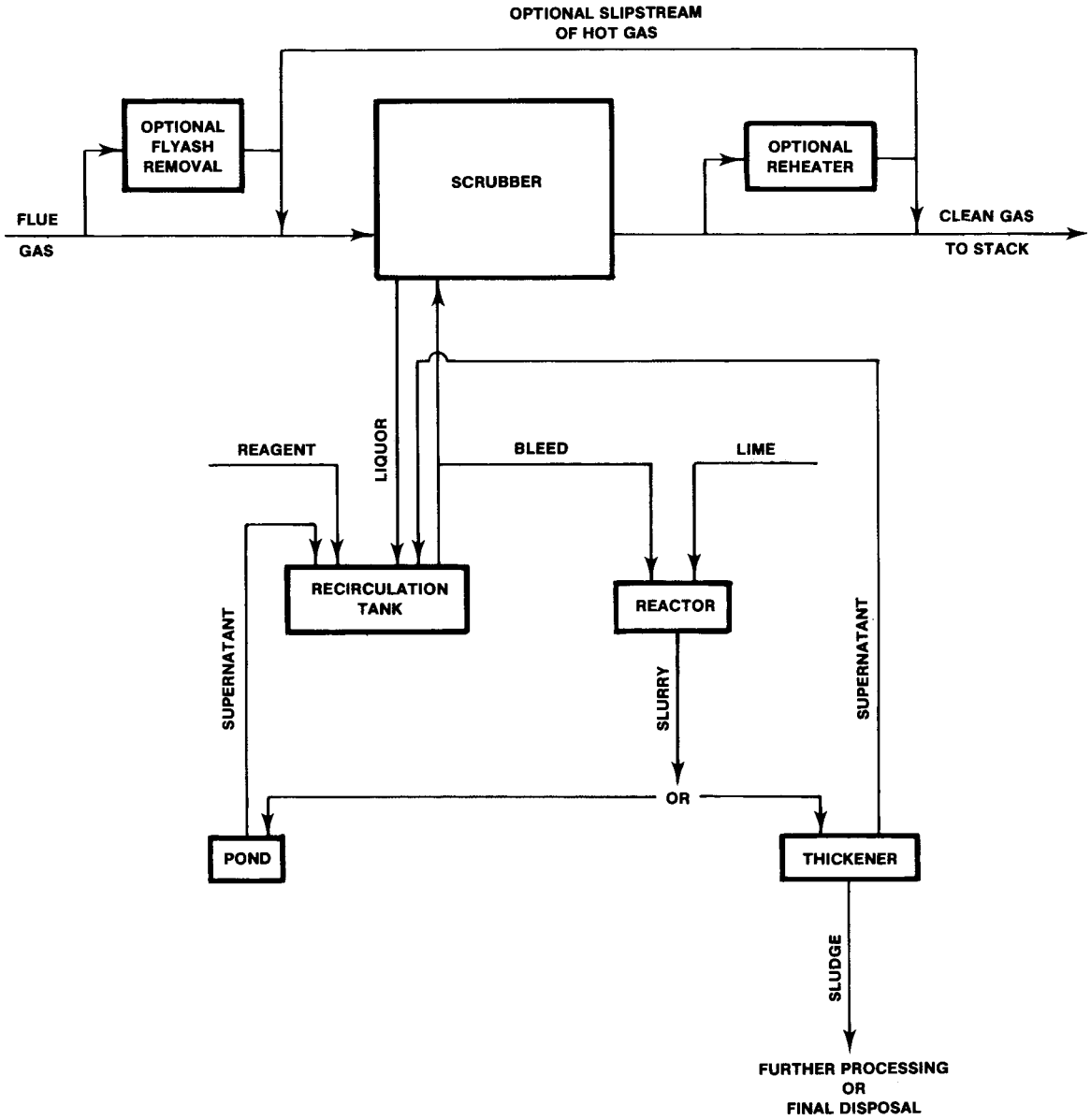


Figure 3-2. Typical Lime-Regenerated Double-Alkali Scrubber Flow Scheme.

Table 3-1

IDENTIFICATION OF CHEMICAL PHASES OF FGD SLUDGE SOLIDS

Facility	Coal Source	Absorbent	Method of Particulate Control	Weight Percent of Chemical Phase					Source
				$CaSO_3 \cdot \frac{1}{2}H_2O$	$CaSO_4 \cdot 2H_2O$	$CaCO_3$	Flyash	Other	
Kansas City Power & Light Hawthorn 4	Eastern	Limestone	Marble bed	17	23	15	45		(1) (2)
Commonwealth Edison Will County 1	Eastern	Limestone	Venturi	50	15	20	15		(1) (2)
City of Key West Stock Island	Eastern	Limestone	Mechanical Collector	20	5	74	1		(1) (2)
Kansas City Power & Light LaCygne	Eastern	Limestone	Venturi	40	15	30	15		(1) (2)
Arizona Public Service Cholla	Western	Limestone	Flooded Disc Scrubber	15	20	0	65		(1) (2)
Arizona Public Service Cholla	Western	Limestone		10.8	17.3	2.5	58.7	14.3 $CaS_2O_3 \cdot 6H_2O$	(3)
Tennessee Valley Authority	Eastern	Limestone		18.5	21.9	38.7	20.1	4.6 $MgSO_4 \cdot 6H_2O$	(3)
Shawnee - Turbulent Contact	Eastern	Limestone		21.4	15.4	20.2	40.9	3.7 $MgSO_4 \cdot 6H_2O$	(3)
Absorber - 3 dates	Eastern	Limestone		21.8	31.2	4.5	40.1	1.9 $MgSO_4 \cdot 6H_2O$	(3)
Southern California Edison Mohave	Western	Limestone		8.0	84.6	6.3	3.0	1.5 NaCl	(3)
Louisville Gas and Electric Paddy's Run 6	Eastern	Lime	Electrostatic Precipitator	94	2	0	4		(1) (2)
Southern California Edison Mohave 2	Western	Lime	Electrostatic Precipitator	2	95	0	3		(1) (2)
Tennessee Valley Authority Shawnee	Eastern	Lime		48.8	6.3	2.5	40.5	1.9 $MgSO_4 \cdot 6H_2O$	(3)
Duquesne Light Company Phillips	Eastern	Lime		12.9	19.0	0.2	59.7	9.8 CaS_3O_{10}	(3)
Utah Power and Light Gadsby	Western	Double Alkali		0.2	63.8	10.8	8.6	17.7 $CaSO_4$	(3)
General Motors Parma	Eastern	Double Alkali		12.9	48.3	7.7	7.4	19.2 $CaSO_4 \cdot \frac{1}{2}H_2O$ 6.9 $Na_2SO_4 \cdot 7H_2O$	(3)
Scholz	Eastern	Double Alkali		65-90	5-25	2-10	Nil		(4)

Source: (1) Princiotta, F. T., Sulfur Oxide Throwaway Sludge Evaluation Panel (SOTSEP), 2 Vols., Report No. EPA-650/2-75-010a and EPA-650/2-75-010b, 1975.

(2) Ifeadi, C. N., "Sludge Disposal-Trends in the Utility Industry," EPA FGD Symposium, Atlanta, GA, November 1974.

(3) Leo, P. P. and J. Rossoff, Control of Waste and Water Pollution from Power Plant Flue Gas Cleaning Systems: First Annual R&D Report, EPA-600/7-76-018, October 1976.

(4) Lunt, R. R., et al., An Evaluation of the Disposal of Flue Gas Desulfurization Wastes in Mines and the Ocean: Initial Assessment, EPA-600/7-77-051, May 1977.

Table 3-2

TRACE ELEMENT COMPOSITION OF FGC SOLIDS
(CONCENTRATION IN PPM)

Identification: Coal type: Sorbent:	Station 1 Western Low-Sulfur Lime		Station 4 Eastern High-Sulfur Limestone		Station 5 Eastern High-Sulfur Limestone	Analytical Technique	Detection Limit (ppm)
	Sludge	ESP Ash	Sludge	ESP Ash	Sludge		
Antimony	4.3	1.0	7.5	4.4	6.7	Extraction/AA	.16
Arsenic	4.0	3.2	12	61	6.7	AA	.5
Barium	500	3600	4400	15,000	< 20	Li_2CO_3 $Na_2B_4O_7$ fusion/XRF	50
Beryllium	1.5	5.2	1.0	5.2	1.8	Extraction/AA	1.6
Boron	68.7	179	211.	1040	41.8	Colorimetry	3
Cadmium	0.40	.39	1.1	4.2	25	Extraction/AA	.2
Chromium	1.6	5.6	4.0	8.9	5.2	Acid/digestion/AA	40
Copper	38.9	43	104.	238	65	AA	4
Fluorine	1017	377	950.	2880	266	Na_2CO_3 fusion/ion-selective electrode	1.2
Germanium	<1.0	1.2	2.4	9.2	5.9	Colorimetry	.2
Lead	1.6	6.4	2.4	4.0	190	Extraction/AA	.8
Manganese	56.	157	147.	370	340	AA	40
Mercury	<0.010	.126	0.46	< .010	0.101		
Molybdenum	81.	7.0	8.0	12	9.6	Extraction/AA	1.6
Nickel	13.	34.2	26.0	92.9	75.2	Extraction/AA	8
Selenium	4.13	1.7	3.8	16.4	2.1	HNO_3-$HClO_4$ digestion/fluorescence	0.1
Vanadium	<50	<50	<100	< 100	< 100	AA	4
Zinc	13.9	92	169	386	2050	AA	4
Comments:	Electrostatic precipitator for flyash control upstream of scrubber		Electrostatic precipitator for flyash control upstream of scrubber		Scrubber used for both particulate and SO_2 control		

Source: Holland, et al., Environmental Effects of Trace Elements from Ponded Ash and Scrubber Sludge, EPRI RP 202, September 1975.

Calcium sulfite crystals take the form of extremely thin, fragile platelets. The size of the platelets is about 10 to 100 microns in lateral dimension and 0.1 to 0.5 microns in thickness. The disparity in thickness to lateral dimension causes single crystals to be fragile. As shown in Figure 3-3, the platelets usually occur in clusters or rosettes which are somewhat stronger than the single crystal. The degree of clustering is attributed to the manner or chemical conditions under which the crystals are formed. Factors affecting crystal growth are varied and complex. They include pH, temperature, nucleation, concentrations and any shocks or stresses imposed on the system.

The crystal structure is responsible for many of the physical properties of calcium sulfite scrubber sludges. The rosettes and platelets form an open structure, with water filling the voids. These rosettes are not easily compacted by normal settling and in filtering the fragile crystals break, tending to clog the filter cloth. As a result, sulfite-predominant sludges will dewater to about 35 percent solids by settling and can be filtered to only about 50 percent solids.

The crystalline form of calcium sulfate is blocky and elongated, as shown in Figure 3-4. The blocky shapes vary in size from 1 to 100 microns along each edge. This crystal shape results in better settling and dewatering characteristics in comparison to sulfite crystals. Sulfate sludges settle in thickeners or ponds to 60-70 percent solids, and will filter to as much as 85 percent solids.

Because of the more favorable characteristics of the sulfate form, insofar as disposal is concerned, a trend appears to be developing which favors inclusion of an oxidation step. Noting the improved dewatering properties of sulfate sludges, several scrubber manufacturers have recently offered a forced-oxidation option to convert the sulfite sludge to sulfate. In some cases, the oxygen (air) is added to a reaction tank of the scrubber system; in others, it is added in an external oxidizer. This process is discussed in Section 10 - FORCED OXIDATION.

Although not practiced in commercial U.S. systems, the use of oxidation catalysts has found favor in some Japanese systems and in the Saarberg-Holter process in Germany. These catalysts are proprietary materials and are reportedly effective in enhancing forced oxidation.

The formation of sulfate-predominant sludge in earlier scrubbers often resulted in undesirable (sometimes catastrophic) quantities of scale in the scrubber vessels

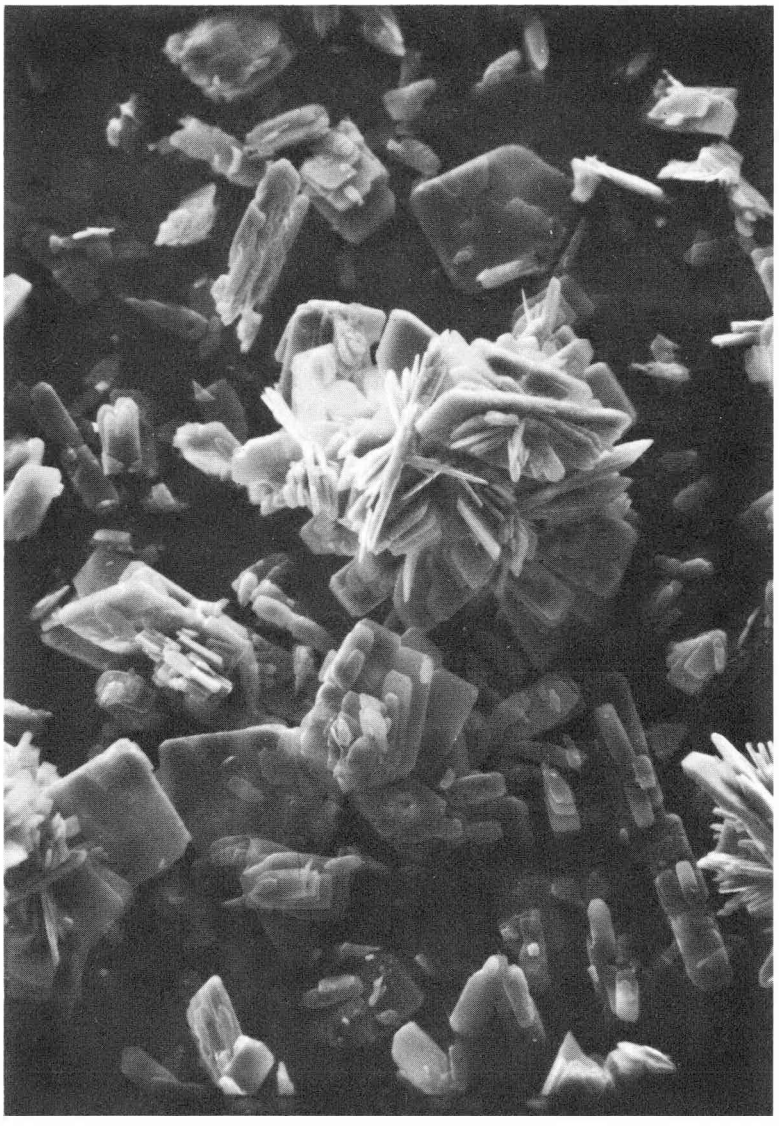


Figure 3-3. Calcium Sulfite Sludge.

Courtesy: Dravo Lime

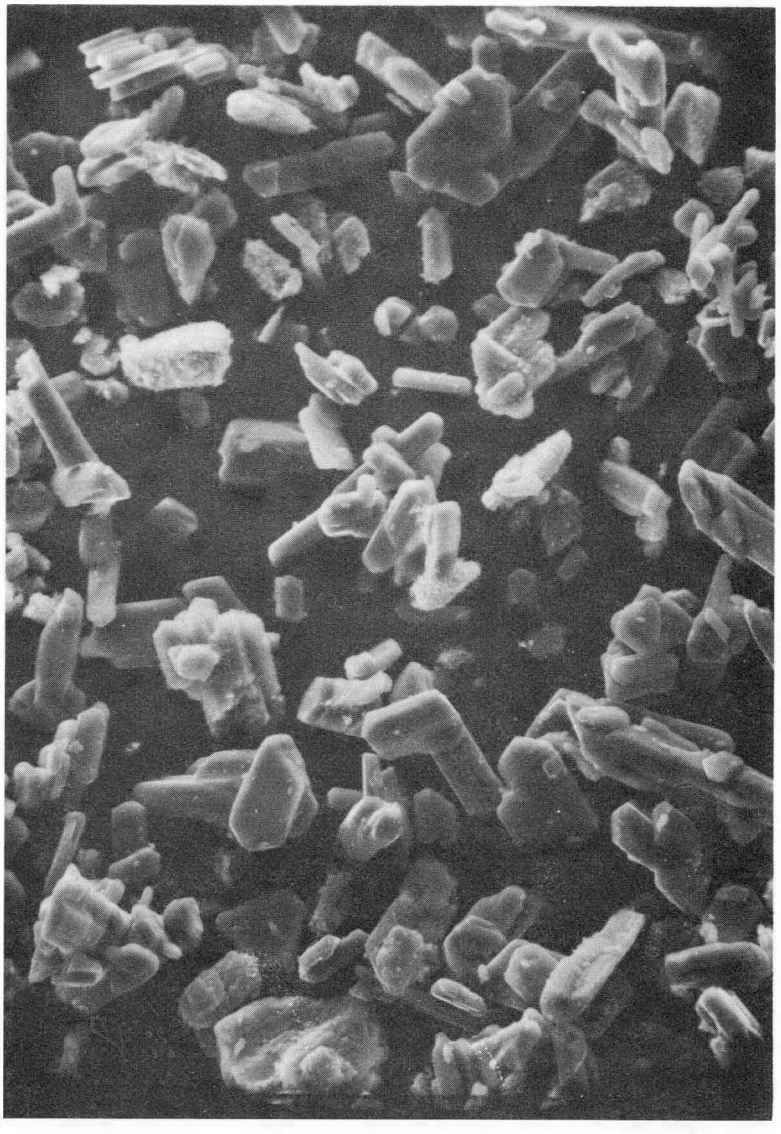


Figure 3-4. Calcium Sulfate Sludge.

Courtesy: Dravo Lime

and piping. In newer scrubbers, the use of a properly designed hold tank allowing a delay or reaction step, with or without forced oxidation and with optimization of chemical conditions, has enabled operation with high proportions of sulfate with minimal scaling. The use of lime or limestone containing reactive magnesium oxide has also been reported to reduce scaling.

The water retention of sulfite-containing sludges, along with the crystalline structure, result in a pseudo-thixotropic behavior. That is, the apparently solid sludge mass will reliquify when vibrated or agitated. Sulfite sludges also retain water for a longer time after disposal than sulfate sludges.

Even after drying and oxidation occurs on the surface of a sulfite sludge waste, water can be brought to the surface by reworking. Sludges containing predominantly calcium sulfate are readily dewatered. These physical properties are extremely important in the practical application of material handling techniques. Since sulfite sludges retain so much water, they remain very fluid and can be efficiently transported only by pumping. Ponds containing these sludges generally will not dewater sufficiently to be suitable for any future use except perpetual sludge storage. The thixotropic properties and retained water mean that rubber-tired vehicles lose traction when working on the sludges. Material which appears solid, becomes wet and very fluid when agitated by excavation, handling or truck transport. Dry disposal in a landfill is virtually impossible, because the material acts like a fluid rather than a solid.

Several notable exceptions to the generalizations expressed above have been observed. The FMC double-alkali system at the Peoria Caterpillar Company Basic Engine Plant produces a sulfite/stoker-flyash sludge which is easily dewatered in a vacuum filter and can be handled and disposed of in a dry state. After filtering, this sludge is sufficiently dry that it can be transported by truck to a sanitary landfill, mixed with natural soil and other waste and incorporated into a landfill. The good dewatering property of this sulfite sludge is claimed by FMC to result from proprietary and patented operating conditions which they developed. Also, it should be noted that this sludge does contain flyash; a fact which could significantly alter the sludge's physical characteristics.

The characteristics of calcium sulfate are such as to suggest the possibility of direct, dry disposal. The Chiyoda Thoroughbred 121 Scrubber at the Scholz Electric Generating Station of Gulf Power Company yielded a gypsum product of 98 percent purity which could be dewatered by settling to 80 percent solids. This material

has possibilities for utilization or for disposal by "stacking". Scrubber gypsum is similar in many respects to phosphogypsum waste, a product of the fertilizer manufacturing industry. Phospho-gypsum waste material has long been disposed of by stacking in large, structurally stable stockpiles, some as high as 150 ft. This method of disposal is described in Section 16 - GYPSUM STACKING.

Scrubbing Liquor

The term "wet" scrubbing is self-descriptive insofar as illustrating that water is the most necessary component in the scrubbing process. It is the medium in which the scrubber reactions take place. It is also an important constituent to be considered relative to disposal.

Water is the only principle constituent of FGD sludges that is not a total waste by-product of the scrubbing process. Water removed from the sludge is recycled through the system for re-use. The other principal constituents must be removed from the scrubbing system and disposed. Because the water is recycled, some type of dewatering either precedes or accompanies final disposal of all calcium-based scrubber sludge. Final solids content can vary from 30 to 80 percent depending on sludge components and the method and efficacy of dewatering.

The amount of water held by a sludge is directly affected by the morphology of the sludge solids and the solid morphology is determined by the proportions of calcium sulfite and calcium sulfate. Similarly, the ease and extent of dewatering are affected by the ratio of these constituents. These effects were discussed in this section. (See Calcium Sulfite/Sulfate Solid Phase)

The presence of water in sludge affects both the physical and chemical nature of the final disposal material. Generally, an increase in the proportion of water above optimum results in less desirable physical properties from a disposal standpoint. Optimum moisture content is discussed in Section 8 - DISPOSAL AREA DESIGN. Chemically, the water usually contains high concentrations of dissolved solids which will affect the quality of the leachate generated by the sludge. Leachate in this Manual refers to the water which contacts and moves through the disposed sludge material. The physical and chemical effects of waste water on FGD sludge disposal will be discussed below.

The flyash, calcium sulfite and calcium sulfate in FGD sludges exist mainly as silt-size particles, 1 to 100 microns in diameter. The sludge, being a mixture

of these particles and water, behaves in many ways like non-plastic, silty soil. As such, an increase in water content:

- Reduces disposal efficiency by decreasing the quantity of solid waste that can be placed in a given volume
- Reduces the extent to which the sludge can be compacted. Additional compaction efforts will not increase the density of the solid waste
- Reduces the shear strength of the material and, as a result, reduces the bearing capacity of the disposal area
- Reduces the viscosity, thus improving pumpability
- Increases the permeability of the final products, resulting in greater quantities of leachate being generated
- Increases the total weight and volume of material that must be handled to dispose of the solid wastes

Some of the effects of water also occur with sludge stabilized with flyash or fixed with lime or a commercial product. The shear strength and compressive strength of the fixed sludge is greatly affected by the water content. Maximum strength will be obtained within the shortest time only if the waste has the optimum water content.

Table 3-3 shows that the liquid phase of scrubber sludge contains high concentrations of total dissolved solids. The principal soluble species are calcium, magnesium, sodium, chloride, sulfite, and sulfate. In addition, many elements, including heavy metals, are present in minor or trace concentrations.

Water retained in the sludge contains essentially the same dissolved solids found in the scrubber liquor and, as such, acts as a blowdown of the scrubber system. Because these constituents are water soluble, they will also be found in leachate from disposal areas. Laboratory leachate studies involved with the EPA/TVA tests at the Shawnee Power Station show that approximately five pore volumes are required to displace substantially all the interstitial liquor. After the displacement of the adherent scrubber liquor, the dissolved solids in the leachate result from the dissolution of the solid sludge components, and the concentration is held constant by the solubilities of gypsum, calcium carbonate and calcium sulfite.

The calcium and magnesium present in solution come principally from the reagent in lime/limestone/flyash systems and from the lime reactor in the double-alkali system. Both the sulfite and sulfate ions come from the reaction products from the scrubber. Sodium may come from make-up water, flyash or reagent depending on the

source of make-up water, the types of ashes and the composition of the reagent. In double-alkali systems, most of the sodium comes from the residual sodium salts not washed out of the filter cake. The chloride in the scrubber liquor comes principally from the coal and is scrubbed from the flue gas with the SO_2. High concentrations of chloride in the scrubber liquor may cause corrosion in the scrubber. Most of the trace elements also originate from the coal either as vaporous species or components of the flyash. But, in some systems, significant amounts of trace elements may be contributed by the make-up water and the reagent.

Excess Scrubbing Reagent

Excess scrubbing reagent, either lime or limestone, is required in the wet SO_2 scrubber to provide high SO_2 removal efficiencies. Lime stoichiometries of 1.10 (10% excess lime addition) are normal with a wet lime scrubber. On the other hand limestone stoichiometries of 1.2 to 1.4 (as high as 1.5) are used. The higher utilization of the lime results from higher reactivity, i.e., the tendency to dissolve in the scrubber liquor at a much faster rate. As shown in Table 3-1, the $CaCO_3$ portion of the solid phase may range from 0.2 weight percent to as high as 40 to 70 weight percent.

The non-reactive components (grit) in the reagent are usually carbonates, silicates, aluminates, sulfates and ferrite. Whether lime or limestone is used, some or all of these will be present and must be handled in the feed to, and as discard from, the reagent system. If lime is used, the grit is rejected in the slaking system and is sent to waste (thickener or pond) from that point. If limestone is used, the grit is carried through the wet-milling step and the slurry system. From there, the grit can recycle in the system or be rejected in the bleed stream. Whichever reagent is used, the grit eventually adds to the quantity of solid waste.

Typical lime analyses are shown in Table 3-5 and trace element analyses of both lime and limestone are shown in Table 3-6. Typical limestone analyses are contained in Table 3-7. Note that many of the components, such as silica (SiO_2), iron oxide (Fe_2O_3) and alumina (Al_2O_3) will be relatively insoluble in the scrubber liquor. Not only the concentration but also the crystalline phases of the calcium and magnesium carbonates are important in determining the reactivity of the limestone. For example, magnesium and calcium present in the dolomitic form are less soluble and less reactive than calcium and magnesium present in pure phase carbonates. A less reactive limestone will result in excess scrubbing reagent in the sludge solids.

Table 3-5

TYPICAL ANALYSES OF LIME
(All figures in %)

LIME SOURCE		A	B	C	D	E	F
Silicon Dioxide	SiO_2	2.8	--	--	2.0	0.2	1.0
Iron Oxide	Fe_2O_3	0.8	0.2	0.07	2.0	0.09	0.9
Aluminum Oxide	Al_2O_3	--	0.7	0.2	--	--	--
Calcium Oxide	CaO	91.1	94.0	94.0	90.0	99.0	55.5
Magnesium Oxide	MgO	5.6	1.5	0.5	1.0	0.08	38.0
Total Sulfur	S	0.09	--	--	1.0	--	0.1
Insoluble Matter		3.24	1.5	0.8	2.0	--	3.1

Note: Analyses seldom add up to 100%. Only major constituents and minor ones of significance are shown in most specifications. In example (A), Silicon Dioxide is included in "Insoluble Matter" also, resulting in a total exceeding 100%.

(F) is a dolomitic lime. All others are high calcium limes.

The amount of "grit" remaining after slaking cannot be determined from a chemical analysis.

Source: Preparation and Handling of Lime Slurries, Bulletin TP-80-M, Wallace & Tiernan, Belleville, NJ (Undated).

Table 3-6

TRACE ELEMENT ANALYSES OF
LIME AND LIMESTONE SAMPLES
(ppm)

ELEMENTS	STATION NUMBER				
	1	2	3	4	5
Sb	5.3	3.1	<.80	1.3	3.2
As	3.0	2.9	.83	.66	2.7
Ba	<30.	<30.	<30.	<30.	<30.
Be	3.0	.14	<.27	.37	.17
B	6.45	45.1	11.2	10.8	17.4
Cd	.28	.24	.92	.90	.65
Cr	1.2	3.5	.61	.57	<.80
F	105.	134.	307.	103.	117.
Ge	<1.0	<.1	<.1	<.1	<.11
Hg	<.010	<.012	<.010	<.010	<.020
Pb	1.3	10.	26.	14.	13.
Mn	29.8	83.5	43.6	20.3	290.
Mo	150.	.04	15.	8.9	12.
Ni	4.3	4.62	<12.	<6.0	6.20
Se	.08	.17	.086	.30	.22
V	<50.	<24.	<160.	<24.	<160.
Zn	9.6	--	71.4	28.0	48.
Cu	5.8	14.0	9.3	15.6	2.4

All results are reported as the average of duplicate analyses. Analyses are in ppm on a dry sample basis.

Source: Holland, W. F., et al., Environmental Effects of Trace Elements from Ponded Ash and Scrubber Sludge, Radian Corporation, EPRI RP 202, September, 1975.

Table 3-7

TYPICAL ANALYSIS OF LIMESTONE[a]
(All Values in Weight Percent)

	1	2	3	4	5	6	7	8
CaO	54.54	38.90	41.84	31.20	29.45	45.65	55.28	52.48
MgO	0.59	2.72	1.94	20.45	21.12	7.07	0.46	0.59
CO	42.90	33.10	32.94	47.87	46.15	43.60	43.73	41.85
SiO	0.70	19.82	13.44	0.11	0.14	2.55	0.42	2.38
Al O	0.68	5.40	4.55	0.30	0.04	0.23	0.13	1.57
Fe O [b]	0.08	1.60	0.56	0.19	0.10	0.20	0.05	0.56
SO	0.31		0.33			0.33	0.01	
P O			0.22		0.05	0.04		
Na O	0.16		0.31	0.06	0.01	0.01		
K O			0.72		0.01	0.03		
H O			1.55		0.16	0.23		n.d.
Other			0.29		0.01	0.06	0.08	0.20

[a]1 = Indiana high-calcium stone
2 = Lehigh Valley, PA,"cement rock"
3 = Pennsylvania "cement rock"
4 = Illinois Niagaran dolomitic stone
5 = Northwestern Ohio Niagaran dolomitic stone
6 = New York magnesian stone
7 = Virginia high-calcium stone
8 = Kansas Cretaceous high-calcium stone (chalk)

[b]Includes some Fe as FeO.

[c]Includes some elemental S.

Source: Chemistry and Technology of Lime and Limestone, R. S. Boynton, John Wiley & Sons, Inc., New York, 1966.

Flyash

Flyash can be present in sludges in proportions varying from a trace to 50 percent and more. The quantity is governed by:

- Presence or absence of upstream removal devices
- Efficiency of those devices
- Quantity of ash and sulfur in the coal
- Efficiency of scrubbing process for flyash removal
- Use of alkaline flyash as a scrubber reagent
- Use of flyash as a stabilization or dewatering agent for sludge disposal

The elements forming the major and minor chemical constituents of flyash are summarized in Table 3-8 according to coal source. From another task of this EPRI project (RP 786), Radian Corporation reported that, in general, eastern ashes were low in calcium, alkalinity, sulfate and magnesium, while western ashes were high in these same species. Eastern ashes were generally high in silica (SiO_2), alumina (Al_2O_3) and iron (Fe_2O_3) while western ashes contained less of these species.

Figure 3-5, a photomicrograph of flyash, shows the characteristic spherical nature of flyash particles which are ususally from 1 to 500 microns in diameter.

Increased trace element concentrations in the disposed material result from the inclusion of flyash with sludge and have caused some environmental concerns as discussed later in this section. Table 3-9 shows the concentrations of these elements found in samples of electrostatic precipitator flyash. As noted in previous instances of sludge components, the mere presence of these constituents does not indicate that any or all will be soluble in the scrubber liquor or in leachate from disposed sludge.

Dry flyash is often mixed with scrubber sludge to stabilize the sludge for disposal, and use of this mode of sludge stabilization will increase in the future, as shown in Table 2-2. The possible disposal benefits obtained by blending dry flyash with scrubber sludge include:

- Reduced moisture content of the resultant waste
- Decrease in permeability
- Increased structural strength if the flyash possesses any cementitious characteristics.

Table 3-8

RESULTS OF CHEMICAL ANALYSES OF FLYASHES

FLYASH NUMBER	COAL SOURCE[a]	MOISTURE[b] (%)	LOSS ON[c] IGNITION (%)	RESIDUE[d] AFTER IGNITION (%)	Na_2O	K_2O	MgO	CaO	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	SO_3	UNDETER-MINED
1	Northern Great	0.18	0.41	99.59	2.93	1.00	10.2	26.6	25.4	11.0	11.1	0.55	<0.02	6.52	4.6
	Plains (L)	0.16	0.43	99.57	3.37	1.04	10.4	27.3	24.6	12.5	11.2	0.48	<0.02	6.89	2.2
2	Powder	0.11	0.32	99.68	1.74	0.68	5.29	29.7	31.4	18.6	6.74	1.67	1.14	2.89	0.1
	River (S)	0.11	0.43	99.57	1.23	0.60	5.29	31.1	31.7	19.7	6.74	1.62	<0.02	3.40	-1.4
3	Black Mesa (B)	0.10	3.24	96.76	2.10	0.95	2.53	13.1	51.5	22.4	5.88	1.19	<0.02	0.72	-0.3
		0.13	3.20	96.80	1.97	0.90	2.50	13.2	52.0	22.6	5.78	1.23	0.13	0.85	-1.1
4	Appalachian (B)	0.44	5.81	94.19	0.50	2.23	1.07	3.85	48.0	22.4	18.7	1.25	0.26	3.10	-1.3
5	Illinois (B)	1.04	1.76	98.25	0.39	2.16	1.30	1.27	48.0	25.9	16.3	1.50	<0.02	0.16	3.1
6	Green River (S)	0.14	1.20	98.80	0.62	1.18	1.72	5.97	60.4	23.6	3.33	0.67	0.16	0.24	2.0
		0.15	1.64	98.36	0.56	1.12	1.66	6.28	61.1	22.4	3.67	0.70	1.23	0.34	1.0
7	Wilcox (L)	0.06	0.43	99.57	0.60	0.75	5.14	22.9	46.1	15.8	5.78	1.60	0.03	1.41	-0.1
8	Appalachian (B)	0.06	3.35	96.65	0.82	3.89	1.95	1.03	54.7	28.5	7.50	1.15	0.40	0.17	-0.1
9	Green River (S)	0.37	1.48	98.52	2.14	1.24	2.73	5.50	64.8	18.7	4.06	1.02	0.22	0.36	0.8
10	Appalachian (B)	0.10	20.46	79.54	0.59	2.73	1.50	1.44	51.4	24.6	17.2	1.00	0.13	0.19	0.8
11	Appalachian (B)	0.21	4.35	95.65	0.50	3.22	1.58	1.60	51.5	27.9	9.60	1.27	0.02	0.07	2.8
12	Appalachian (B)	.50	5.7	94.3	.46	2.08	.84	2.07	50.7	22.6	19.3	1.18	.42	.23	0.1
13	Appalachian (B)	.80	6.4	93.6	.48	2.30	.89	1.16	55.2	22.9	15.5	1.13	.33	.12	0.0
14	Appalachian (B)	0.06	1.31	98.69	0.44	2.76	1.54	1.43	55.8	30.3	6.10	1.52	0.10	0.09	0.2

[a] L = Lignite coal source; S = Subbituminous coal source; B = Bituminous coal source.

[b] Sample was dried at 105°C consistent with method designated by ASTM C-311

[c] Sample was ignited at 750°C consistent with method designated by ASTM C-311

[d] Represents the portion of the dry material which is not ignitable at 750°C.

Source: Jones, B. F., et al., Evaluation of the Physical Stability and Leachability of Flue Gas Cleaning Wastes, Radian Corporation, EPRI FP 671, Volume 2, 1978.

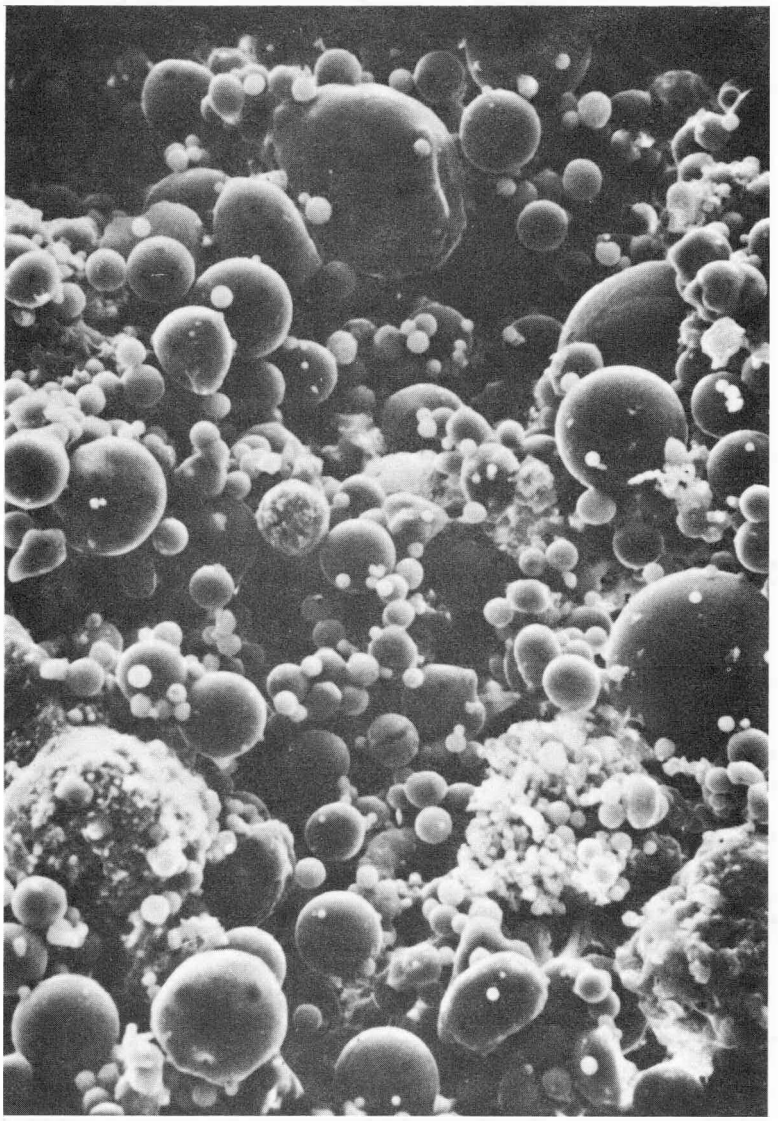


Figure 3-5. Phillips Power Station Flyash.

Courtesy: Dravo Lime

Table 3-9

PRECIPITATOR ASH TRACE ELEMENT ANALYSES
(ppm)

	STATION NUMBER			
ELEMENT	1	2	3	4
Sb	1.0	1.5	2.5	4.4
As	3.2	74.	56.6	61.
Ba	3,600.	700.	750.	15,000.
Be	5.2	7.5	13.1	5.2
B	179.	274.	392.	1,040.
Cd	.39	1.4	5.3	4.2
Cr	5.6	3.6	28.0	8.9
F	377.	83.9	210.	2,880.
Ge	1.2	12.1	25.1	9.2
Hg	.126	<.010	.146	<.010
Pb	6.4	17.	27.	4.0
Mn	157.	242.	273	374.
Mo	7.0	6.4	5.9	12.
Ni	34.2	75.1	108.	92.9
Se	1.7	3.27	14.7	16.4
V	<50.	<100.	<25.	<100.
Zn	92.	102.	854.	386.
Cu	43.	113.	59.	238.

All results are reported as the average of duplicate analyses. Analyses are in ppm on a dry sample basis.

Source: Holland, W. F., et al., The Environmental Effects of Trace Elements from Ponded Ash and Scrubber Sludge, Radian Corporation, EPRI RP 202, September, 1975.

The addition of flyash to sludge decreases the water content of the final disposal product, thus creating a more desirable fill material. The dewatering of the sludge is a result of the large volumes of dry flyash added to the sludge. Also, further dewatering of the ash/sludge mixture can occur through hydration reactions, if the flyash contains significant quantities of calcium and is alkaline in nature. Flyash addition as a stabilization process has been used at several plants, including the Martin Lake Plant of Texas Utilities Generating Company and Southwest Plant of Springfield City Utilities, as shown in Table 2-1.

The unique particle morphology of flyash affects the final waste product when it is added dry to scrubber sludge. The spherical shape is reported to decrease the viscosity of scrubber sludge (1). This would tend to improve pumpability characteristics of the sludge. Flyash can aid in sludge disposal operations because drainage is improved by the presence of particles larger than those in sulfite-sulfate sludge alone (2). On the other hand, alkaline flyashes can decrease the permeability of a disposal mixture through hydration reactions which fill the pore spaces of a material (3). A decrease in permeability would result in less leachate.

Finally, many flyashes from western coals possess pozzolanic properties which structurally stabilize sludge. The increased strength obtained by mixing alkaline flyash with sludge creates a landfill or pond possessing greater load bearing capacity than FGD slurry alone. Also, the waste material is rendered less permeable as previously mentioned. Overall, the addition of flyash to sludge appears to be a growing trend and Table 2-2 shows that the practice is planned at a number of additional plants.

Flyash is sometimes removed along with the SO_2. A disadvantage in this is that the material load to be handled in the scrubbing system is increased. The presence of flyash also requires the use of erosion-resistant construction materials, thus adding to the cost of the scrubber system.

Both soluble and insoluble elements result from the inclusion of flyash. A significant portion of the calcium, magnesium, and sodium compounds in the ash are present in the oxide form; as such, they are a ready source of alkalinity for scrubbing the SO_2. Magnesium and sodium are subsequently concentrated by recycle in the scrubber system while calcium precipitates. Soluble chloride, phosphate and nitrate compounds in the flyash contribute a portion of those compounds present

in the scrubbing liquor. These compounds are undesirable in that they are corrosive and increase the total dissolved solids in the waste disposal sludge.

FACTORS AFFECTING COMPOSITION

Some of the most important factors affecting the characteristics of scrubber sludge include:

- Extent of oxidation
- Amount of flyash present
- Coal - characteristics and consumption
- Reagent - type, quantity, purity
- Water - quantity, quality

Extent of Oxidation

The extent of oxidation determines the SO_3/SO_4 ratio of scrubber sludge. As discussed previously the morphologies of calcium sulfite and calcium sulfate sludges are very different. Calcium sulfate possesses superior dewatering characteristics, physical properties, bulk density and stability as a disposal waste.

Upstream Flyash Removal

The presence or absence and efficiency of upstream flyash removal equipment probably affects the composition of scrubber sludge more than any other factor. Total removal of flyash in an alkaline-ash scrubber with coal sulfur in the range of low sulfur coals, 0.4 to 1.05 percent, will result in a sludge with a preponderant quantity of aluminum, iron and silica compounds from the flyash, and a lesser quantity of scrubbed sulfur as calcium sulfate. This would be the case with the scrubbers at Montana Power Company's Colstrip Plant and Northern States Power Company's Sherburne County Generating Plant. In comparison, the lime sludges from scrubbing the flue gas after the high-efficiency electrostatic precipitators (ESP) on the No. 5 and 6 Units of the Conesville Generating Plant of the Columbus and Southern Ohio Electric Company and the No. 3 Unit of the Bruce Mansfield Plant of the Pennsylvania Power Company could be expected to be almost completely composed of calcium sulfite before flyash is added for disposal. An indication of the effect of flyash removal is shown in Table 3-10. This presents analyses of lime sludges when flue gas is scrubbed before and after an ESP. The lower quantities of SiO_2, Al_2O_3 and Fe_2O_3 in the "after-ESP" sludge is indicative of the lower flyash content and shows the effect of upstream flyash removal.

Table 3-10

CHEMICAL ANALYSES OF LIME PROCESS SLUDGES

	% DRY SOLID BASIS	
	BEFORE ESP	AFTER ESP
CaO	18.1	43.2
MgO	2.4	.2
Total S	7.2	18.9
SO_2	12.1	33.0
SO_3	2.9	5.9
CO_2	3.2	6.7
SiO_2	31.6	4.9
Al_2O_3	18.3	3.4
Fe_2O_3	4.3	0.6

Source: Selmeczi, J. G. and Knight, R. G., "Properties of Power Plant Waste Sludges," presented at 3rd Symposium on Flyash Utilization, March, 1973, Bureau of Mines Information Circular 8640.

Coal Characteristics

The following coal characteristics affect sludge composition:

- Ash quantity. If the ash content of the combusted coal changes due to a change in source, in mining practices or in cleaning plant practices, the scrubbed ash quantity and sludge composition will also vary.
- Ash quality. Very alkaline ashes may sorb SO_2 in the gas phase thus reducing the amount of scrubbing required.
- Sulfur quantity. The sulfur content of a coal affects composition by changes in the proportions of sulfur compounds and ash, if the latter is not collected upstream from the SO_2 scrubber and is included in the sludge. With or without flyash, lower sulfur coals will move the SO_3/SO_4 ratio toward a predominant sulfate form because any excess of combustion air will result in proportionally more oxygen for reaction with the lower content of sulfur. Also, as noted previously, an increase in sulfur content increases total sludge solids quantity--the dry sulfite/sulfate sludge amounting to about five times the weight of the sulfur removed by scrubbing.
- Heating value. If the heating value of a coal decreases due to an increase in ash and consumption consequently increases, sludge composition will be affected as described for ash quantity. If the decrease in heating value is caused by an increase in moisture content, the sludge composition and quantity will not be affected.
- Trace elements. Trace elements in the coal may be released to the bottom ash, flyash or flue gas. Some of those in the latter two may be found in the scrubber sludge, especially with no or inefficient upstream flyash removal, when alkaline flyash is used as the scrubbing reagent, or when flyash is mixed with sludge for disposal. Since various coal seams have varying proportions of the trace elements, sludge composition will vary accordingly. Table 3-11 shows the trace element content of five coals. The wide variance for some elements is apparent.

Reagent

Lime affects sludge composition in the following ways:

- Lime has been and generally continues to be the most reactive reagent of those used in sludge-producing scrubbers (other than in double-alkali). It is usually of a more consistent and higher purity than limestone, thus contributing less grit and non-reactive material.
- Magnesium oxide, naturally occurring or purposely added to lime to promote SO_2 removal, contributes a more soluble form of sulfate to the sludge and can thus add to leachate problems. The maintenance of a higher-than-normal pH (about 10.5) in the sludge due to added lime or the presence of alkaline flyash, will precipitate the magnesium as the hydroxide.
- Being more reactive, lower stoichiometry has usually been possible with lime than with limestone. Regardless, the unused or excess lime is reported as calcium carbonate in the sludge because lime

Table 3-11

TRACE ELEMENT CONTENT OF COAL SAMPLES
(ppm by wt., dry)

ELEMENTS	STATION NUMBER				
	1	2	3	4	5
Sb	.43	.34	.82	.08	.33
As	.26	8.7	3.5	.87	4.6
Ba	300.	100.	100.	440.	100.
Be	.44	1.3	2.1	.29	.16
B	27.9	36.5	62.1	37.7	96.9
Cd	.028	.05	.30	.11	7.9
Cr	1.5	1.2	3.4	1.8	.45
F	54.	193.	144.	78.5	372.
Ge	<1.0	2.9	4.4	.48	4.5
Hg	.140	.199	.212	.131	.322
Pb	.90	1.4	4.3	.15	41.
Mn	16.0	60.4	41.5	26.2	142.
Mo	<.13	1.3	.39	.87	.41
Ni	2.3	12.9	18.7	3.67	51.7
Se	4.2	2.24	3.15	.98	3.2
V	<13.	<16.	<13.	<13.	<12.
Zn	40.	68.6	68.1	16.2	780.
Cu	7.6	22.2	28.	5.2	41.5

Values represent the average of duplicate determinations.

Source: Holland, W. F., et al., Environmental Effects of Trace Elements from Ponded Ash and Scrubber Sludge, Radian Corporation, EPRI RP 202, September, 1975.

reacts with carbon dioxide. If the unused lime has not reacted with CO_2 it will tend to increase the sludge pH in thickeners or ponds.

Limestone affects sludge composition in the following ways:

- Limestone contains more inerts than lime and therefore contributes more grit to the sludge.
- Limestone, too, can contain magnesium in the oxide form as proposed by a U.S. scrubber manufacturer and as reported in the literature (4). The same problem with soluble magnesium sulfate as noted with lime can, therefore, be encountered.
- The proportion of unreacted limestone ($CaCO_3$) is governed by the stoichiometry and utilization. It will generally not affect the pH of the sludge by continued contact, unless the sludge should be quite acidic.

Alkaline flyash resulting from the combustion of many western coals and lignite is receiving increasing attention as a partial or total reagent in wet scrubbers (5,6).

- In addition to increasing the quantity of sludge to be handled, it can contribute a variety of chemical species as shown in Table 3-12. However, it should be noted that many of these species are insoluble in the scrubber liquor.
- In some cases, such as at Montana Power Company's Colstrip Generating Units 1 and 2, the flyash and SO_2 are removed in the same scrubber vessel, all the alkaline flyash being available for use as reagent (7). Supplemental alkalinity is provided by quick-lime. The operating practices at this plant and the scrubber design have resulted in almost 100 percent oxidation of the sludge to the sulfate form; however, this is reported as being common when alkaline flyash is used.
- In other cases, the flyash is removed by electrostatic precipitators; the necessary quantity is then slurried and added to the scrubber system for pH adjustment. This is the case at the Minnkota Power Cooperative, Inc., Milton R. Young Unit 2. The boilers are cyclone-fired, producing 30 percent flyash and 70 percent bottom ash. The fuel is lignite yielding an alkaline flyash averaging 25 percent CaO (8). It is estimated that the use of flyash as the scrubbing reagent will result in operating cost reduction of over $500,000/yr. The scrubber sludge is dewatered by vacuum filter and disposed of in mined-out areas of a strip mine.

Water Content

Both the quantity and quality of water discarded with the sludge affect its characteristics. The quantity affects processing and disposal practices; the greater the quantity, the more difficult the disposal. As described earlier, water has more influence on the physical properties of sludge than any other component.

Table 3-12

TYPICAL ASH COMPOSITION FROM WESTERN COALS
(Wt%)

STATE		% of MOISTURE-FREE COAL ASH	% of MOISTURE-FREE COAL SULFUR	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	MgO	Na_2O	K_2O	SO_3
Colorado	Min.	3.0	0.4	34.8	15.2	3.2	1.0	0.01	0.4	0.4	0.1	0.1	0.2
	Avg.	10.0	0.7	50.4	26.8	6.1	1.3	0.5	6.2	1.1	0.7	0.3	5.2
	Max.	19.2	1.1	71.8	34.2	11.9	1.7	2.8	12.8	2.9	3.0	0.8	15.1
Montana	Min.	4.2	0.4	21.9	13.8	2.9	0.6	0.02	1.8	1.4	0.1	0.3	2.4
	Avg.	12.6	0.6	35.4	21.5	5.3	0.8	0.4	13.4	4.6	2.8	0.7	13.3
	Max.	19.3	0.9	53.6	31.9	8.0	1.2	0.76	31.4	10.4	8.1	1.8	26.2
New Mexico	Min.	2.9	0.6	28.9	14.3	3.6	0.9	0.02	1.7	0.8	0.1	0.1	0.5
	Avg.	10.5	1.3	49.2	21.8	13.8	1.1	0.06	6.4	2.0	0.7	0.6	4.7
	Max.	16.3	3.2	61.9	30.0	27.3	1.3	0.12	14.0	4.2	2.2	1.1	17.3
North Dakota	Min.	7.5	0.5	15.0	8.0	4.1	0.6	0.04	14.5	3.3	0.5	0.1	16.6
	Avg.	11.8	1.0	26.3	12.1	6.9	0.7	0.2	21.1	6.4	4.4	0.3	20.6
	Max.	16.9	1.5	40.4	16.8	10.1	0.9	0.42	36.0	10.8	8.2	0.6	27.4
Utah	Min.	5.7	0.4	39.4	9.1	3.7	0.6	0.03	3.5	0.3	0.4	0.1	1.8
	Avg.	7.7	0.8	51.4	15.1	7.4	1.0	0.6	11.8	3.3	1.7	0.6	6.0
	Max.	9.6	2.2	63.2	20.3	19.3	1.3	1.4	21.9	7.6	4.3	1.4	8.6
Wyoming	Min.	6.4	0.6	24.5	14.2	9.0	0.9	0.21	9.4	4.4	0.1	0.5	14.4
	Avg.	10.4	1.2	31.5	16.9	9.6	1.3	0.36	20.1	4.5	0.1	0.5	15.2
	Max.	14.4	1.8	38.6	19.6	10.3	1.8	0.51	30.8	4.7	0.2	0.6	16.1

Source: Monsanto Research Corporation, Evaluation of Low-Sulfur Western Coal Characteristics, Utilization, and Combustion Experience, PB 243 911, May, 1975.

The quality of water directly affects the water pollution potential of disposed sludge. Any dissolved species present in the water (liquor) can be displaced as leachate from sludge disposal areas.

There are several sources for the dissolved species found in the scrubber liquor:

- Elements which are sorbed directly from the flue gas
- Species which are dissolved from the reagent
- Minor and trace elements which are dissolved from any flyash present in the scrubber
- Dissolved solids which are present in the make-up water

All of the above species may be further concentrated in the liquor by circulation in a closed loop system or through evaporation of the water in the scrubber.

PREDICTING SLUDGE COMPOSITION

It is not possible to predict the chemical composition and physical properties of sludge with a high degree of accuracy prior to actual operation of a new scrubber. This occurs because of the large number of system operating variables which influence scrubber characteristics.

Ideally, a scrubber could be installed with no long-term provision for sludge disposal. A small, lined basin could be designed to retain the sludge for an interim period of, say, five years. During that period, a normal operating mode could be established for the scrubber so that the sludge is being generated in a consistent manner. During this interim period, the sludge could be tested periodically to determine the variation in its physical and chemical properties. Then based on actual operating data, a sludge disposal system could be designed and implemented which best suits the actual sludge being generated.

While such a system is ideal, it is not usually practical. In most cases, utilities must know how they will handle the sludge from a new facility and win approval from the regulatory agencies long before the sludge is generated. They must, therefore, use other methods of estimating what they think the sludge composition and properties will be.

There are several alternatives:

- Use data from a pilot plant operated on an installation similar to the new facility.

- Use data from actual operating installations which have system components similar to that at the new, planned installation.
- Use data, such as that reported herein, which is gained from general operating experience at a number of installations.
- Combination of the methods given above.

The following points may be helpful in developing an estimate of sludge composition:

- Guarantee on upstream particulate removal. This value, correlated with the amount and quality of coal to be burned, can give a good approximation of the quantity of particulates in the scrubber influent. With the scrubber manufacturer's guarantee on particulate removal, an estimate of the quantity of flyash in the sludge can be made.

  Care must be taken in accepting ESP guarantees without reservation. This is especially true when design is based on resistivity measurements which (1) have been made on random coal-seam cores which do not reflect a projected mining program, (2) are based on "typical", "average", or "design" coals, or (3) are based on data that give maximum and minimum values for ash constituents but not the complete analysis (9). The preferred coal data for design purposes would be based on the analyses of a number of representative samples from mining operations in the same seam that will be used to supply the planned unit(s).

- Guarantee or purchase specifications on dewatering equipment. A manufacturer's guarantee on filters, centrifuges or thickeners must be based on thorough experience and good data on similar equipment operating on sludge which is expected to be similar. Most manufacturers tend toward conservatism in the design of this type of equipment--a practice to be desired in buying for a first unit in a new scrubber plant. With his guarantee, an estimate of the water content of the sludge can be made.

- SO_3/SO_4 ratio. This is an important parameter and one that is difficult to evaluate. Probably the best approximation can be obtained from an operating installation using the same type of scrubber. It will be impossible to have other important factors, e.g., coal, reagent, boiler, particulate concentration, all reflect an individual plant condition. The estimate will be subject to considerable variance, unless forced oxidation is to be used. In that case, many of the variables can be eliminated from consideration.

- Reagent specifications. The specifications for reagent purchase can give information on several items of interest in the composition of sludge: (1) the minimum value of CaO in lime or $CaCO_3$ in limestone, and concurrently, the grit or inerts can give some measure of the quantity and type of non-reactive components that must be handled with the sludge, (2) reactivity will give a similar measure, especially lime, for the non-calcined material as well as a check on the quantity of inerts, (3) magnesium oxide content as an additive or a natural component will give some idea of the very soluble magnesium sulfate that may be found in the water portion of the sludge.

- Coal characteristics. A knowledge of coal characteristics and composition, as determined on samples from existing mines or on cores from new mines can contribute considerable input of value: (1) the quantity of ash will help to predict the quantity of flyash found in the scrubber influent, either with or without upstream particulate removal, (2) as noted above, a knowledge of heating value and sulfur are necessary to determine coal and reagent usage, (3) the concentration of chloride will aid in estimating the chloride accumulation in the scrubber liquor, a portion of which will leave the system as the very soluble calcium chloride, (4) trace metals are of interest, but a correlation of the extremely small quantities normally present in coal with the concentrations in the scrubber liquor is virtually impossible, (5) a knowledge of the affinity for sulfur oxides of the specific coal ash is, in some cases, very pertinent in determining the sulfur oxide quantity to be found in the sludge (10); (6) if flyash is to be used in the scrubber sorbent, the available alkalinity to be expected will affect the quantity of reagent used, with corresponding changes in the sludge composition.
- Liquor blowdown from system. An estimate of scrubber liquor loss or blowdown from the system is of use in arriving at a value for the total dissolved solids (TDS) in the water portion of the sludge. In closed systems, i.e., those with no intentional drainage of liquor, the TDS can reach values which may affect considerably the leachable material in disposed sludge. The best source for this type of data is operators of scrubbers with similar conditions.
- Make-up water analysis. The constituents of make-up water will vary widely from site to site. As generating stations approach the no-discharge status, the variety and concentration of dissolved solids can be expected to increase considerably. An estimate of these values will require detailed consideration of all contributing water circuits at the site. Once again, this analysis is of concern because of the recycling and concentration of scrubber water, resulting in high concentrations of dissolved solids.

SLUDGE PHYSICAL PROPERTIES

The physical and engineering properties of FGD sludges are dependent on sludge composition. The major constituents in sludges can vary as discussed in earlier sections. Sludge composition generally includes sulfur oxide reaction products, unreacted alkalinity, flyash, and adherent liquor. Flyash quantities may range from near-zero to more than 90 percent depending on upstream ash removal systems or ash alkalinity utilization practices at a particular site. Sulfur oxide reaction products could be present mainly as calcium sulfite hemihydrate or as calcium sulfate dihydrate depending on the degree of oxidation attained. In general, oxidation will result in higher concentrations of calcium sulfate. It is obvious that a rather wide range of sludge compositions is possible and therefore a wide range of physical and engineering properties will be observed.

Engineering properties of FGD sludges at typical installations are given in Table 3-13 and described in the paragraphs below. These engineering properties represent those of unfixed and unoxidized sludges. The engineering properties in alkaline flyash or chemical agents are discussed in the Section - FACTORS AFFECTING PHYSICAL PROPERTIES.

Table 3-13

TYPICAL ENGINEERING PROPERTIES OF FGD SLUDGES

Moisture Content, %	120 to 400
Solids Content, % by weight	20 to 45
Dry Bulk Density, lb/ft^3	22 to 33
Permeability, cm/sec	10^{-4} to 10^{-5}
Compression Index	1.9
Angle of Internal Friction	~20
Cohesion	None
Unconfined Compressive Strength	None

Solids Content

In evaluating moisture contents and percent solids of FGD sludges, some confusion has resulted from different methods of computation. Percent solids is reported as the percent of the total weight of the sludge due to the solid constituents. In contrast, moisture content is computed as the ratio of the weight of the sludge liquid to the weight of the sludge solids, expressed as a percentage.

Results of percent solid levels achieved in laboratory tests designed to simulate dewatering by settling, settling followed by draining, filtration, and centrifugation are reported in Table 3-14. The settled sludges presented in Table 3-14 have solids contents ranging from 37 to 67 percent. These values correspond to moisture contents of 170 to 49 percent, respectively, of the dry weight of the sludge solids.

Table 3-14

PERCENT SOLIDS ACHIEVED BY VARIOUS LABORATORY DEWATERING TECHNIQUES

Location and Scrubbing Process	Fly Ash (%)	Percent Solids (%)			
		Settled	Drained	Filtered	Centrifugation
Eastern Limestone	20	45.0	51.7	65.0	55.8
(two samples)	40	52.9	58.3	65.9	63.3
Eastern Lime	41	43.4	45.3	56.0	49.9
Eastern Lime	60	47.6	54.2	47.0	57.2
Western Lime	59	46.7	60.9	53.4	60.9
Western Lime	3	66.6	67.2	80.3	75.0
Eastern Dual Alkali	7	40.0	43.9	57.3	50.9
Western Dual Alkali	9	37.4	37.8	43.1	62.2

Source: Leo & Rossoff as reported by Lunt et al., 1977. An Evaluation of the Disposal of Flue Gas Desulfurization Wastes in Mines and the Ocean: Initial Assessment, EPA 600/7-77-051.

The low solids content of untreated unoxidized FGD sludge partially explains the fluid nature of the material, particularly when the difference in specific gravity of the sludge solids and liquor is considered. For a sludge-solids specific gravity of 2.5, a 45 percent solids sludge by weight is 65 percent water by volume.

The standard laboratory test for determining the moisture content of the soil and soil-like materials is ASTM D2216, Laboratory Determination of Moisture Content of Soil. This test procedure is generally suitable for determining the moisture content of sludges with one modification. The ASTM procedure is based on determining the moisture content of soil through measurement of the weight lost when the sample is dried in an oven at 150°C. A problem arises with FGD sludges, in that some of the constituents are hydrated salts that will lose some or all of their water of hydration when heated to 105°C. Tests have shown that using a drying temperature of 70°C will allow accurate determination of FGD sludge moisture contents without loss of the water of hydration. Therefore, when determining the moisture content of FGD sludges, use the procedures of ASTM D2216, but modify the drying temperature to 70°C.

Bulk Density

For comparing different FGD wastes or different disposal schemes, dry bulk density is the parameter that is most easily compared. Dry bulk density is the weight of the sludge solids that will occupy a unit volume. The bulk density is an important parameter since it determines, in part, the volume of the disposal area required. For a specific power plant, increasing the bulk density of the FGD wastes will reduce the size of the disposal area.

Settled FGD sludges have dry bulk densities from about 22 to 33 lb/ft^3. In comparison, compacted flyash has a dry bulk density of about 70 to 99 lb/ft^3.

Determination of the bulk density of a sludge sample is not a straightforward procedure, since the bulk density will change depending upon the degree of compaction to which the sample is subject.

If landfilled sludges are strong enough to support the weight of personnel, the bulk density can be determined in the field by ASTM D1556, Test for Density of Soil in Place by the Sand-Cone Method. In this test procedure, a quantity of sludge is excavated and weighed. The volume of the material excavated is determined by measuring the volume of the hole remaining, through use of the sand-cone apparatus. An alternate method which is applicable to field testing, but which requires a more sophisticated apparatus, is ASTM D2167, Test for Density of Soil in Place by the Rubber Balloon Method.

If landfilled sludges are strong enough to support equipment, but not so strong that they prevent sampling by soil drilling methods, samples can be obtained and the bulk density determined in the laboratory at some later time by ASTM D2937, Test for Density of Soil in Place by the Drive Cylinder Method. This method of bulk density determination is particularly suited for inclusion in drilling programs where the work is performed by outside contractors.

If it is desired to know the bulk density that can be obtained by compacting the sludge during placement in a landfill, two laboratory methods are commonly used. ASTM D698, Test for Moisture-Density Relations of Soils using 5.5 lb Rammer and 12-in Drop and ASTM D1557, Test for Moisture Density Relations of Soils using 10 lb Rammer and 18-in Drop are both suitable for determining the bulk density that can be obtained in field compaction operations. The selection of one method over the other is largely a matter of individual preference.

Whatever test method is used, the basic principle involved is the determination of the weight of a known volume of sludge. Thus, for fluid sludge or loosely-dumped dry sludges, merely weighing a filled container of known volume and subtracting the weight of the container may be suitable for determining the bulk density of the sludge.

Permeability

The permeability of untreated FGD sludges is 10^{-4} to 10^{-5} cm/sec. These values are equivalent to those for fine to very fine sand, with drainage characteristics rated as good to poor.

The importance of permeability is that it determines, in large measure, the volume of leachate which can drain from the sludge. A reduction in permeability from 10^{-4} to 10^{-5} cm/sec, for example, will reduce the volume of leachate by a factor of 10.

Permeability tests are performed by applying a hydraulic head to a prepared sample. The fluid which passes through the sample in a specified time is collected and weighed and permeability is determined. The hydraulic head may be either variable or constant. For a variable or "falling head" pressure only the hydrostatic pressure of the fluid is applied. As the fluid flows through the sample the head is reduced. To maintain a constant head additional pressure may be applied either by an external source or by fluid make-up during the test.

Compressibility

FGD sludges behave in a manner dissimilar to soils when compressed. The compressibility of sludges and soils is most easily described by the Compression Index. This parameter is directly proportional to the compressibility of the material under an applied load.

Typical Compression Index values for soils range from about 0.2 to 0.5. Tests on untreated FGD sludge have shown values as high as 1.9. Compression of untreated FGD sludges, therefore, may be as much as 4 to 10 times as great as normal soils. The corresponding expected settlement of buildings located on reclaimed disposal areas would restrict future land use.

The ASTM test for determining the compressibility of fine-grained soils is D2435, Test for One-Dimensional Consolidation Properties of Soils. While this method has

proven generally reliable for soils, it is questionable whether it gives meaningful results when used to test FGD sludges. After examining consolidation test results on FGD sludges, several investigators have concluded that the method may not provide a suitable model of the field behavior of FGD sludges (3). Additional laboratory and field testing appear warranted in regard to developing a procedure for the compressibility of FGD sludges.

Strength

The shear strength of FGD sludges determines the steepness of the slope to which the material can be placed, and the magnitude of foundation loads that the material will support without failure.

The shear strength of granular materials, including FGD sludge, is dependent on the load applied to the material. The greater the magnitude of the applied load, the greater the shear strength. The ratio of shear strength to applied load is a constant which is equal to the tangent of the angle of internal friction. Therefore, the greater the angle of internal friction, the greater the shear strength of the material. Tests on untreated FGD sludge indicate an angle of internal friction of about 20°. For comparison, loose sands have friction angles of about 30°; saturated silts have friction angles of about 20° and behave in a manner similar to FGD sludges. The other component of shear strength is cohesion, which is equal to one-half the unconfined compressive strength. Cohesion is the shear strength which exists when no load is applied to the material. Saturated clays may have a cohesion as high as thousands of pounds per square foot and a friction angle of 0°. Testing of untreated FGD sludges shows little or no cohesion. Having no cohesion, the material has no unconfined compressive strength.

One common method of evaluating the shear strength of FGD sludges, particularly if they have been stabilized, is the pocket penetrometer. There is no ASTM standard for this test and because the results may vary considerably from other strength testing methods, it is not recommended except for qualitative comparisons.

A relatively simple laboratory test of shear strength for samples with some degree of cohesion is the unconfined compressive strength test, ASTM D2166, Test for Unconfined Compressive Strength of Cohesive Soil. For higher strength samples, ASTM D1633, Test for Compressive Strength of Molded Soil-Cement Cylinders may be a suitable alternate testing procedure.

If more detailed information is desired concerning the relative contributions of cohesion and internal friction to the shear strength of the sludge, ASTM D3080, Direct Shear Test of Soils Under Consolidated Drained Conditions is a suitable testing procedure. A very specialized testing procedure called triaxial testing is performed in some cases where detailed information concerning the behavior of the sludge during shear failure is necessary. ASTM D2850, Test for Unconsolidated, Undrained Strength of Cohesive Soils in Triaxial Compression is used in these cases.

Other Parameters

Other soils tests that are commonly run on FGD sludges are grain size determinations, specific gravity and liquid and plastic limits. The appropriate ASTM test designations for these procedures are:

ASTM D422 - Particle-Size Analysis
ASTM D854 - Test for Specific Gravity of Soils
ASTM D423 - Test for Liquid Limit of Soils
ASTM D424 - Test for Plastic Limit and Plasticity Index of Soils

Another physical parameter of interest, particularly when dealing with fluid sludges, is the viscosity of the material. No standardized test has been developed which has been shown suitable for evaluating the viscosity of FGD sludges. As in the case of compressibility, viscosity is an area where additional laboratory and field testing is required in order to develop a suitable procedure.

FACTORS AFFECTING PHYSICAL PROPERTIES

The physical properties of FGD sludges are affected mainly by the composition of the sludge (see SLUDGE COMPOSITION). This section highlights test results (3) on the effects of key factors on (1) unconfined compressive strength, (2) compacted density, and (3) permeability. The key factors considered are:

- Flyash content of the sludge
- Sulfite-to-sulfate ratio in the sludge
- Lime content
- Moisture content

Unconfined Compressive Strength

Flyash Source and Composition. This is the most critical parameter affecting the unconfined compressive strength of ash/sludge mixtures. Alkaline flyash (produced

by burning lignite and subbituminous coal) imparts the highest strength. In one case sludge mixed with alkaline flyash attained an unconfined compression strength of 4300 psi, as compared to 4000 to 8000 psi for concrete. Ashes with low calcium content, such as those produced by burning eastern bituminous coal, impart very low strength when mixed with sludges.

The hardening mechanisms of flyash are enhanced at high pH values. In flyash-water mixtures this high pH regime is established if the flyash contains a high amount of alkali and alkaline earth oxides. Normally, the alkaline species most abundant in the flyash is calcium oxide. The relationship of the development of unconfined compressive strength in sludge/ash mixtures to the leachable alkalinity expressed as calcium oxide is shown in Figure 3-6. These values were taken from flyashes of lignite, sub-bituminous and bituminous coals. Radian has successfully used correlations such as these to predict the unconfined compressive strengths of flyash/sludge mixtures given the leachable alkalinity or calcium oxide content of the flyash.

Flyash Content. Increasing the ratio of flyash to sludge generally increases the strength. In one series of tests, an increase in ash content from 17 to 90 percent increased the compressive strength by a factor of 25 to 40.

Sulfite-Sulfate Ratio. No effect on strength results from various SO_3/SO_4 proportions in laboratory tests.

Lime Addition. The effect of added lime on the strength of ash/sludge mixtures depends on the type of flyash. Addition of lime to sludge/ash mixtures prepared from flyash low in calcium resulted in greater strength increases than lime addition to mixtures containing high-calcium flyash. Some mixtures made with high-calcium flyashes even showed decreases in strength when lime was added. Although some anomalous results were obtained, it should be noted that the addition of lime to sludge/ash mixtures does not automatically insure a greater strength material.

Moisture Content. Moisture affects sludge/flyash mixes in much the same way as portland cement is affected. That is, the strength increases with decrease in the water/cement ratio. However, some water is necessary for the hydration reactions, which are responsible for the strength, to take place.

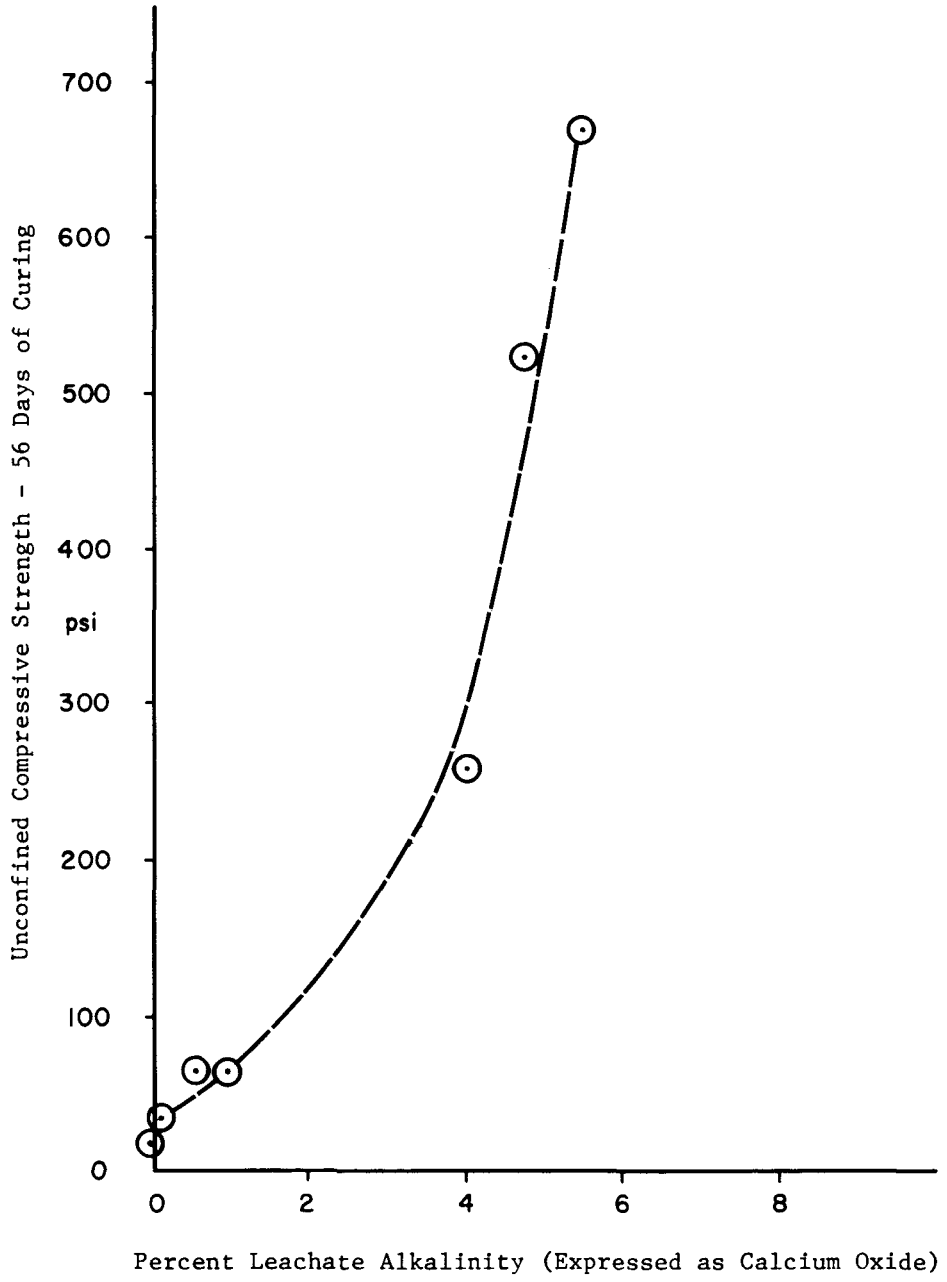


Figure 3-6. Correlation of Unconfined Compressive Strength of 50% ash/50% Sludge Mixtures with Leachable Alkalinity of Flyash.

Source: Jones, B. F., et al., Evaluation of the Physical Stability and Leachability of Flue Gas Cleaning Wastes, Radian Corporation, EPRI FP-671, Volume 2, 1978.

Freeze-Thaw Effect. Flyash/sludge mixtures were subjected to five alternative cycles of freezing and thawing during the 14-28 day curing period to evaluate the influence of winter conditions on the stabilization of FGD sludge by the addition of flyash. In general, the freeze-thaw cycles had no effect on the unconfined compressive strength of the mixtures. In some cases, the strength of the flyash/sludge mixes increased with freeze-thaw cycles.

Compacted Density

The degree of compaction of flyash/sludge/water mixtures depends on the compaction energy and physical properties such as particle size, particle size distribution and moisture content. The density of the compacted material is used as a measure of the degree of compaction and, as a function of moisture content, goes through a maximum. The maximum density, which is the point of optimum moisture content, is determined by compacting solid-water mixtures with increasing content using the same degree of compaction energy. The exact conditions used in soil laboratories are standardized (ASTM D-698, Method A).

Laboratory compaction tests have been performed to establish the moisture-density relationship of flyash/sludge mixtures and selected scrubber sludges. The results are useful when landfill is the method chosen for flyash and sludge disposal. Placing a fill material at the optimum moisture will insure minimum settlement, minimum permeability, maximum shear strength, and maximum utilization of the disposal site.

Tests showed that optimum moisture for flyash/sludge mixtures and selected sludges alone varied from 16 to 35 percent with the exception of Paddy's Run sulfite sludge which showed a value of 65 percent. The high optimum moisture obtained with Paddy's Run sludge resulted from the sludge's rosette-like structure, making it capable of entrapping much water. Maximum dry density varied from 52 lb/ft^3 for Paddy's Run sludge to 94 lb/ft^3 for a 90 percent flyash/sludge mix.

Sludge Type. As the sulfate content increases, the optimum moisture value decreases and the unit dry density increases.

These results indicate a possibility of optimizing disposal costs. Forced oxidation results in an increase in weight and tonnage to be transported. Volume, however, is decreased, so that less disposal space is required. Shawnee's oxidized-sludge dry density was 82 lb/ft^3 compared to 52 lb/ft^3 for Paddy's Run sulfite

sludge. Allowing for difference in molecular weights, the gypsum required 18 percent less volume for disposal in this specific case.

Ash Type and Content. As the ash content of the waste is increased the optimum moisture value generally decreases. At high ash contents (greater than about 50 percent) the maximum dry density of the waste is mainly controlled by the specific density of the flyash.

PREDICTING PHYSICAL PROPERTIES

This section describes methods for predicting the strength and permeability of sludge prior to actual operation of a disposal system. The methods of prediction may be used for plants with scrubbers already in operation or for new or existing plants planning on constructing or retrofitting scrubbers.

The first step in predicting physical properties of sludge is to estimate the relative proportions of flyash and scrubber sludge to be considered. If sludge alone is to be disposed of, the strength and permeability will be similar to the typical values given in Table 3-13. However, if flyash is present the engineering properties of the sludge will be altered depending on the ash/sludge ratio. For operating scrubbers the ash/sludge ratio may be calculated from the mass flow rates of existing solid waste streams. For new plants the waste composition may be estimated using the procedures outlined in the section - PREDICTING SLUDGE COMPOSITION. This method of estimating an ash/sludge ratio essentially entails using the sulfur content of the coal, ash content of the coal, sulfur and ash removal efficiencies, amount of inerts from the reagent and the lime or limestone stoichiometry to calculate the sludge and flyash mass flow rates.

Once the ash/sludge ratio of the waste has been determined, the strength and permeability of the waste can be predicted as explained in the following two sections.

Unconfined Compressive Strength

The unconfined compressive strength of a waste mixture can be determined directly or through indirect estimates using the ash/sludge ratios obtained as described above. Direct determination would encompass batching the actual ash and sludge in the required proportions and determining the unconfined compressive strength through ASTM methods D2166 or D1633. The moisture content required for batching can be

obtained from estimates of the expected moisture of the ash/sludge mixture or the moisture determined as optimum (ASTM D698) can be used.

If ash or sludge is not available for strength testing, indirect estimates of the strength must be employed. The flyash source and composition is the major determinative factor in the strength of ash/sludge mixtures. Therefore, a flyash from a plant burning similar coal from the same formation as the coal of interest can be batched with scrubber sludge from a scrubber of similar design to the proposed system and the unconfined compressive strength determined. However, it must first be confirmed that the coal source used is similar in mineral phase composition to the coal source for the plant of interest.

A second indirect method of predicting an unconfined compressive strength does not entail an actual strength determination. Rather, the strength is estimated based on the alkalinity of the flyash to be produced and the expected ash/sludge ratio. The leachable calcium oxide of a flyash can be directly correlated with the strength of a flyash/sludge mixture (see Figure 3-6). Once again, it is best to use a flyash produced by a plant burning the same coal.

Permeability

Permeability is determined directly by batching the ash and sludge in the proportions expected and measuring the permeability using one of the methods described in Section 7 under Leachate Quantity.

Indirect methods of determining permeability employ the same methods as described for unconfined compressive strength. Either a similar ash and sludge is batched or correlations based on a variety of ash/sludge mixtures are used.

A very good correlation exists between the unconfined compressive strength and the permeability coefficient of ash/sludge mixtures. This correlation is shown in Figure 3-7. Therefore, for fairly accurate estimates of permeability, only the unconfined compressive strength of the waste need be known. A detailed discussion of permeability in sludge/ash mixtures is given in EPRI FP-671, Vol. 2.

ENVIRONMENTAL CONCERNS

The environmental concerns involved with the disposal of FGD sludge include:

- Health effects
- Structural stability

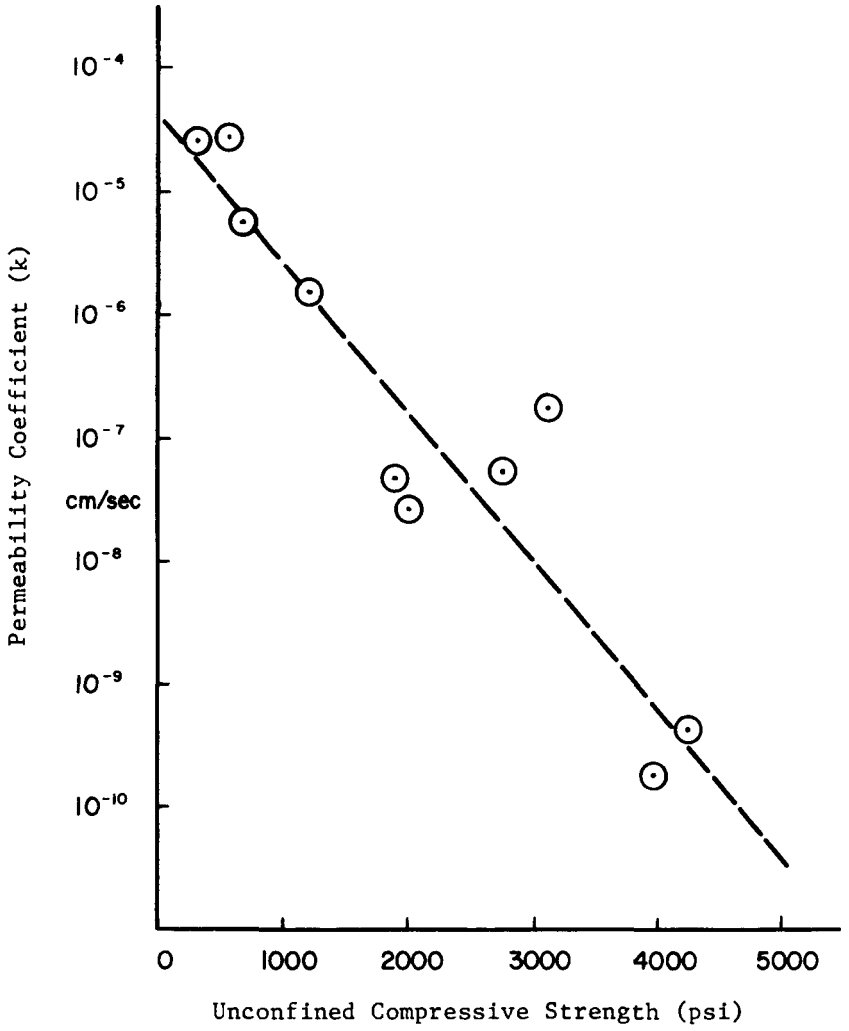


Figure 3-7. Correlation of Permeability with the Unconfined Compressive Strength of Flyash/Sludge Mixtures.

- Land use
- Aesthetic effects/public relations

Health Effects

The primary concern with health effects is centered on the possibility that ground or surface waters will be deleteriously affected by major or trace elements in leachate from the disposal area. Fears have been expressed concerning the toxic effects of certain components on humans, animals, aquatic life and plant life. Maximum contaminant levels have been established by the EPA for primary (health) and secondary (welfare) standards for drinking water. Pollutant limits have been established for continuous and short-term (as long as 20 yrs) irrigation use. Pollutant concentrations in scrubber liquor and disposal area leachate have been compared with these various EPA standards. This is not an entirely valid comparison because the various effects of attenuation, dispersion and dilution will all act to reduce the levels found in scrubber liquor and leachate. Comparison of limiting values with scrubber liquor and leachate represent something of a worst-case condition and should be evaluated in that light.

A tabulation of the various contaminant/pollutant levels has been made and compared to the range and mean of a number of analyses of scrubber liquor and coal ash leachates in Tables 3-15 and 3-16. Short-term irrigation limits have been added to the former. It will be noted that the mean values exceed the most stringent limits in Table 3-15 for boron, fluorine, mercury, molybdenum and selenium. In Table 3-16, they exceed the limits for cadmium, chromium, fluorine, manganese and selenium. The presence of these trace elements in the concentration reported indicates that potential effluents from scrubber sludge disposal areas may have to be monitored and, in some cases, controlled.

The source of the trace elements, as previously noted, are the flyash, makeup water and reagent. Of these, the flyash contributes the most. Also, as shown in Table 3-9, flyash from various locations, and representing various coal seams, shows extremely large variations in some parameters. Therefore, the type and quantity of flyash in the disposal waste will largely determine the trace element composition of the disposal site leachate.

Although not listed in Table 3-15 and 3-16, the major constituents of scrubber sludge liquors and leachates could contribute to making a potable or irrigation source unsatisfactory. Total dissolved solids, sulfate, sulfite, chloride, calcium

Table 3-15

TRACE ELEMENT CONCENTRATION IN SCRUBBER LIQUOR[a]

Species	Range mg/l	Mean[d] mg/l	EPA Primary Drinking[b] mg/l	EPA Secondary Drinking[c] mg/l	NAS-NAE Irrigation Continuous mg/l
Antimony	.09 to 2.9	.2	--	-- --	-- --
Arsenic	.004 to .3	.009	.05	--	--
Barium	--[e]	--[e]	1	--	--
Beryllium	.0006 to .14	.013	--	--	.1
Boron	.9 to 46	--[e]	--	--	.75
Cadmium	.002 to .044	.032	.01	--	.01
Chromium	.005 to .4	.08	.05	--	.1
Cobalt	.1 to .7	--[e]	--	--	.05
Copper	.002 to .6	.20	--	1	.2
Fluorine	.7 to 3.0	1.5	1.4 to 2.4	--	2
Iron	.02 to 8.1	--[e]	--	.3	5
Lead	.001 to .4	.016	.05	--	5
Manganese	.007 to 2.5	.74	--	.05	.2
Mercury	.0004 to .07	<.01	.002	--	--
Molybdenum	.07 to 6.3	--[e]	--	--	--
Nickel	.005 to 1.5	.09	--	--	.2
Selenium	.001 to 2.2	.14	.01	--	.02
Silver	.005 to .6	--[e]	.05	--	--
Tin	3.1 to 3.5	--[e]	--	--	--
Uranium	--	--[e]	--	--	--
Vanadium	.001 to .67	--[e]	--	--	--
Zinc	0.03 to 2.0	0.18	--	5	--

[a]Thirteen different sludge liquors were reviewed.

[b]EPA's National Interim Primary Drinking Water Standard (NIPDWS).

[c]EPA's National Secondary Drinking Water Regulations (NDWR).

[d]Underscored values are equal to or greater than most stringent reference standard.

[e]Sufficient data were not available for the meaningful calculation of a significant mean.

Source: Holland, W. F. and Jones, B. F., "Potential for Ground Water Contamination by Trace Elements in Ponded Ash and Scrubber Sludge," presented at the ASCE Spring Convention and Exhibit, April, 1978, Pittsburgh, PA, Preprint 3289.

Table 3-16

REPRESENTATIVE TRACE ELEMENT CONCENTRATIONS IN COAL ASH LEACHATE[a]

Species	Range mg/l	Mean[d] mg/l	EPA Primary Drinking[b] mg/l	EPA Secondary Drinking[c] mg/l	NAS-NAE Irrigation	
					Continuous mg/l	Short-Term mg/l
Aluminum	--	--	--	--	5.0	20.0
Antimony	.002 to .04	.02	--	--	--	--
Arsenic	.0001 to .42	.03	.05	--	2.0	10.0
Barium	.1 to .5	.31	1	--	--	--
Beryllium	.0004 to .01	.002	--	--	.1	0.5
Boron	.17 to 3.2	1.2	--	--	.75	2.0
Cadmium	.0001 to .005	.002	.01	--	.01	0.05
Chromium	.0006 to .07	.035	.05	--	.1	1.0
Cobalt	.0003 to .011	.005	--	--	.05	5.0
Copper	.004 to .08	.03	--	1	.2	5.0
Fluorine	.2 to 20	5	1.4 to 2.4	--	2	15.0
Iron	.01 to 4.6	.59	--	.3	5	20.0
Lead	.006 to 0.25	.02	.05	--	--	10.0
Lithium	--	--	--	--	2.5	--
Manganese	.001 to .90	.27	--	.05	.2	10.0
Mercury	.0004 to .08	.007	.002	--	--	--
Molybdenum	.002 to .056	.02	--	--	.01	0.05
Nickel	.001 to .12	.04	--	--	.2	2.0
Selenium	.001 to .12	.02	.01	--	.02	--
Silver	.0003 to .01	.004	.05	--	--	--
Tin	--	--	--	--	--	--
Uranium	.002 to 0.1	.006	--	--	--	--
Vanadium	.005 to .23	.14	--	--	--	--
Zinc	.01 to .4	.07	--	5	--	--

[a]Thirty different coal ash leachates and pond liquors were reviewed.

[b]EPA's National Interim Primary Drinking Water Standards (NIPDWS).

[c]EPA's National Secondary Drinking Water Regulations (NSDWR).

[d]Underscored values are equal to or exceed most stringent reference standard.

Source: Holland, W. F. and Jones, B. F., "Potential for Ground Water Contamination by Trace Elements in Ponded Ash and Scrubber Sludge," presented at the ASCE Spring Convention and Exhibit, April, 1978, Pittsburgh, PA, Preprint 3289.

and magnesium are all possible contributors and may require control. Total dissolved solids, in particular, can be expected to be higher than acceptable drinking water standards and may be a limiting factor in some cases. These constituents originate from the scrubbing process, the flyash and the reagent. Excess dissolved solids are objectionable in drinking water because of possible physiological effects and unpalatable mineral taste (11).

Structural Stability

Stability of sludge disposal areas can be of concern with both wet and dry disposal processes. With wet disposal areas, failure of a confining dike or embankment could result in damage to both life and property. It is essential that such structures be well and conservatively engineered, be constructed according to the planned procedure and under close supervision, and be maintained and monitored to prevent and/or detect any structural weakness.

Dry disposal areas--landfills-can be subject to slides unless preliminary construction/preparation procedures are well planned and implemented, placement and compacting are controlled, and drainage and diversion facilities are maintained. All of these precautions are also necessary in order to yield an area that is suitable for reclamation and re-use as a recreational area or building site as described in Section 8 - DISPOSAL AREA DESIGN.

Land Use

Designation of any piece of land as a sludge disposal area necessarily means that the property will not be available for other use for quite a period of time. In sparsely settled areas, this is of little consequence. However, in urban and near-urban areas, this can cause problems. Screening for visual effect, site management to minimize the active area and control noise and dust, and a step-wise reclamation program are advisable.

In urban areas, there are also possible hazards to humans and animals with both types of disposal. Ponds should be fenced and well-posted to warn of dangers involved with either standing water or quicksand-like sludge surfaces. Landfills are attractive to drivers of recreational vehicles and to persons looking for a disposal area. Controlled public access is required by the non-hazardous waste regulations to prevent exposure of the public to potential health and safety hazards.

Public Relations

From initial planning to final closure of a disposal area, good public relations are necessary. Once again, this is more a problem in urban areas than in sparsely populated areas, but it is a growing concern with both. This will be more thoroughly discussed in Section 6 - SITE SELECTION.

The aesthetic impact of any disposal area is objectionable. Sludge disposal can be even more distasteful to the public and neighbors than disposal of ash from power stations. Fugitive dust from landfill areas or from dried surfaces of ponds has been experienced and has required that corrective measures be taken. When the sludge is transported by truck, spillage on public highways has resulted in problems, both in causing slippery conditions when wet and dusty conditions when dry. The additional density of traffic resulting from trucks carrying the waste can also cause public relation problems. The subject of transportation is discussed in Section 13 - TRANSPORTATION.

The operating utility would be well-advised to include public relations in their planning for sludge disposal areas. Answers for all the foregoing concerns will be needed at some time during relations with regulatory agencies and the public. This need will be especially evident during the site selection process (Section 6 - SITE SELECTION) and any hearings involved with permitting.

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Section 4

SOLID WASTE QUANTITY

PURPOSE

The purpose of this section is to illustrate methods for calculating the quantity of scrubber waste expected to be produced from a given FGD installation. Three general methods are provided here--a numerical method, a tabular method, and a graphical method. The first method provides a reasonably precise estimate of scrubber waste quantities. The second two methods provide more general level estimates.

INTRODUCTION

Two factors--the quantity of dry solids and volume of wet solids--are important in consideration of disposal. The volume figure is especially important in determining the land area required for disposal. In addition, both weight and volume figures are important for sizing and designing stockpiles, surge equipment, temporary storage facilities, transport systems, and other elements of the disposal system. The methods of estimation are based on the use of lime, limestone and alkaline flyash as the scrubber reagents. The double-alkali waste quantity for a given sulfur will be essentially the same as that for the lime method, after regeneration of the sodium salt; only minor quantities of sodium sulfate/sulfite, not removed by washing, will be added to the waste.

FACTORS AFFECTING WASTE QUANTITY

It is difficult to make generalities regarding the quantity of waste produced from FGD systems because the production rate is a function of a large number of variables. Factors affecting the amount of scrubber waste produced include:

- Fuel consumption
- Ash content of fuel
- Sulfur content of fuel
- Overall particulate removal efficiency
- Upstream particulate removal efficiency
- SO_2 removal efficiency
- Efficiency and extent of dewatering

- SO_4/SO_3 ratio
- Specific gravity of waste solids
- Type of reagent
- Excess reagent
- Reagent grit

For the numerical method outlined below, it is necessary to know or estimate values for all the factors listed above. For the tabular and graphical methods, a more limited number of input variables is needed because some simplifying assumptions are used. With either of the methods, the accuracy of the input variables will be reflected in the estimated sludge quantities.

The proper input will vary, depending upon the intended use for the estimates. There are three operating conditions to consider for sizing elements of the disposal operation:

1. lifetime load
2. average load
3. peak load

Each of these conditions should be considered in the design of the system. Design of the disposal area, for example, should be based on the expected lifetime load (say 45 or 50% capacity factor) over the full life of the facility. However, storage or surge components should be designed for periods when the plant will be operating at 100% load.

NUMERICAL METHOD

The following example illustrates the numerical method for estimating waste quantities. This method is the most accurate of those provided and is recommended for detailed design purposes; it fully takes into account all the variables listed above and shows their relative significance. The method is applicable to all situations when the appropriate input is utilized.

The variables noted in the previous section can be estimated using the following methods or sources:

- Fuel consumption--calculate from the heating value of the fuel, heat rate of the unit(s), unit rating(s) and capacity factor.
- Ash content of fuel--obtain from fuel analysis.

- Sulfur content of fuel--obtain from fuel analysis. Note that this value should be that of the fuel actually burned, with credit being taken for sulfur removed by cleaning or by the pulverizers (See Appendix A). Also note that alkaline ash can retain significant but unpredictable quantities of sulfur in the boiler.
- Overall particulate removal efficiency--a function of particulate removal method, ash content, and other variables. Use best data available based on knowledge of similar systems in operation. Maximum expected is about 99.8% overall removal.
- Upstream particulate removal efficiency--variable depending on type of system. Use best data available from similar systems or from manufacturer's guarantee.
- SO_2 removal efficiency--this will be governed by emission regulations. Figure 4-1 illustrates the degree of SO_2 removal required to achieve the 1979 NSPS Standards. See Appendix A for additional details. Knowing the heating value and sulfur content of the fuel to be burned, the removal efficiency can be read from Figure 4-1. For example, a 10,000 Btu/lb fuel with 1.0% sulfur would require 70% removal to comply with the standards. The same fuel with a sulfur content of 2.0 would require 85% removal. Figure 4-2 shows the Btu and sulfur content of fuels which will require more than 90% removal of SO_2 in order not to exceed the overall ceiling of 1.2 lb SO_2 per million Btu. For example, a coal of 8,000 Btu content and a sulfur of over 4.8% would require more than 90% SO_2 removal.
- Reagent type and purity--obtain from scrubber supplier and reagent vendor.
- Efficiency and extent of dewatering--for estimating waste quantities, assume values reported for operating systems.
- SO_4/SO_3 ratio--this is difficult to accurately predict. Considerable variation is expected. Without better information, assume a ratio of 20/80 for lime and limestone scrubbers, 60/40 for alkaline flyash and 90/10 with forced oxidation. The sulfite will usually be higher in the newer lime and limestone scrubbers where tight ducts and equipment discourage air inleakage. Sulfate will be higher in alkaline flyash scrubbers where the pH of 4.5 to 5.5 favors solubility of and consequent oxidation of the sulfite to sulfate. With forced oxidation the sulfate may approach 100%.
- Specific gravity of waste solids--not an important variable. Assume a specific gravity value of 2.4 unless better information is available.
- Excess reagent--this quantity is variable depending upon the type of system and system operation. Current typical values are 10% excess reagent for lime and 10 to 30% for limestone systems.
- Reagent grit--if possible, obtain an analysis of the reagent to be utilized in the scrubber. Lacking this, assume 5% for either lime or limestone.

Table 4-1 lists the assumptions made for four typical plants, all equipped with two 500 MW units and all expected to experience an average 45% capacity factor over a

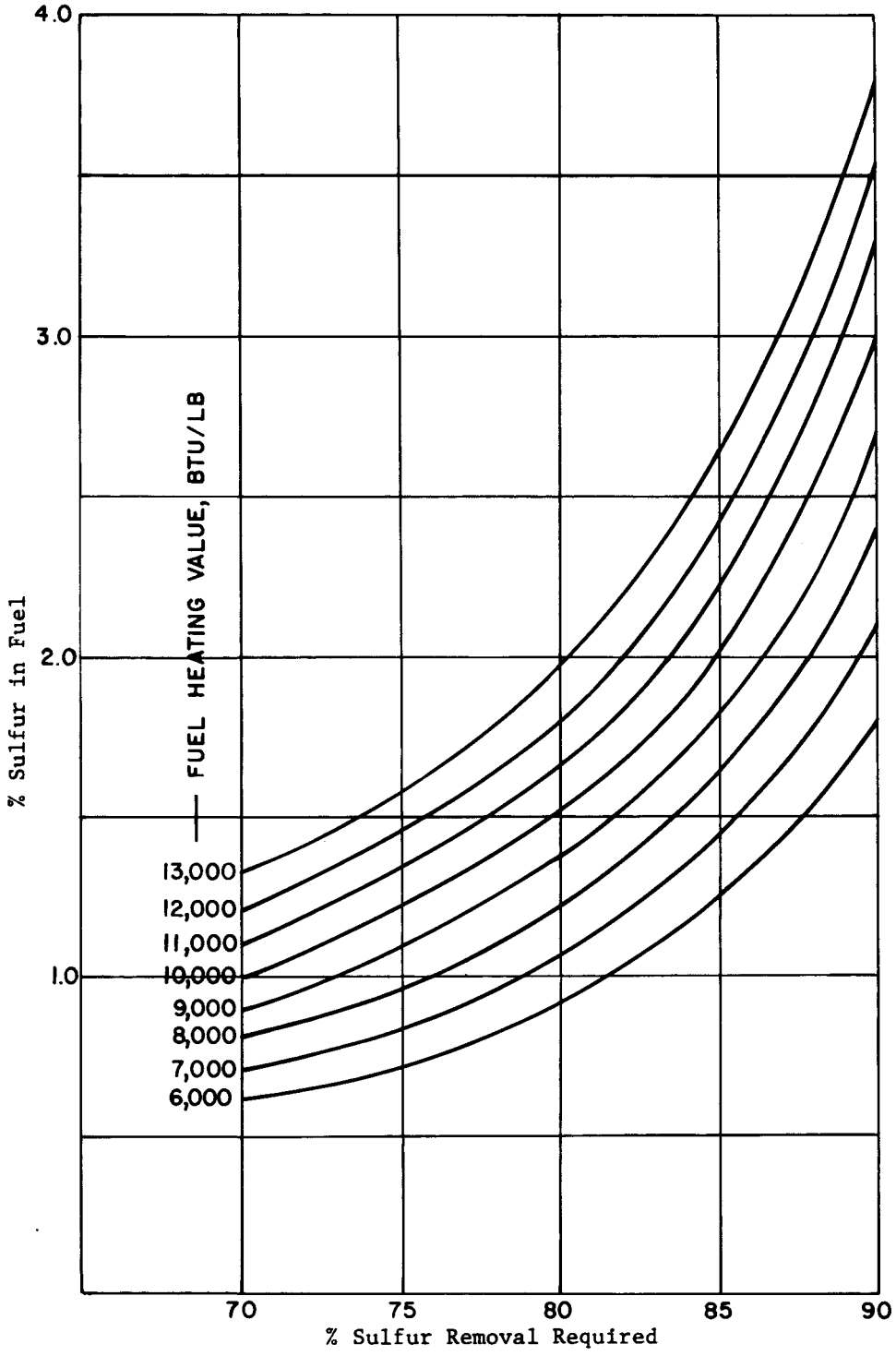


Figure 4-1. SO_2 Removal Required to Meet 1979 NSPS Standards.

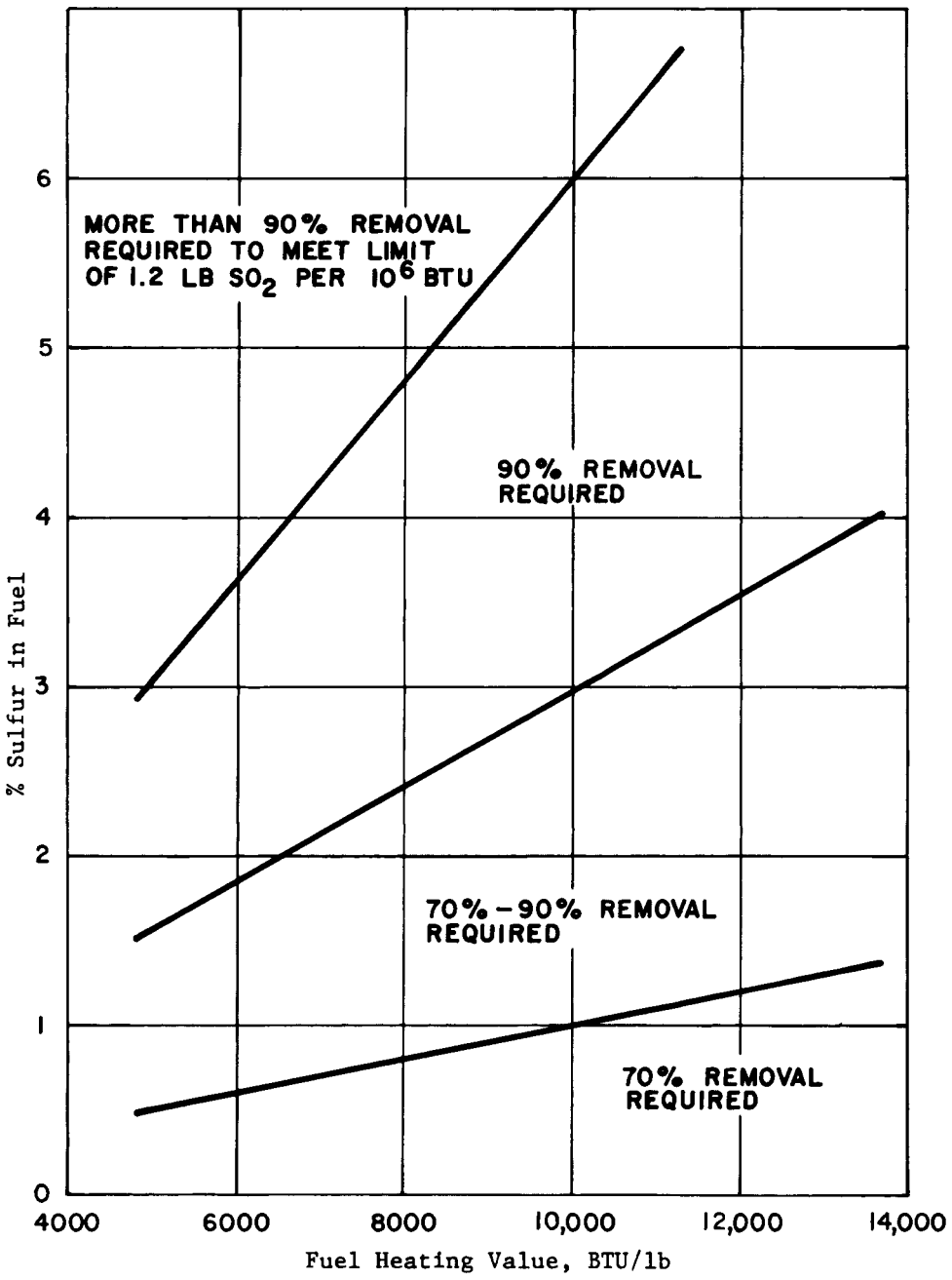


Figure 4-2. SO_2 Removal Required to Meet 1979 NSPS Standards.

Table 4-1

ESTIMATION OF SCRUBBER WASTE QUANTITIES

ASSUMPTIONS				
Plant				
Unit	2 @ 500 Mw			
Capacity Factor, %	45 (over 30-yr life)			
Example:	1	2	3	4[a]
Heat rate, Btu/kWh	10,000	10,000	10,000	9,000
Fuel				
Btu/lb	12,500	12,500	12,500	8,000
Ash content, %	12	12	12	8.5
Flyash/bottom ash	80/20	80/20	80/20	80/20
Sulfur content, %	3.5	3.5	3.5	0.6
Annual consumption @ 45% capacity factor, t	1,577,000	1,577,000	1,577,000	2,217,000
Air Quality Control System (AQCS)				
Upstream flyash removal efficiency, %	99	99	99	NA
Overall flyash removal efficiency, %	99.8	99.8	99.8	99.8
SO_2 removal, %	90	90	90	70
Scrubbing reagent	Lime	Limestone	Limestone	Flyash
Reagent purity, %	95	95	95	NA
Reagent Stoichiometry	110	130	130	NA
Excess and unreacted reagent as $CaCO_3$, t	43,400	102,500	102,500	NA
SO_4/SO_3	20/80	20/80	90/10[c]	60/40
Thickener underflow solids,%	35	35	35	35
Final solids in waste, %	45	45	70	70
Waste solids specific gravity	2.4	2.4	2.4	2.4

[a]The fuel may be either sub-bituminous coal or lignite.
[b]All the sulfur is assumed to be found in the scrubber influent, none retained by the ash. All sulfur assumed to go to SO_2, no SO_3.
[c]With forced oxidation.
[d]Examples 1, 2 sludge is settled. Examples 3, 4 sludge is vacuum filtered.

30 year life. Example 1 involves the use of 3.5% sulfur coal and lime as the scrubbing reagent. Examples 2 and 3 cover the use of the same coal with limestone as the scrubbing reagent without and with forced oxidation. The final example illustrates the use of lignite or sub-bituminous coal with the alkaline flyash used as the reagent. Significant savings in reagent costs can be achieved by utilizing the alkalinity of the compounds of calcium, potassium, magnesium and sodium in such ash (1,2,3). As described in those references, some or all of the required SO_2 removal can be obtained with the alkaline ash, depending on the source of coal and the required SO_2 removal. Where additional alkalinity is required, it can be provided by lime or limestone. In Example No. 4 it is assumed that there is no upstream flyash removal, and the flyash furnishes all the alkalinity that is required. With the currently required SO_2 removal, it should be recognized that additional alkali may be required with a corresponding, but minor, increase in sludge quantity.

Table 4-2 shows a detailed calculation for the plant in Example 1 - using a lime scrubber. The same set of equations was used for the three other example plants, with the results summarized in Table 4-3.

The summary in Table 4-3 shows the effect of certain variables in the examples:

- The dry waste solids from lime scrubbing are about 82% of those from limestone, primarily because of lower stoichiometry and lower equivalent weight of the excess reagent.
- The higher dry solids weight with forced oxidation results from the higher equivalent weight of the sulfate component in the oxidized waste.
- The much lower weight of combined flyash and dry sludge solids in Example 4 reflects the lower sulfur content of the fuel (about 1/6 that in the other examples) and the lower requirement for SO_2 removal. The lower ash content has little effect, since more fuel must be burned to obtain the necessary heat input.
- Waste volume at two different solids contents is of interest in showing the effect of ponding disposal for Examples 1 and 2 and landfill disposal for Examples 3 and 4. This is especially evident in the limestone scrubbing, where the landfill volume at 70% solids is about 60% that of ponding at 45% solids.

These same examples are used in Section 9, where various processing and disposal options are discussed in detail. More of a real-life appraisal of required waste disposal volumes is provided by including flyash in the various options.

Table 4-2

ESTIMATION OF WASTE QUANTITIES
Calculations - Example 1

Annual Fuel Consumption

Tons/year = (unit rating, kW x days/yr x hr/day x capacity factor x heat rate, Btu/kWh) ÷ (2000 lb/ton x heating value, Btu/lb)

= (1×10^6 kW x 365 x 24 x .45 x 10,000) ÷ (2000 x 12,500)

= 1,577,000 t/yr

Ash Production

1. Total ash produced

   Total ash = coal consumption x % ash

   = 1,577,000 t/yr x 0.12

   = 189,200 t/yr

2. Total flyash produced

   Total flyash = total ash x % flyash

   = 189,200 t/yr x 0.80

   = 151,400 t/yr

3. Flyash collected in precipitator

   Precipitator flyash = total flyash x precipitator efficiency

   = 151,400 t/yr x 0.99

   = 150,000 t/yr

Sludge Production

4. Flyash collected in the scrubber

   Scrubber flyash = total flyash x {(overall particulate removal efficiency) - (upstream particulate removal efficiency)}

   = 151,400 t/yr x (0.998 - 0.990)

   = 1,210 t/yr

Table 4-2 (Cont.)

ESTIMATION OF WASTE QUANTITIES - EXAMPLE 1

5. Weight of $CaSO_4 \cdot 2H_2O$

$$\text{Sulfate solids} = \text{coal consumption} \times \text{\% S in coal} \times \text{SO_2 removal efficiency} \times \text{fraction of S solids as } CaSO_4 \cdot 2H_2O \times \frac{\text{mole weight } CaSO_4 \cdot 2H_2O}{\text{mole weight S}}$$

$$= (1{,}577{,}000 \text{ t/yr}) (0.035) (0.9) (0.20) \left(\frac{172}{32}\right) = 53{,}450 \text{ t/yr}$$

6. Weight of $CaSO_3 \cdot \frac{1}{2}H_2O$

$$\text{coal consumption} \times \text{\% S in coal} \times \text{SO_2 removal efficiency} \times \text{fraction of S solids as } CaSO_3 \cdot \tfrac{1}{2}H_2O \times \frac{\text{mole weight } CaSO_3 \cdot \frac{1}{2}H_2O}{\text{mole weight S}}$$

$$= (1{,}577{,}000 \text{ t/yr}) (0.035) (0.9) (0.80) \left(\frac{129}{32}\right) = 160{,}200 \text{ t/yr}$$

7. Weight of dry waste solids

Dry waste solids = sum of items 4, 5, 6, and excess and unreacted reagent

$$= 1{,}210 + 53{,}450 + 160{,}200 + 43{,}400 = 258{,}300 \text{ t/yr}$$

8. Weight of water @ 45% solids content

$$\text{Weight of water} = \left(\frac{\text{\% of total as water}}{\text{\% of total as dry solids}}\right) \times \text{weight of waste solids}$$

$$= \frac{0.55}{0.45} \times 258{,}300 \text{ t/yr} = 315{,}700 \text{ t/yr}$$

Table 4-2 (Cont.)

ESTIMATION OF WASTE QUANTITIES - EXAMPLE 1

9. Total weight of wet sludge @ 45% solids content

Weight of wet sludge = weight of dry waste solids + weight of water

= 258,300 t/yr + 315,700 t/yr = 574,000 t/yr

10. Volume of solids

$$\text{Volume of solids} = \frac{\text{weight of dry solids x 2,000 lb/t x 0.037 yd}^3\text{/ft}^3}{\text{unit weight of water x specific gravity of solids}}$$

$$= \frac{258{,}300 \text{ t/yr x } 2{,}000 \text{ lb/t x } 0.037 \text{ yd}^3\text{/ft}^3}{62.4 \text{ lb/ft} \times 2.4}$$

$$= 127{,}400 \text{ yd}^3\text{/yr}$$

11. Volume of water

$$\text{Volume of water} = \frac{\text{weight of water x 2,000 lb/t x 0.037 yd}^3\text{/ft}^3}{\text{unit weight of water}}$$

$$= \frac{315{,}700 \text{ t/yr x } 2{,}000 \text{ lb/t x } 0.037 \text{ yd}^3\text{/ft}^3}{62.4 \text{ lb/ft}}$$

$$= 374{,}400 \text{ yd}^3\text{/yr}^3$$

12. Total volume of wet sludge @ 45% solids

Total sludge volume = volume of dry solids + volume of water

= 127,400 + 374,400 = 501,800 yd^3/yr

13. Volume required for disposal @ 45% solids

Volume = 501,800 yd^3/yr x 6.198×10^{-4} ac-ft/yd^3

= 311 ac-ft/yr

Table 4-3

ESTIMATION OF WASTE QUANTITIES
Summary of Examples 1-4

Average Annual Waste Quantity				
Equation	Example			
	1	2	3	4
1. Total Ash Produced, t	189,200	189,200	189,200	177,400
2. Total Flyash Produced, t	151,400	151,400	151,400	150,800
3. Flyash Collected in Precipitator, t	150,000	150,000	150,000	NA
4. Flyash Collected in Scrubber, t	1,210	1,210	1,210	150,500
5. $CaSO_4 \cdot 2H_2O$, t	53,450	53,450	240,500	30,060
6. $CaSO_3 \cdot \frac{1}{2}H_2O$, t	160,200	160,200	20,200	15,010
7. Weight of Excess and Unreacted Reagent as $CaCO_3$, t	43,400	102,500	102,500	NA
8. Weight of Dry Waste Solids, t	258,300	316,300	363,200	195,600**
9. Weight of Water at x% Solids Content, t*	315,700	386,500	155,600	83,830
10. Total Weight of Wet Sludge at x% Solids Content, t*	574,000	702,800	518,800	279,400
11. Volume of Solids, yd^3	127,400	156,000	179,200	96,500
12. Volume of Water, yd^3	374,400	458,400	184,500	99,410
13. Total Volume of Wet Sludge at x% Solids Content, yd^3*	501,800	614,400	363,700	195,900
14. Volume Required for Disposal at x% Solids, ac-ft*	311	381	225	121

*45% in Examples 1 and 2, 70% in Examples 3 and 4.
**Includes flyash.

TABULAR METHOD

Using this method the weight and volume of SO_x waste expected can be obtained fairly quickly. No excess reagent, grit or flyash quantities are included in Examples 1, 2 and 3. Flyash is included in Example 4. Values in the tables were obtained by use of the equations given in Table 4-2. The procedure for using the tables is as follows:

Weight of Dry Solids

Step 1: Determine or assume Btu and sulfur content of coal.

Step 2: Calculate fuel requirements (million t/yr) from the heat input of the fuel and unit heat rate and unit size using the equation given in Table 4-2.

Step 3: Determine or assume SO_4/SO_3 ratio. Lacking better information, assume a ratio of 20/80 for lime and limestone scrubbers, 60/40 for alkaline flyash and 90/10 for those using forced oxidation.

Step 4: For lime/limestone scrubbing, enter Table 4-4 under the row and column matching the assumed conditions and read out the weight of dry SO_x solids per million tons of fuel. For alkaline flyash scrubbing follow the same procedure but use Table 4-5.

Step 5: Calculate the annual weight of dry SO_x solids by multiplying fuel requirements (from Step 2), times the number obtained from Step 4.

As an example, assume one million tons of a 10,000 Btu fuel with 2.0% sulfur content will be burned with the emissions scrubbed in a lime scrubber. From Table 4-4, the annual waste production would be 73,000 tons having a 20/80 ratio of sulfate to sulfite. This same Btu coal with 5% sulfur would result in the production of 194,000 tons of the same ratio waste. Considering a similar situation with alkaline flyash, Table 4-5 shows that combustion of a 0.5% sulfur content and 8% ash fuel would result in the production of 81,000 tons of scrubber waste from one million tons of fuel. This includes all the flyash removed from the emissions.

Volume of Wet Solids

Step 6: Determine or assume solids content of wet waste.

Step 7: Using the values from Steps 5 and 6, enter Table 4-6 in the appropriate row and column to obtain the volume of waste/1000 tons of dry solids.

Step 8: Multiply the annual weight of dry solids in 1000 tons (from Step 5) by the number obtained from Table 4-6 (Step 7). The result is the total volume of waste produced in yd^3 or ac-ft.

Table 4-4

WEIGHT OF DRY SO_x SOLIDS RESULTING FROM SCRUBBING EMISSIONS FROM ONE MILLION TONS OF FUEL TO MEET 1979 NSPS STANDARDS

LIME/LIMESTONE SCRUBBING - EXAMPLES 1, 2, 3

Btu	S %	Required Removal %	Sulfur Removed 1000t	Weight SO_x Solids, 1000 t SO_4/SO_3	
				20/80	90/10
6,000	0.5	70	3.5	15	18
	1.0	82	8.2	35	42
	2.	90	18.0	77	93
	3.	90	27.0	116	140
	4.	90	36.4	156	189
	5.	93	46.5	200	242
8,000	0.5	70	3.5	15	18
	1.0	76	7.6	32	39
	2.	90	18.0	77	93
	3.	90	27.0	116	140
	4.	90	36.0	156	189
	5.	91	45.5	196	237
10,000	0.5	70	3.5	15	18
	1.0	70	7.0	30	36
	2.	85	17.0	73	88
	3.	90	27.0	116	140
	4.	90	36.0	156	189
	5.	90	45.0	194	234
12,000	0.5	70	3.5	15	18
	1.0	70	7.0	30	36
	2.	82	16.4	70	85
	3.	88	26.4	114	137
	4.	90	36.0	156	189
	5.	90	45.0	194	234
14,000	0.5	70	3.5	15	18
	1.	70	7.0	30	36
	2.	79	15.8	67	82
	3.	86	25.8	111	134
	4.	89	35.6	153	185
	5.	90	45.0	194	234

Table 4-5

WEIGHT OF DRY SO_x - FLYASH SOLIDS RESULTING FROM SCRUBBING EMISSIONS FROM ONE MILLION TONS OF LIGHNITE OR SUB-BITUMINOUS COAL FOR 70% SO_2 REMOVAL

ALKALINE FLYASH SCRUBBING - EXAMPLE 4

Fuel Characteristics		Dry SO_x - Flyash Solids Weight
% S	% Ash	1000t
0.3	6	58
	7	66
	8	74
	9	82
	10	90
0.5	6	65
	7	73
	8	81
	9	89
	10	97
0.7	6	72
	7	80
	8	88
	9	96
	10	104
0.9	6	78
	7	86
	8	94
	9	102
	10	110

NOTE: 70% removal is sufficient when burning fuel of no more than 1.0% S and no more than 10,000 Btu/lb.

Table 4-6

QUANTITY OF WET SCRUBBER SOLIDS CONTAINING
ONE THOUSAND TONS OF DRY
SOLIDS OF 2.4 SPECIFIC GRAVITY

% DRY SOLIDS IN WASTE	QUANTITY PER 1000 TONS OF DRY SOLIDS		
	VOLUME		WEIGHT
	yd^3	ac-ft	t
5	23,000	14.2	20,000
10	11,200	6.94	10,000
15	7,210	4.47	6,670
20	5,230	3.24	5,000
25	4,050	2.51	4,000
30	3,250	2.01	3,330
35	2,700	1.67	2,860
40	2,270	1.41	2,500
45	1,940	1.20	2,220
50	1,680	1.04	2,000
55	1,460	0.904	1,820
60	1,280	.793	1,670
65	1,130	.700	1,540
70	1,000	.620	1,430
75	888	.550	1,330
80	789	.489	1,250
85	702	.435	1,180
90	625	.387	1,110

Weight of Wet Solids

Step 9: Enter Table 4-6 with the assumed solids content of the wet waste and read out the weight of waste containing 1000 tons of dry solids.

Step 10: Multiply the dry solids figure in 1000 tons (Step 5) by the number obtained from Table 4-6 (Step 9). The resultant is the total weight of wet solids produced.

Following the example started earlier, the waste containing 194,000 tons of dry solids would weigh 194 x 2220 = 430,700 tons at 45% solids content.

GRAPHICAL METHOD

The graphical method utilizes the same plant conditions. The curves were developed by use of the equations given in Table 4-2. Following the principles outlined previously, the weight and volume of SO_x waste can be estimated using a few simplifying assumptions and calculations. No ash is included in the estimates for Examples 1, 2 and 3. The procedure for the graphical method is:

Weight of Dry Solids

Step 1: Determine or assume the sulfur content of the fuel, also the ash content for lignite or sub-bituminous coal.

Step 2: Calculate the fuel requirement (million tons/year) from the heat input, heat rate, and unit size using the equation given in Table 4-2.

Step 3: Determine or assume SO_4/SO_3 ratio. Lacking better information, assume a ratio of 20/80 for lime and limestone scrubbers, 60/40 for alkaline flyash and 90/10 with forced oxidation.

Step 4: With above data enter Figure 4-3 on the X-axis and read on the Y-axis the weight of dry solids expected per million tons of fuel burned. Use Figure 4-4 for alkaline flyash scrubbing.

Step 5: Calculate the annual weight of dry SO_x solids by multiplying fuel requirement in millions of tons per year (Step 2) by the number obtained from Step 4.

Using the same example as before, assume one million tons of fuel with 5.0% sulfur content will be utilized. From Figure 4-3, the annual production of dry solids would be about 190,000 tons having a 20/80 ratio of sulfate to sulfite per million tons of fuel. For alkaline flyash scrubbing, Figure 4-4 shows that a fuel with 0.5% sulfur and 8% ash would yield 81,000 tons of dry solids per million tons of fuel.

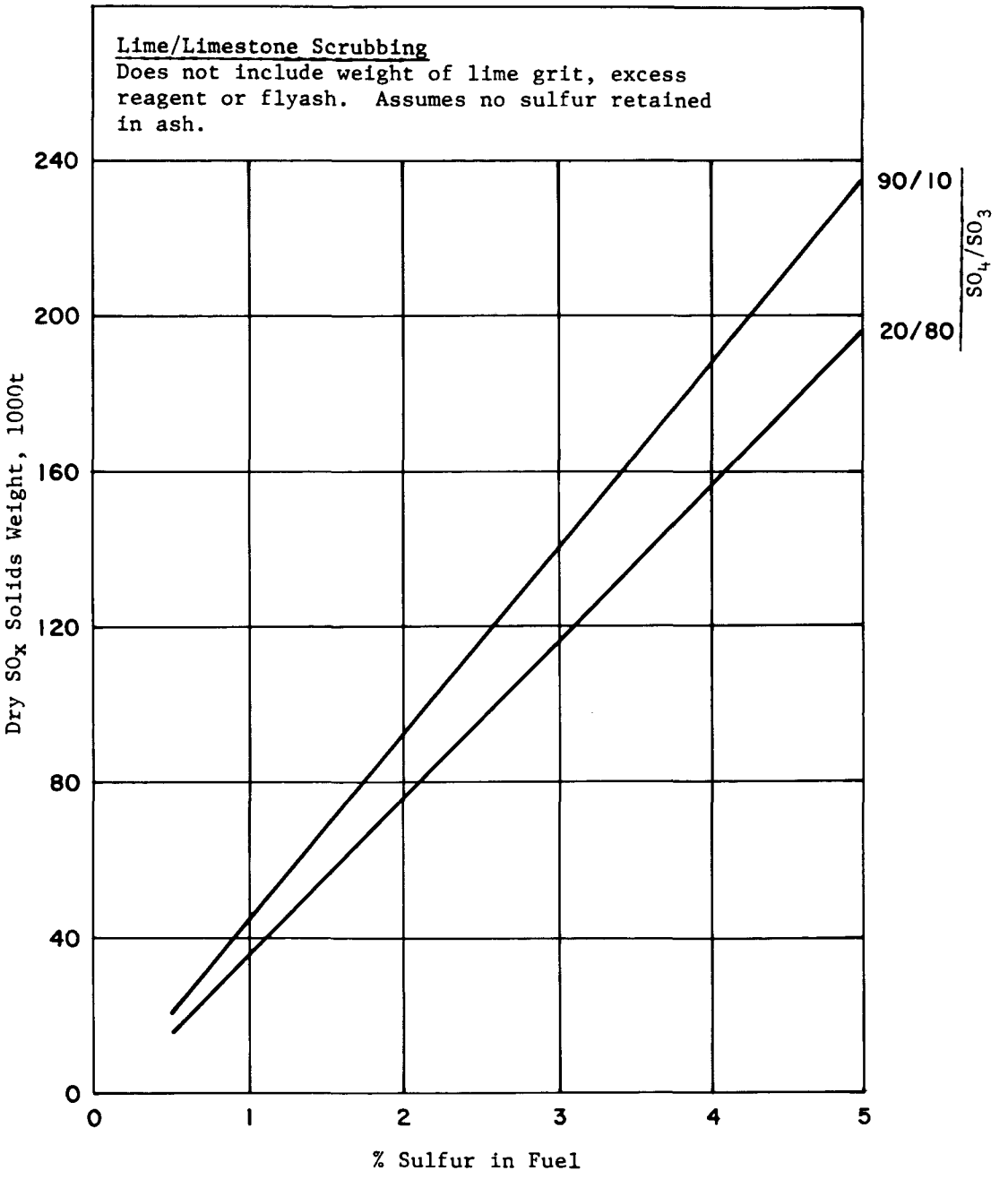


Figure 4-3. Estimated Dry SO_x Solids Weight per Million Tons of Fuel Burned with SO_2 Removal to Meet 1979 NSPS Standards

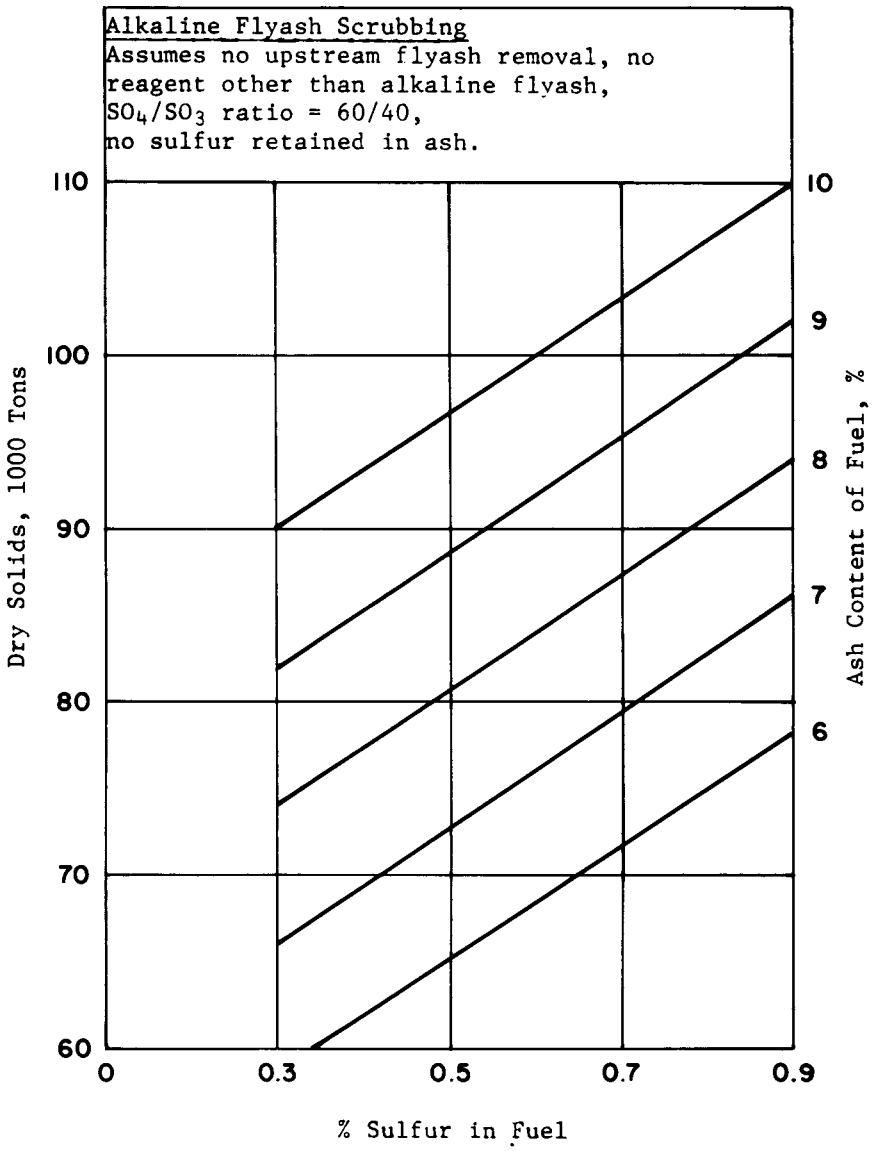


Figure 4-4. Estimated Dry Solids Weight per Million Tons of Fuel Burned with 70% SO_2 Removal to Meet 1979 NSPS Standards

Volume of Wet Solids

Step 6: Calculate annual weight of dry solids produced (Steps 1 through 5 above) per one million tons of fuel.

Step 7: Determine or assume solids content of waste.

Step 8: Enter Figure 4-5 and read out the volume of waste/1000 tons of dry solids.

Step 9: Multiply the annual weight of dry solids (from Step 6) by the number obtained from Step 8. The resultant is the total volume of waste produced in yd^3 or ac-ft.

For example, the 190,000 tons of dry solids derived from the one million tons of 5% sulfur coal in the example above, would require about 190 x 1950 = 370,500 yd^3 or 230 ac-ft for ponding as a 45% slurry.

If this same sludge settled to 60%, the volume would be reduced to 234,000 yd^3 or 145 ac-ft.

Weight of Wet Solids

Step 10: Enter Figure 4-6 with the assumed solids content of the wet waste and read out the weight of waste containing 1000 tons of dry solids.

Step 11: Multiply the dry solids figure (Step 6) by the number obtained in Step 10. The result is the total weight of wet solids produced per thousand tons of dry solids.

Following the same example used previously, the slurry containing 190,000 tons of solids at 45% solids content would weight 190 x 2200 = 418,000 tons.

As noted previously, the equations and assumptions presented in this section, are also used in Section 9 where the various processing alternatives are explored. In that section, flyash disposal is also considered and included in the calculations.

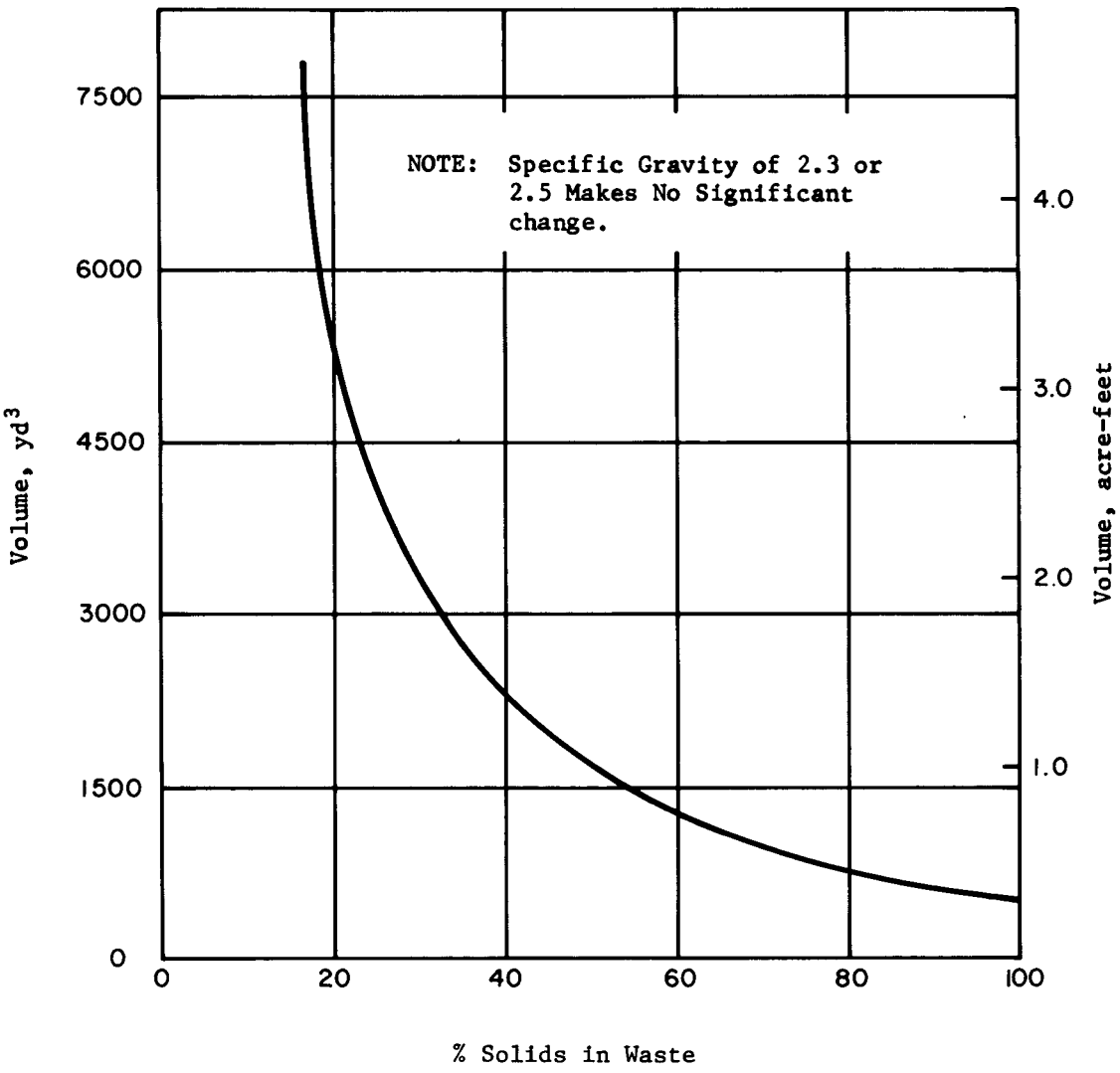


Figure 4-5. Volume of Waste Containing 1000 Tons of Dry SO_x Solids of 2.4 Specific Gravity.

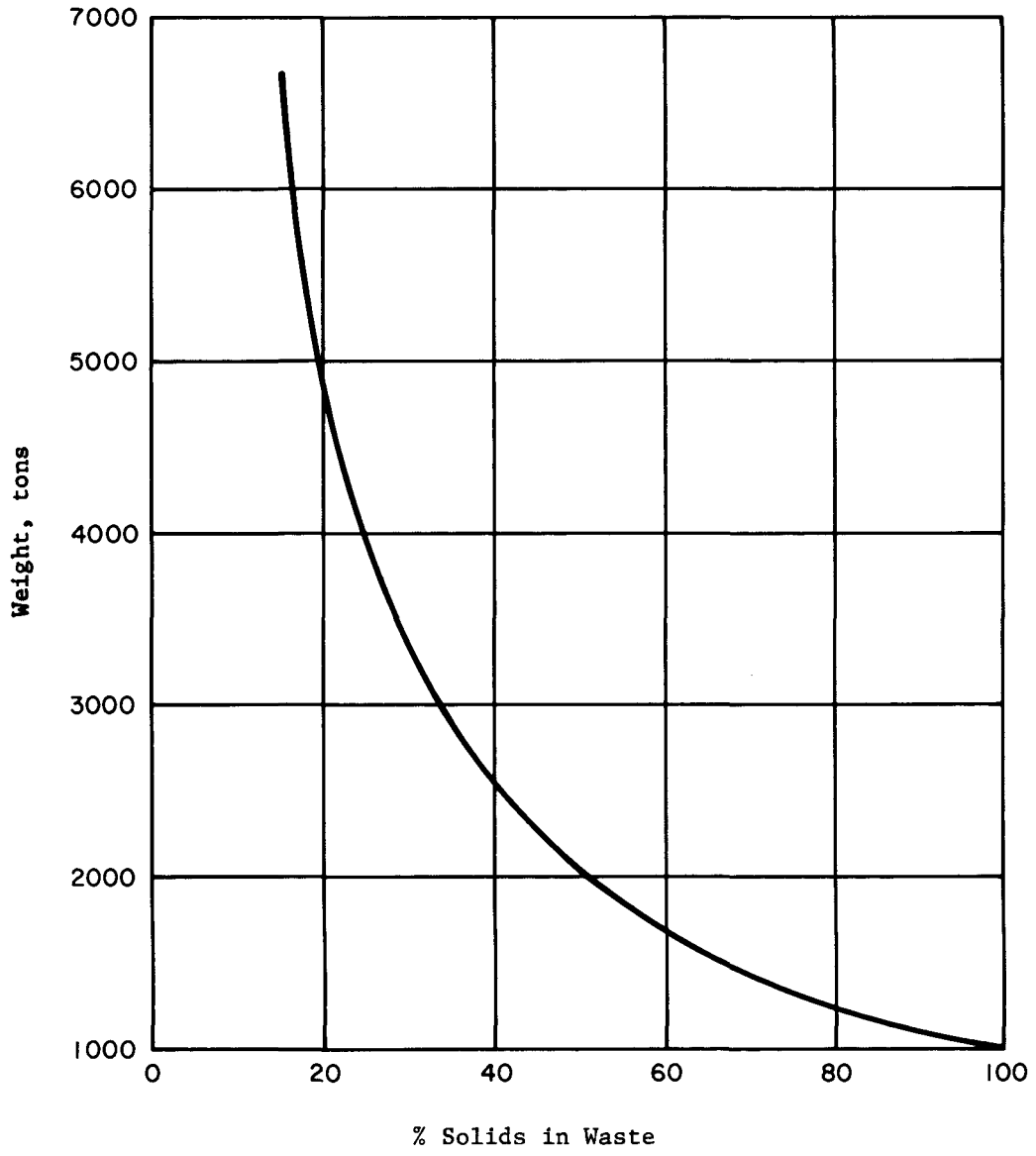


Figure 4-6. Total Weight of Waste Containing 1000 Tons of Dry SO_x Solids.

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Section 5

DISPOSAL ALTERNATIVES

PURPOSE

The purpose of this section is to provide introductory information on the relative advantages, disadvantages, and limitations of the two generic FGD waste disposal alternatives and to give examples of the use of the alternatives by operating companies.

INTRODUCTION

There are two basic types of FGD sludge disposal systems: wet (ponding) and dry (landfilling). In wet disposal systems, the FGD sludge is transported to and deposited in the disposal site in a fluid state. Dry disposal systems employ one or more processing steps to dewater the sludge, so that it may be handled and disposed of as a solid material. The decision to use either wet or dry disposal is of paramount importance and should be considered carefully because it will have an overriding influence on disposal system components.

The majority of existing FGD sludge disposal systems are wet systems. However, wet disposal is not necessarily advantageous over dry disposal in all cases. In fact, both methods have relative advantages and disadvantages, and which type of system is optimum will depend on the specific disposal situation. Section 9 - PROCESSING ALTERNATIVES gives examples of some calculations to aid in determining the optimum disposal method. Section 2 - CURRENT DISPOSAL PRACTICES provides a summary of disposal practices of utilities across the United States. Examples of various alternatives are described and flow diagrams and pertinent photographs are shown later in this section.

WET DISPOSAL

The common factor in all wet disposal systems is that the sludge is transported and deposited in the final disposal site in a fluid state. The degree of sludge processing may vary considerably. In some systems, the scrubber bleed stream is piped directly to the disposal pond, with supernatant returned to the scrubber system for

make-up water. In other systems, the bleed stream is treated prior to final ponding. Some systems use thickeners and/or interim settling ponds to reduce water content, thereby reducing the size of the final disposal pond, reducing water balance problems at the pond, and minimizing costs.

Another alternative is preliminary dewatering followed by the addition of a commercial fixation chemical (e.g. Calcilox) prior to placement in the disposal pond. In all cases, the final disposal site is a pond of one type or another. The sludge in all currently-operating systems is piped to the disposal pond, although transport by tank trucks or barges is a possible but unlikely alternative for wet disposal systems.

Applicability

Wet disposal systems are applicable to all lime, limestone and alkaline flyash wet scrubbing systems. Since the scrubbing system produces the sludge as a solid/liquid slurry, the waste is already in a form amenable to wet disposal. Double-alkali sludges, on the other hand, are not generally amenable to wet disposal because they are dewatered to recover the soluble scrubbing reagent. It would be possible to remix the filter cake with water to produce a pumpable slurry, but it is more logical and economical to use dry disposal.

Wet disposal is a versatile alternative having wide applicability. It is applicable to plants with wet or dry ash handling systems, oil-fired boilers, alkaline-ash scrubbing, and plants with or without upstream particulate control. In contrast, dry disposal systems may require significant quantities of dry flyash.

While wet disposal systems are often advantageous, they are not universally applicable. Climatic conditions, regulatory requirements, and/or site-related constraints may make wet disposal undesirable or uneconomic. In areas of high precipitation, excess water in the pond may make wet disposal infeasible, particularly if supernatant discharge is not permissible. Alternately in arid regions, excessive evaporative losses from a large pond may be unacceptable where water is to be conserved in the system. Regulatory constraints, such as the requirement for a pond liner, may make dry disposal preferable in some cases. The most common constraint is the absence of suitable land area of sufficient size in close proximity to the plant for pond or impoundment construction. Locations suitable for impoundments are generally less common than those suitable for landfills.

Advantages/Disadvantages

Wet disposal systems offer several advantages over dry systems. The principal advantages are inherent simplicity and low operating cost. From an operational standpoint, there is nothing easier than pumping the scrubber bleed or thickener underflow to a final disposal pond. The system provides the flexibility of accepting wide variations in bleed quantity and solids concentration, and can be operated easily under a wide range of operating conditions with minimum manpower requirements. Further, most utilities are experienced in this type of disposal.

Simple ponding of untreated sludge is nearly always the least expensive disposal method for disposal sites located on-site or within a few miles of the power plant. While capital costs for wet systems are somewhat higher than for dry disposal, operating costs are considerably lower. Increased capital costs in wet systems result from the complexity of design and construction of the disposal area, pumping system, and pipeline. Future costs associated with abandonment and reclamation of the disposal site have not been documented, but are likely to be higher for wet systems than for dry.

Another important advantage of wet systems is greatly reduced problems of noise, fugitive dust, and traffic to and from the disposal area. In fact, once construction of the disposal system is complete, these problems are virtually eliminated. Wet disposal systems, therefore, have low public visibility, a factor which can substantially reduce public relation problems.

Disadvantages of wet disposal systems as compared to dry systems include the larger disposal volumes required, the necessity of constructing dams and dikes and the possibility of increased leachate volumes. The relative inflexibility of wet systems with regard to system modifications and the potential reclamation or exclusion problems upon abandonment are also disadvantages.

With wet disposal systems, the sludge is deposited in the disposal area by sedimentation. Even after prolonged settling, solids content of the sludge is likely to be only 35 to 50% solids. In comparison, sludge handled by dry disposal methods may be as much as 70 to 80% by weight. Wet disposal systems may, therefore, require up to about twice the disposal volumes required by comparable dry systems.

In wet systems, dams or dikes must be constructed to contain the sludge or the pond may be constructed partially or completely below grade by excavation. Even if the above-grade structures are constructed of waste ash, the cost associated with the

care necessary to insure successful construction, operation, and maintenance are greater than for normal landfills. Design of dikes and dams is considerably more difficult and costly than landfill design. Details, such as watershed hydrology, system water balance, emergency spillways, and the need for monitoring to determine stability, must be considered to insure safe and satisfactory operation.

The presence of a pool of standing water above the sludge deposited in a wet disposal system will increase the volume of leachate generated. This effect results from the increased head of standing water in the pond, and will persist after abandonment if the system is maintained as a pond. The degree of increase in leachate generation will vary, depending upon site-specific conditions. In most cases, an impervious liner may be necessary to contain leachate within the pond. If the liner cannot be made from on-site materials, the cost for development of the site may become prohibitive.

Wet disposal systems are relatively inflexible to future changes in method of operation. Initial construction of pipelines, pumping facilities and impounding structures often involves a considerable capital investment directed to a specific disposal site and method of operation. Therefore, if some future change, such as extension of the useful life of the plant or addition of presently unplanned units exhausts the disposal site capacity before the power plant is retired, an entire new disposal system must be developed. Alternately, if some future change in plant operation or government regulations prevents complete utilization of the disposal site, capital costs already expended will be wasted. To minimize the impact of these occurrences, it is often advisable to provide staged ponding (develop several smaller ponds), rather than one large pond initially.

Costs and problems associated with the ultimate abandonment and reclamation of wet disposal sites are site-specific, and even generalities are impossible. It is not known if ponded sludge will be self-cementing like phosphogypsum waste, or will remain perpetually unstable. The evidence to date indicates that at least some untreated sludges, especially those containing high sulfite/sulfate ratios, will remain structurally unstable. Eventual reclamation of these areas is, therefore, likely to be difficult and costly, if not impossible. This is a significant environmental consideration.

Wet disposal with fixation can minimize or eliminate at least some of these environmental concerns. If properly applied and operated, a wet disposal system with

fixation can reduce leachate generation (by reducing permeability and, to a certain extent, tying up leachable salts) and improve structural stability so that future reclamation problems are reduced. Thus, for wet disposal systems in which high sulfite/sulfate ratios are expected, one should consider chemical fixation. It should be recognized, however, that in wet systems with fixation, both capital and operating costs are increased. More extensive processing facilities increase capital costs, and the continual addition of fixation chemicals increases operating costs. Whether or not wet disposal systems with fixation have a cost advantage over dry disposal will depend upon the specific situation.

DRY DISPOSAL

In dry disposal systems, the sludge is processed so that it may be deposited in the final disposal site as a solid material, or as a material which will solidify rapidly enough that dams or dikes are not required. In most dry disposal systems, the sludge is processed sufficiently so that it can be handled as a solid material immediately after processing.

The degree of processing necessary for dry disposal varies considerably, but usually involves thickening and dewatering processes. In scrubbing systems with large amounts of ash (such as alkaline-ash scrubbers and scrubbers without upstream particulate removal), extended settling in a pond may dewater the sludge sufficiently to allow excavation and landfilling. Other systems (such as those using high-sulfur and low-ash coals) may require several dewatering steps followed by the addition of stabilizing or fixation agents prior to disposal. Most dry systems include both dewatering and blending processes to produce a material suitable for landfill disposal.

Applicability

Blending of dry material with the sludge aids considerably in reducing its fluid nature. The most commonly used dry material is flyash because it is readily available at the station. As a result, dry disposal may be difficult or uneconomical for systems with little or no dry flyash: utilities with cyclone-fired boilers, wet ash handling or disposal systems, oil-fired boilers, no upstream particulate removal or those with marketable flyash. Dry disposal systems are usually most applicable in arid regions, or on systems with high ash/sludge ratios or high sulfate content, and/or where land is at a premium.

Advantages/Disadvantages

The principal advantage of dry disposal is more efficient use of the disposal site, thereby requiring less overall land area. The waste materials are generally more dense, do not require land area for dams and dikes, and can be placed in configurations not possible with wet disposal systems. When compared to sites for wet systems, those for dry disposal are easier to develop and reclaim.

Siting of dry disposal sites is easier, since many sites suitable for landfills are unsuitable for impoundments. The reverse situation is seldom true. Ultimate site abandonment is similar to that for flyash disposal sites or other landfills. Ultimate reclamation methods for wet disposal sites are unknown, but likely to be more difficult.

Some aspects of management of a landfill site are less difficult than those of ponds. Maintenance of dams and dikes, and water balance problems are eliminated. Rain falling on well-constructed dry disposal sites is diverted or runs off instead of being impounded; however, diversion, drainage and sedimentation facilities are required. (If discharged, a permit may be required.) The absence of a pool of standing water above the wastes, substantially reduces the quantity of leachate produced.

Since processing facilities for dry disposal systems are located near or on the power station site, these systems are flexible with regard to disposal site limitation. For example, if a disposal site is filled or must be prematurely abandoned, the wastes can be diverted to an alternate site, usually without replacement or change of the waste processing facility. In addition, the most common method of transportation with dry disposal is by truck, a method more easily adapted to site changes than pipelines. This also provides the flexibility of developing several smaller sites at different locations over a period of time, without major capital improvement.

The costs of dry disposal systems are distributed differently than those for wet disposal systems. Dry systems are less capital-intensive than wet systems. While sludge processing facilities may be more expensive, these costs are offset by the lower cost of disposal site development and transportation systems. Operating costs, particularly transportation, are usually higher than for wet systems. Which system is more advantageous will depend on factors such as transportation distance and the importance of capital versus operating expenses.

In any case, dry disposal systems are nearly always more expensive than wet systems without fixation. However, when compared to wet systems with fixation, cost differences will vary from one situation to another.

Another disadvantage is the continuing public visibility of dry systems. For utilities in relatively urban locations, the necessity of transporting large volumes of waste materials to a disposal site may be a significant problem. If transport is by truck over public roads, the potential adverse public reaction caused by increased traffic density, noise and spillage, deserves consideration. These problems, as well as noise and fugitive dust at the disposal site, are factors to be considered in selecting a dry disposal system for a candidate disposal site.

OPERATIONAL SYSTEMS

To aid in an understanding of the alternatives available in the processing and disposal of sludge, Table 5-1 classifies some possible processing options under the general headings of wet and dry disposal. The processing steps are shown for each option, and one or more example plant is listed. Following this, a narrative description, flow diagram and illustrative photographs are given for each of the example plants.

Wet Disposal Options

Three options are listed for wet disposal:

1. Simple ponding. The Green River Plant of Kentucky Utilities Company is shown as an example of direct ponding of a bleed stream of scrubber sludge after upstream removal of flyash.

   The LaCygne Plant of Kansas City Power & Light Company is an example of direct ponding of a bleed stream containing both flyash and sludge.

2. Ponding after a preliminary water removal step by a thickener or interim pond. The Sherburne County Plant of Northern States Power Company is an example of the use of a thickener to partially dewater a mixture of flyash and oxidized sludge before pumping to a final disposal pond.

   The Colstrip Plant of Montana Power Company also utilizes this option on a mixture of flyash and sludge, but preliminary dewatering is by interim ponding and the sludge is not force-oxidized.

3. Ponding after fixation. The Bruce Mansfield Plant is shown as an example, in which a flyash-sludge mixture is dewatered in a thickener, with the underflow being mixed with Calcilox^{R} before being pumped to a pond. Note that another example of this option shown in Table 2-1, the Pleasants Station of Monongahela Power Company, fixes only scrubber sludge. Flyash is removed upstream of the scrubber.

Table 5-1

EXAMPLES OF PROCESSING/DISPOSAL OPTIONS

	DISPOSAL METHOD											
	WET				DRY							
Processing Steps	Oxidation	Interim Pond	Thickener	Fixation	Oxidation	Thickener	Interim Pond	Filter or Centrifuge	Add Flyash	Add Flyash and Lime	Stacking	
Option**												Example Plants
1	*	-	-	-								Green River, LaCygne
2	*	●	-	-								Colstrip
	*	-	●	-								Sherburne
3	-	-	●	●								Mansfield
1					*	-	●	-	-	-	-	----
2					*	●	●	-	-	-	-	Cherokee
3					*	●	-	●	-	-	-	M. R. Young
4					*	●	-	●	●	-	-	Southwest
5					-	●	-	●	-	●	-	Conesville
6					●	-	-	●	-	-	-	Chiyoda 101
7					●	-	-	-	-	-	●	Chiyoda 121
					-	-	-	-	-	-	●	USS Agrichemical

*Optional step, used at Sherburne Plant.
**Described on pages 5-7 and 5-9.

As shown in Table 5-1, forced oxidation is a step that can be applied to both Options 1 and 2. There is no advantage to be gained by using it in Option 3, since the Calcilox process is said to be equally effective on sulfite and sulfate sludges.

Dry Disposal/Utilization Options

Seven options are listed for dry disposal:

1. Interim ponding of the bleed stream for dewatering. After dewatering, the sludge, with or without co-disposed flyash, is excavated for removal to a landfill. No example is shown because the option is not easily used, due to difficulty in dewatering to the extent necessary by ponding alone. However, forced-oxidized sludge should dewater sufficiently.

2. The use of thickeners followed by interim ponding before excavation. The Cherokee Plant of Public Service of Colorado is shown as an example of this option. In this case, sludge, removed in the final step of particulate removal, and bottom ash are co-disposed in the interim pond. Dewatering is facilitated by the bottom ash Once again, this option cannot be generally used except with oxidized sludge or with co-disposed ash to aid in dewatering.

3. A two-step dewatering process consisting of the use of a thickener followed by a vacuum filter or centrifuge. This option is most applicable for high-sulfate sludges with or without flyash. The example shown is the Milton R. Young Plant of the Minnkota Power Cooperative. Alkaline ash is used as the primary SO_2 sorbent, and such sludges are generally predominantly sulfate.

4. A two-stage dewatering process followed by the addition of dry flyash, either alkaline or non-alkaline. The Southwest Plant of Springfield (MO) Utilities is used as an example in which non-alkaline flyash is added to a sludge filter cake. Another example (not further described) is the Martin Lake Plant of Texas Utilities Company, where the second stage of dewatering is by centrifuge and alkaline flyash is added.

5. A two-stage dewatering process followed by the addition of flyash and lime. This is the proprietary IU Conversion Systems Poz-O-Tec^R process, and the example shown is that of the Conesville Plant of Columbus & Southern Ohio Electric Company.

6. Oxidation of scrubber sludge followed by a single or two-stage dewatering step. The example shown is that of the prototype Chiyoda 101 scrubber process at Scholz Plant of the Florida Power Company. The dewatered sludge (gypsum) was used in an agricultural application and for trial production of wallboard. This option is not limited to a particular type of scrubber.

7. Oxidation of scrubber sludge followed by "stacking." This particular type of a combination dewatering-disposal step is described and shown in a later narrative and in Section 16 - GYPSUM STACKING. An oxidized bleed stream is dewatered by settling in a final disposal/storage area with the supernatant being returned to the scrubber. The examples shown are those of the prototype Chiyoda 121 scrubber at the Scholz Plant and the process as used at a U.S. Steel Agrichemical Plant. As with Option 6, this option is not limited to a particular type of scrubber.

Table 5-1 shows that forced oxidation is optional in the first four systems, necessary for Options 6 and 7 and of no use in Option 5--the fixation process, which is reportedly effective with sulfite or sulfite/sulfate sludges.

SLUDGE PROCESSING/DISPOSAL	WET DISPOSAL OPTION 1
Power Plant/Location	Green River/Central City, KY
Company	Kentucky Utilities
No. Boilers/MW on Scrubber	3/65
New or Retrofit	Retrofit
Flyash Removal	Cyclone Collectors, AAF Venturi Scrubber
SO_2 Removal	AAF Mobile Bed Scrubber
Scrubber Reagent	Lime

The Green River Plant burns western Kentucky coal of about 10.5% ash and 3 to 4% sulfur in the boilers which exhaust to the scrubbing system. About 80% of the particulates are removed by mechanical collectors, from which the gas goes to a two-stage scrubber. The first or flyash stage is a variable-throat, flooded-approach venturi; the second stage is a mobile bed contactor for SO_2 removal. The entire recycle flow goes to a three-compartment reactant tank, where lime slurry is added as required.

A bleed stream at 10 to 12% solids is sent from the reactant tank to an on-site permanent disposal pond which is lined with naturally-occurring clay. The supernatant is returned to the scrubber system. Figure 5-1 illustrates the sludge handling scheme at Green River. The sludge disposal pond is shown in Figure 5-2.

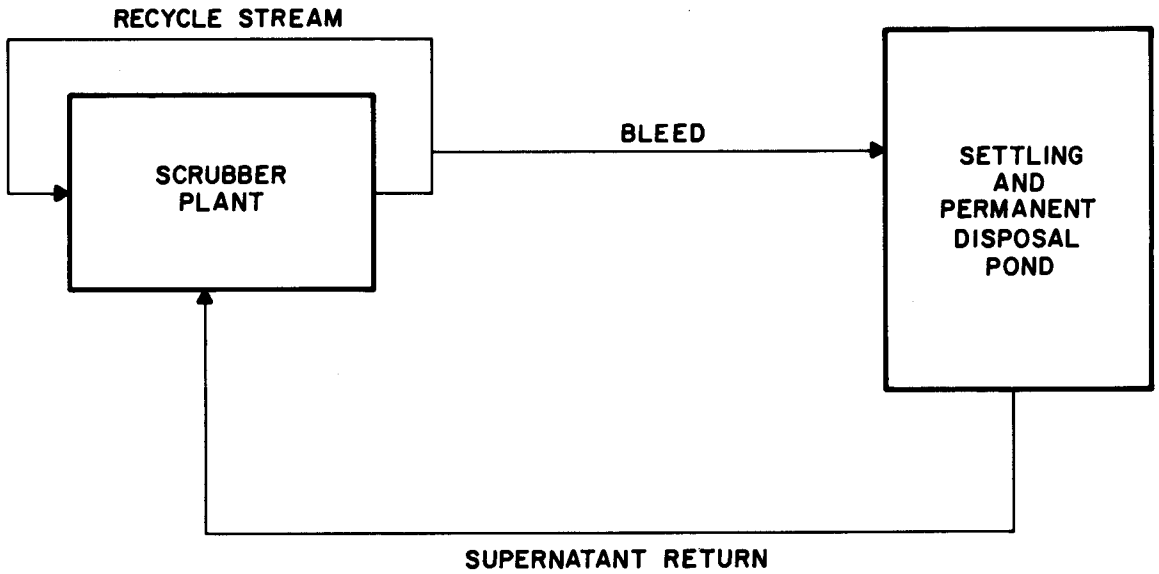


Figure 5-1. Flow Diagram for Wet Disposal Option 1



Figure 5-2. Sludge Disposal Pond
Green River Plant, Kentucky Utilities Company

SLUDGE PROCESSING/DISPOSAL	WET DISPOSAL OPTION 1
Power Plant/Location	LaCygne/LaCygne, KA
Company	Kansas City Power & Light
No. Boilers/MW on Scrubber	1/875
New or Retrofit	New
Flyash Removal	B&W Venturi Scrubber
SO_2 Removal	B&W 2-stage Perforated Tray Absorber
Scrubber Reagent	Limestone

The LaCygne Plant burns local coal, 25 to 30% ash and 6% sulfur, in cyclone burners in the No. 1 Boiler, which is equipped with scrubbers. Particulates are removed by a venturi scrubber section and SO_2 by a 2-stage perforated tray absorber section. Both sections drain to a common sump which, in turn, drains to a recirculation tank. The two scrubber sections, together with the recirculation tank, comprise a module. There is a total of eight modules. Local limestone is used as the reagent and is introduced into the recirculation tank to maintain a pH of 5.5 in the recycle stream.

A bleed stream of 20% solids is taken from the venturi recycle pump discharge to the permanent settling/disposal pond. No thickener is used. After settling, the supernatant is returned to the scrubber plant. The sludge settles to the extent that it can bear a man's weight after several months, and a road carrying truck traffic has been constructed across a section which is several years old. Some sludge has been mixed with cyclone boiler bottom ash for use in building dikes. The sludge handling system is shown in Figure 5-1, and a photograph of the disposal pond is shown in Figure 5-3. The sludge pond shown was built for a four-year life.



Figure 5-3. Sludge Disposal Pond
LaCygne Plant, Kansas City Power and Light Company

SLUDGE PROCESSING/DISPOSAL	WET DISPOSAL OPTION 2 WITH OXIDATION
Power Plant/Location	Sherburne/Becker, MN
Company	Northern States Power
No. Boilers/MW on Scrubbers	2/1480
New or Retrofit	New
Flyash Removal	CE Venturi Scrubber
SO_2 Removal	CE Marble Bed Scrubber
Scrubber Reagent	Alkaline Flyash + Limestone

The Sherburne Plant burns western sub-bituminous coal of about 9% ash and 0.8% sulfur. Particulate removal is by first-stage rod-venturi scrubbers and SO_2 by second stage marble bed scrubbers. There are 12 modules per boiler. Drains from both stages enter a common reaction tank which has facilities for forced oxidation and mechanical agitation. The scrubber reagent is a combination of alkaline flyash and limestone. The latter is added as a 4% slurry to the reaction tank.

A bleed stream is taken from the recycle pump discharge and sent to a thickener. The underflow from the thickeners, at about 30% solids, is sent to an on-site 60-acre, 50-ft deep permanent disposal pond. It is clay lined, and the sides are rip-rapped for wave protection. Consideration has been given to bypassing the thickeners, with the bleed streams being sent directly to the pond.

A flow diagram of the sludge handling scheme is shown in Figure 5-4 and a photograph of the sludge disposal pond is shown as Figure 5-5.

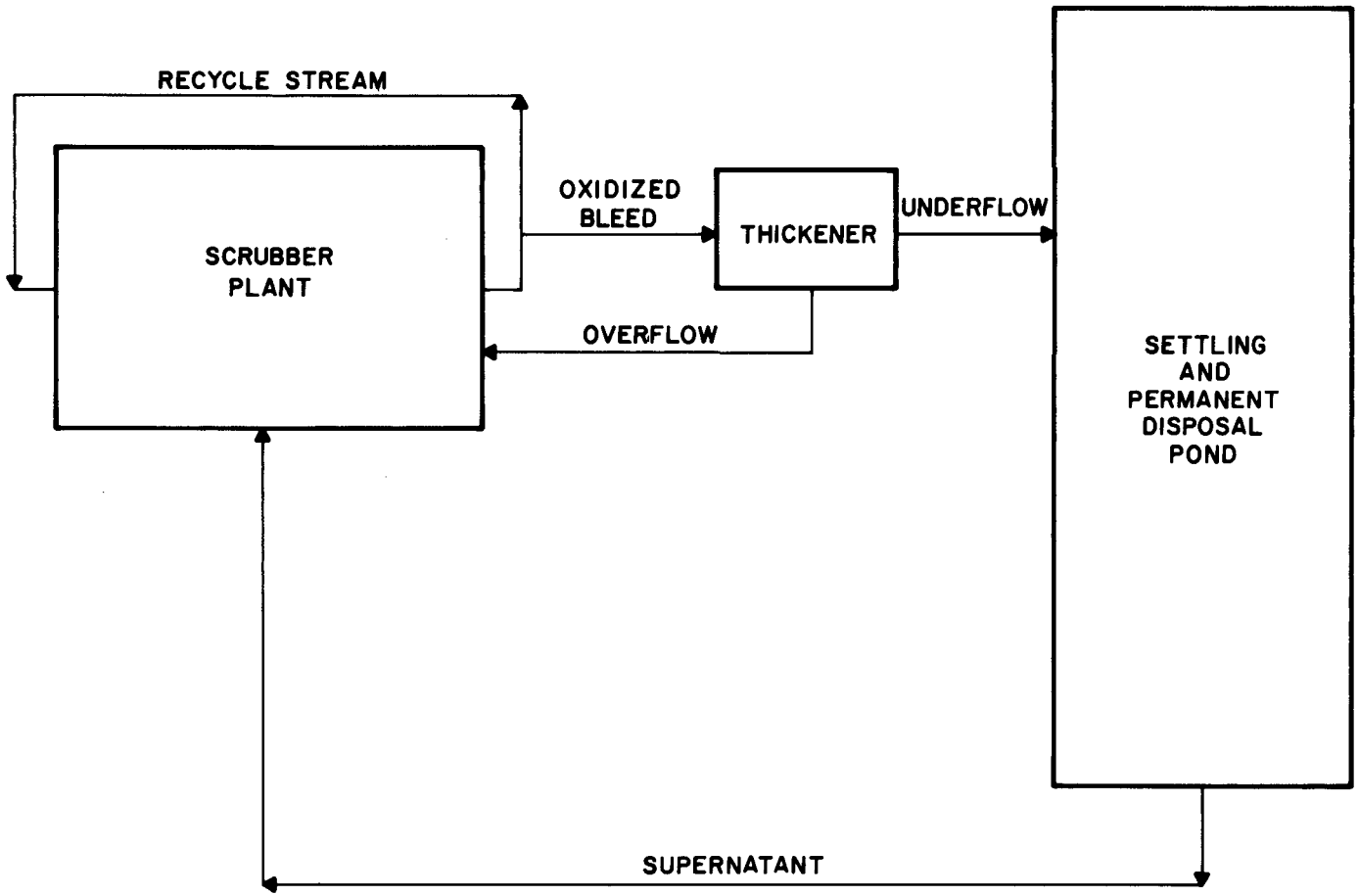


Figure 5-4. Flow Diagram for Wet Disposal Option 2 with Oxidation
Sherburne Plant, Northern States Power Company



Figure 5-5. Sludge Disposal Pond
Sherburne County Plant, Northern States Power Company

SLUDGE PROCESSING/DISPOSAL	WET DISPOSAL OPTION 2
Power Plant/Location	Colstrip/Colstrip, MT
Company	Montana Power
No. Boilers/MW on Scrubbers	2/720
New or Retrofit	New
Flyash Removal	CEA Venturi Scrubber + Koch Tray
SO_2 Removal	CEA Absorber Spray
Scrubber Reagent	Alkaline Flyash + Lime

The Colstrip Plant burns Rosebud Seam coal from an adjacent Western Energy Company mine, with an ash content averaging 8.6% and sulfur content averaging 0.77%. Particulates are removed in an adjustable-throat venturi scrubber. Sulfur oxides are removed by an absorber spray. Each boiler is equipped with three scrubber vessels. Flyash/sulfur-oxide slurry is recycled at about 10 to 12% solids. The alkaline flyash acts as a partial scrubbing reagent with lime addition as necessary to maintain a pH of 5 ± 0.5 in the recycle tank located in the vessel bottom, where mechanical agitation is provided to assure suspension of the solids. The Koch wash-tray system is isolated from the main recycle flow. A bleed stream is taken from the main recycle pumps to the flyash pond; the supernatant is returned to the main scrubber cycle. A separate bleed stream is taken from the wash-tray system to a wash-tray pond. The supernatant from that pond is returned to the wash-tray system.

The settled sludge in the flyash pond is re-slurried and pumped by a floating dredge through a 3-mile pipeline to an evaporation pond. Settled sludge from the wash-tray pond is removed by clamshell bucket to earth movers, then transported to and placed in the flyash pond. Figure 5-6 shows a flow diagram for sludge handling at Colstrip. Figure 5-7 shows the interim pond and 5-8 shows the final disposal pond.

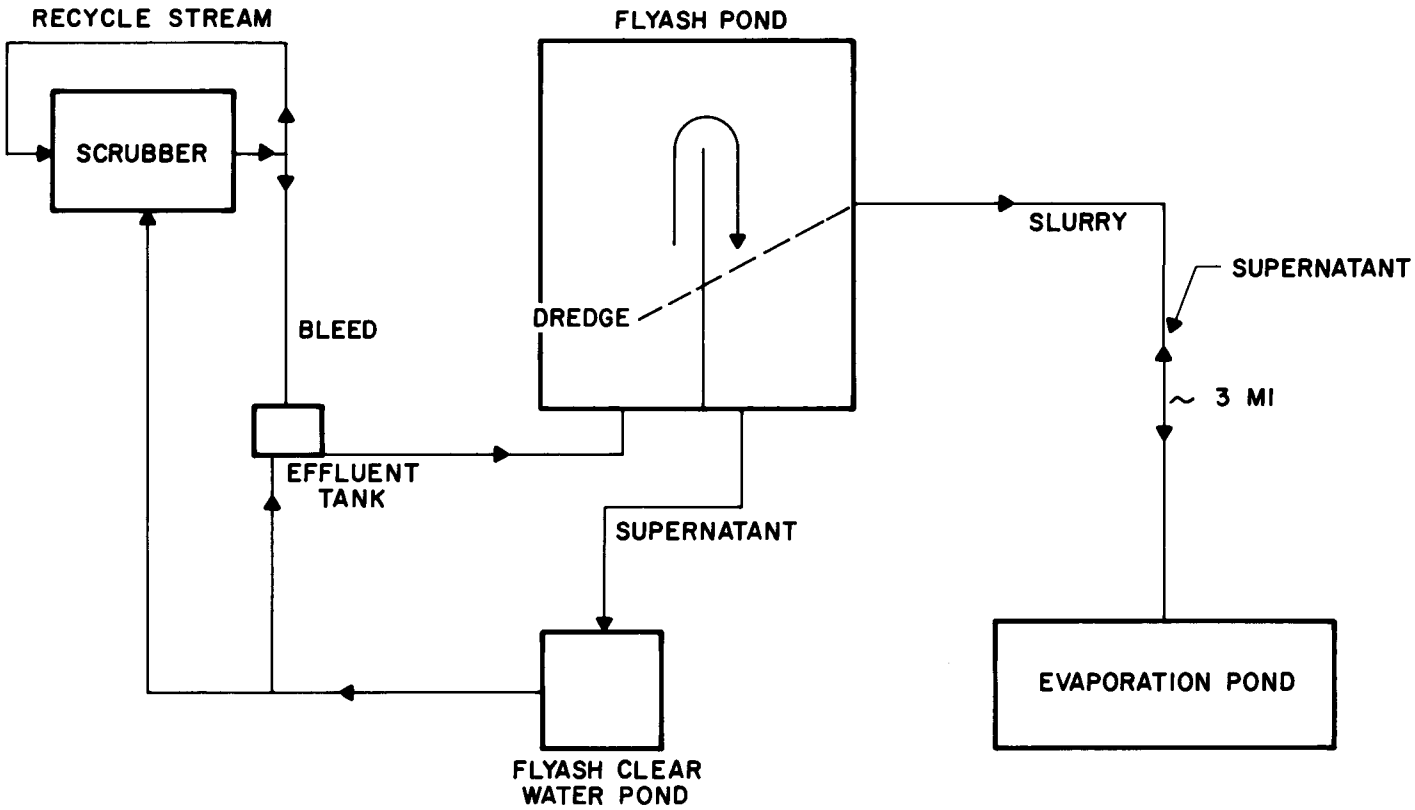


Figure 5-6. Flow Diagram for Wet Disposal Option 2
Colstrip Plant, Montana Power Company



Figure 5-7. Flyash/Sludge Settling Ponds
Colstrip Plant, Montana Power Company



Figure 5-8. Evaporation Pond
Colstrip Plant, Montana Power Company

SLUDGE PROCESSING/DISPOSAL	WET DISPOSAL OPTION 3
Power Plant/Location	Bruce Mansfield/Shippingport, PA
Company	Pennsylvania Power
No. Boilers/MW on Scrubbers	2/1840
New or Retrofit	New
Flyash Removal	Chemico Variable Throat Venturi Scrubber
SO_2 Removal	Chemico Fixed Throat Venturi Absorber
Scrubber Reagent	Lime
Fixative	Dravo Calcilox^R

The Bruce Mansfield Plant burns Pennsylvania and West Virginia coal with an average 15% ash and 3.5% sulfur. The pulverized coal boilers exhaust directly to the first-stage scrubbers with no upstream flyash removal. The liquor entering the scrubbers is maintained at a pH of 7 to 8 by the addition of lime.

A bleed stream at about 15% solids (flyash and SO_x solids) is sent to two 200 ft thickeners. The underflow at approximately 30% solids is pumped to the sludge treatment plant where it is mixed with about 7% Calcilox, then pumped seven miles to an impoundment for final disposal. A flow diagram of the sludge system is shown in Figure 5-9. The sludge treatment plant is pictured in Figure 5-10 and the sludge impoundment in Figure 5-11.

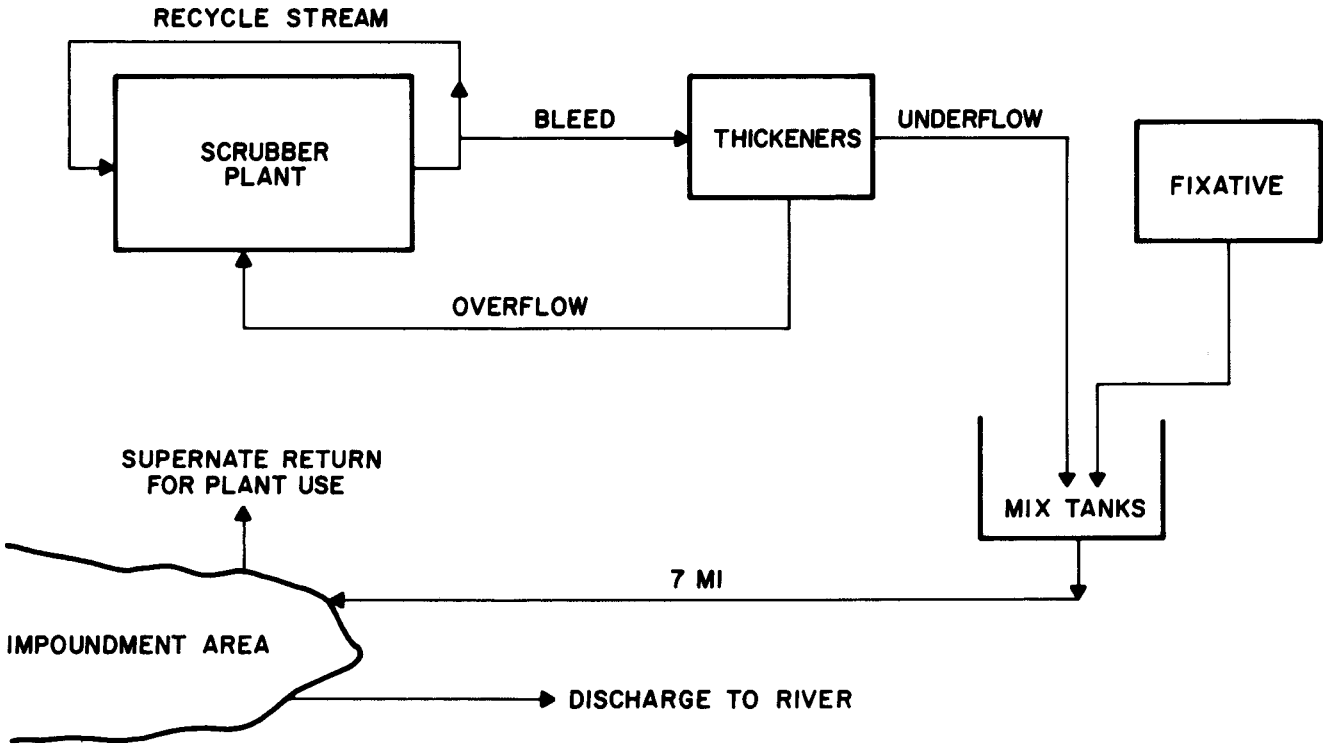


Figure 5-9. Flow Diagram for Wet Disposal Option 3
Mansfield Plant, Pennsylvania Power Company

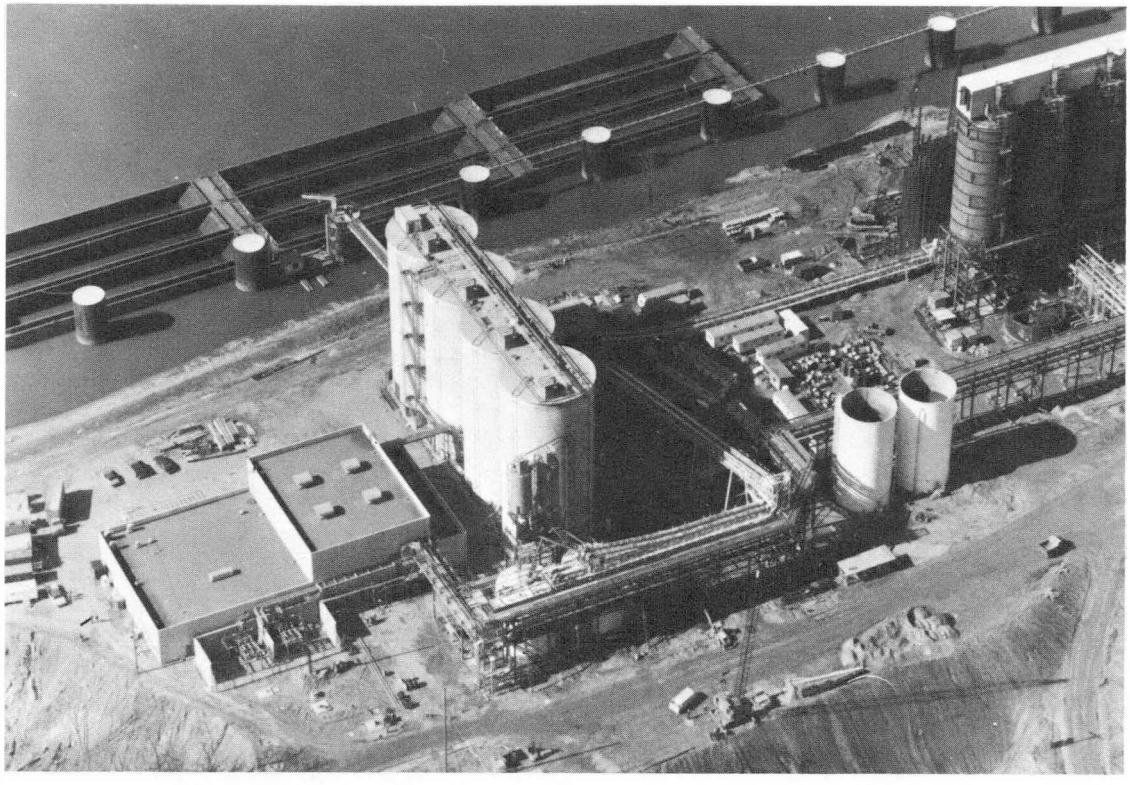


Figure 5-10. Sludge Fixation Plant
Bruce Mansfield Plant, Pennsylvania Power Company



Figure 5-11. Sludge Impoundment
Bruce Mansfield Plant, Pennsylvania Power Company

SLUDGE PROCESSING/DISPOSAL	DRY DISPOSAL OPTION 2
Power Plant/Location	Cherokee/Denver, CO
Company	Public Service Company of Colorado
No. Boilers/MW on Scrubbers	2/460
New or Retrofit	Retrofit
Flyash Removal	Mechanical + ESP + UOP Turbulent Contact Absorber^{R}
SO_2 Removal	Incidental in Scrubbers
Scrubber Reagent	Alkaline Flyash

Colorado subbituminous coal with an average ash content of 8 to 12% and sulfur of 0.35 to 0.55% is burned at the Cherokee Plant. The primary purpose of the scrubbers is to remove flyash which remains in the emissions after passing through the mechanical collectors and electrostatic precipitators. Because of the alkalinity of the flyash, there is incidental SO_2 removal. The resulting sludge is removed in a bleed stream to a thickener where lime is added to increase the pH of the overflow to 6 to 9 to meet regulatory requirements for discharge.

The thickener underflow is directed to one of three primary settling ponds along with the bottom ash. The ponds are used in sequence--one being filled, one being dewatered and one being excavated. The excavated sludge/bottom ash are hauled by truck to an off-site, contractor-owned and operated landfill. A flow diagram for the sludge system is shown in Figure 5-12 and a photograph of a pond being excavated in Figure 5-13.

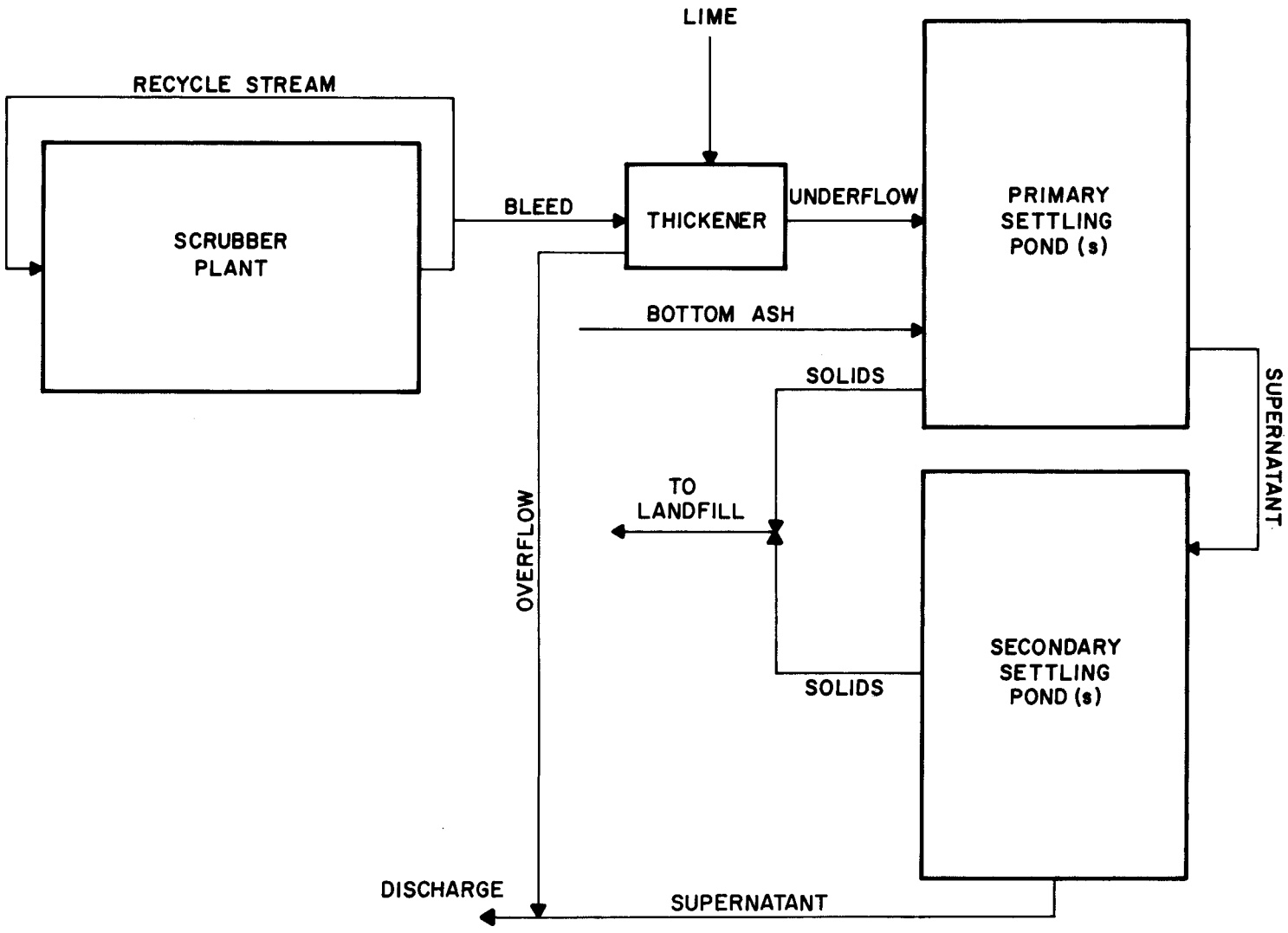


Figure 5-12. Flow Diagram for Dry Disposal Option 2
Cherokee Plant, Public Service Company of Colorado



Figure 5-13. Sludge/Bottom Ash Pond Being Excavated
Cherokee Power Plant, Public Service Company of Colorado

SLUDGE PROCESSING/DISPOSAL	DRY DISPOSAL OPTION 3
Power Plant/Location	Milton R. Young/Center, ND
Company	Minnkota Power Cooperative
No. Boilers/MW on Scrubbers	1/405
New or Retrofit	New
Flyash Removal	ESP
SO_2 Removal	CEA/ADL Spray Tower
Scrubber Reagent	Alkaline Flyash-Lime

The Milton R. Young Plant is a surface-mine-mouth plant burning lignite with an average ash content of 8% and sulfur of 0.8%. The flyash removed by an ESP is alkaline and is used as the sorbent for the SO_2; it can be supplemented with lime, if necessary. The flyash is stored in a silo, from which it is fed to a tank for slurrying with thickener overflow water before introduction to the scrubber.

The thickener underflow along with the underflow from the scrubber wash tray clarifier is fed at 30 to 35% solids to one of two vacuum filters which increases the solids to the range of 60 to 80%. The filter cake is trucked to worked-out portions of the lignite mine, where it is used in the reclamation process. Excess flyash and bottom ash are also disposed in the mine. No effort is made to segregate the wastes during disposal. The alkalinity in the flyash causes cementitious reactions with the sludge, resulting in a product that appears well fixated. The cementitious reaction has caused clogging problems in the piping and thickener.

A flow diagram of the sludge handling system is shown in Figure 5-14. The vacuum filters are shown in Figure 5-15 and a view of the active disposal area in Figure 5-16. A reclaimed portion of the mine/disposal area is shown in Figure 5-17.

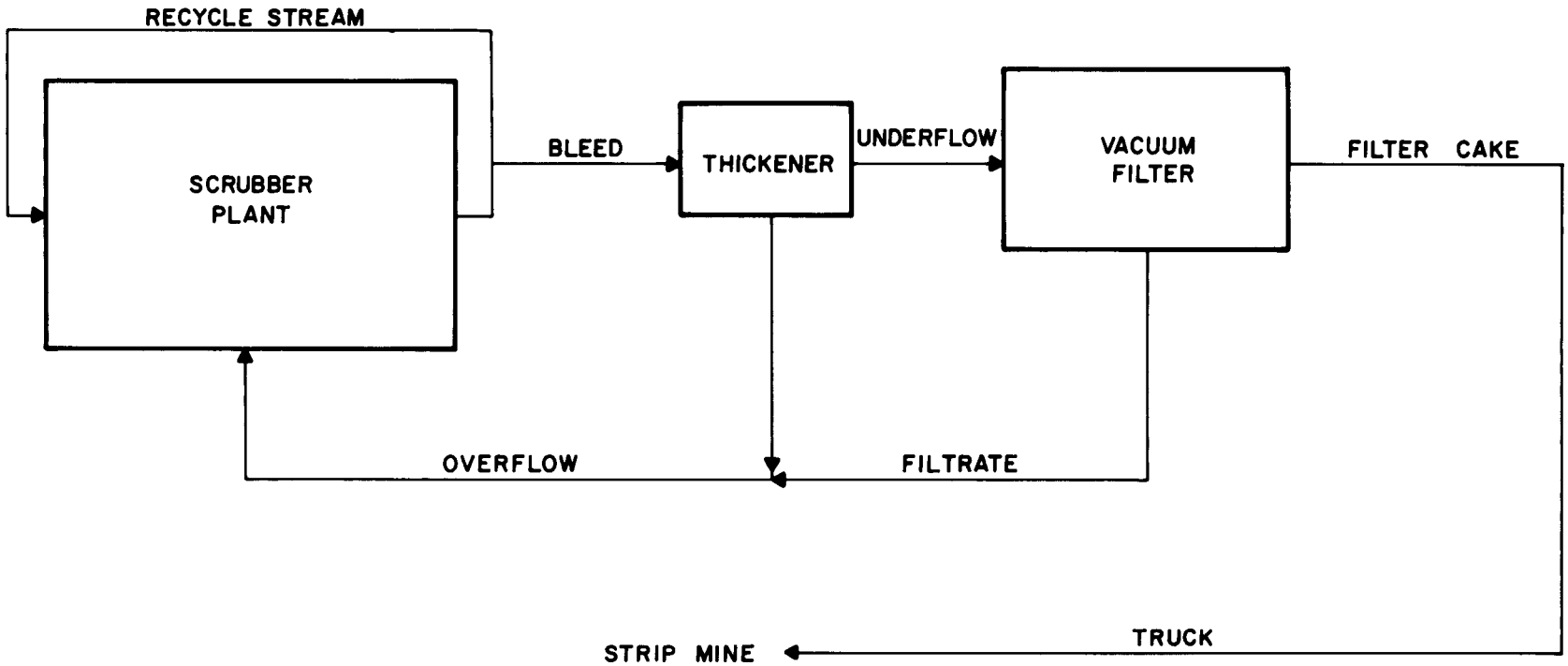


Figure 5-14. Flow Diagram for Dry Disposal Option 3
Milton R. Young Plant, Minnkota Power Cooperative

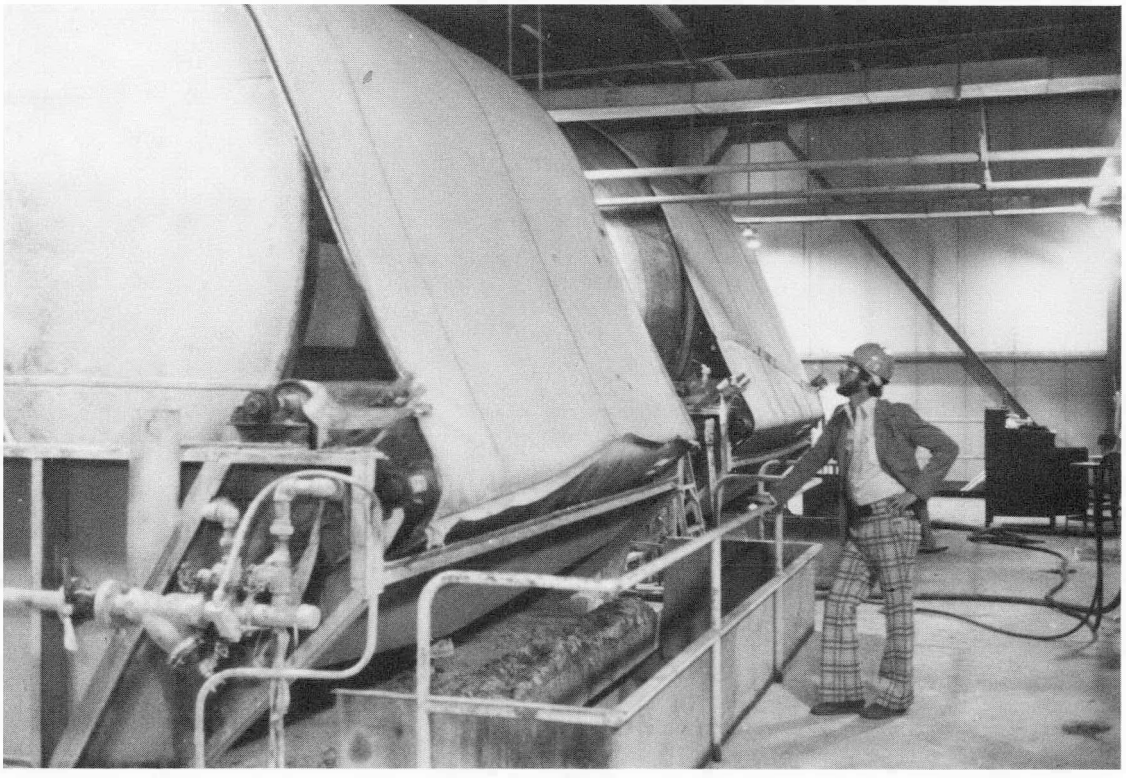


Figure 5-15. Vacuum Filters
Milton R. Young Plant, Minnkota Power Cooperative



Figure 5-16. Active Disposal Area
Milton R. Young Plant, Minnkota Power Cooperative



Figure 5-17. Reclaimed Portion of Mine Disposal Area
Milton R. Young Plant, Minnkota Power Cooperative

SLUDGE PROCESSING/DISPOSAL	DRY DISPOSAL OPTION 4
Power Plant/Location	Southwest/Springfield, MO
Company	Springfield City Utilities
No. Boilers/MW on Scrubber	1/195
New or Retrofit	New
Flyash Removal	ESP
SO_2 Removal	UOP Turbulent Contact Absorber^R
Scrubber Reagent	Limestone

Kansas coal with a sulfur content of 3 to 5% is burned in the boiler with the emissions being directed to a 99.5% efficient ESP before entering the scrubbers. Limestone is used as the scrubber reagent.

A bleed stream from the scrubbers is partially dewatered in a thickener to about 25% solids. The sludge is then further dewatered to about 50% on a vacuum belt filter. The filter cake is mixed in a double shaft, counter rotating mixer with dry flyash. The resulting mixture is conveyed by belt to a truck-loading station, from which it is hauled to an on-site landfill. The sludge mixture is spread and compacted by a bulldozer to result in a firm, structurally stable surface.

Figure 5-18 presents a flow diagram of the sludge handling system. The sludge processing area and truck-loading station are shown in Figure 5-19, and the landfill is pictured in Figure 5-20.

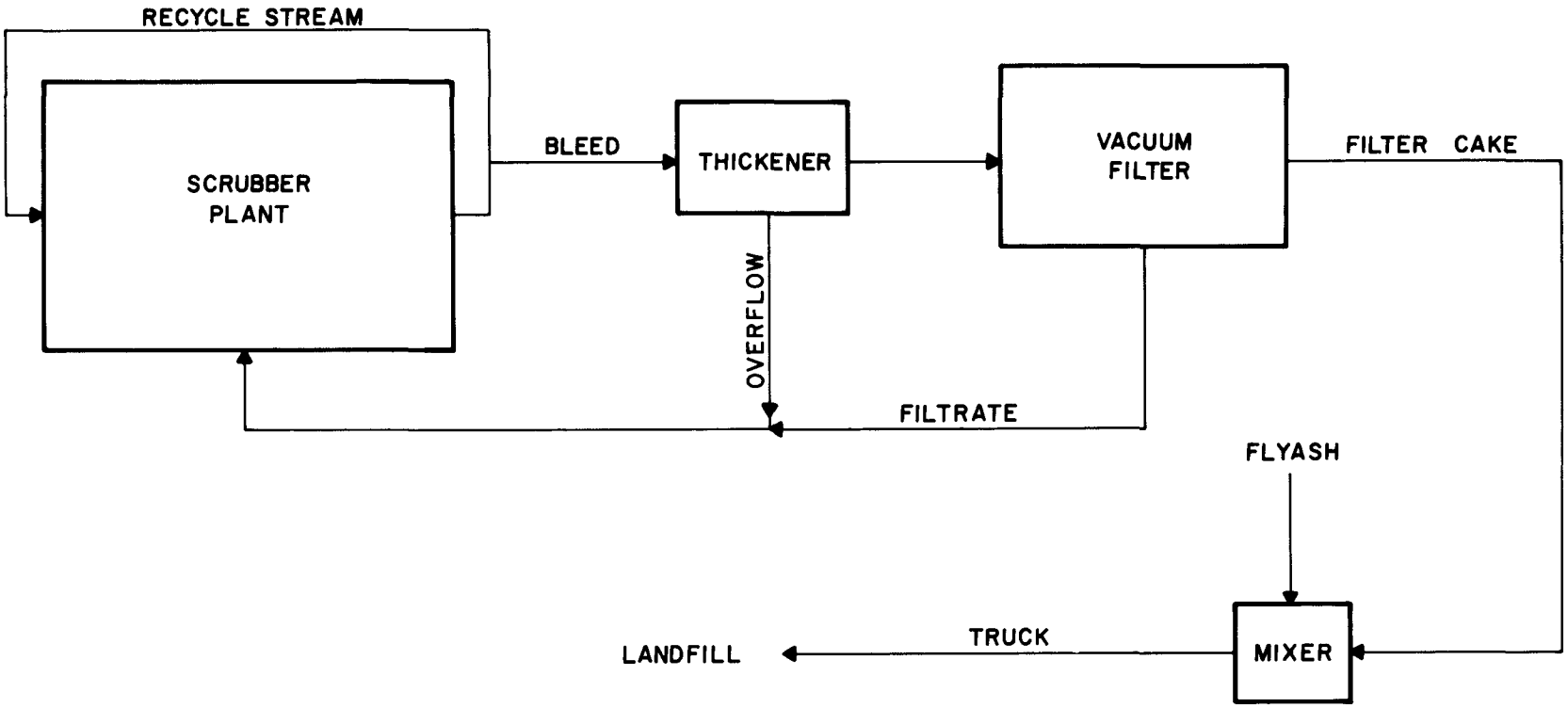


Figure 5-18. Flow Diagram for Dry Disposal Option 4
Southwest Plant, Springfield City Utilities

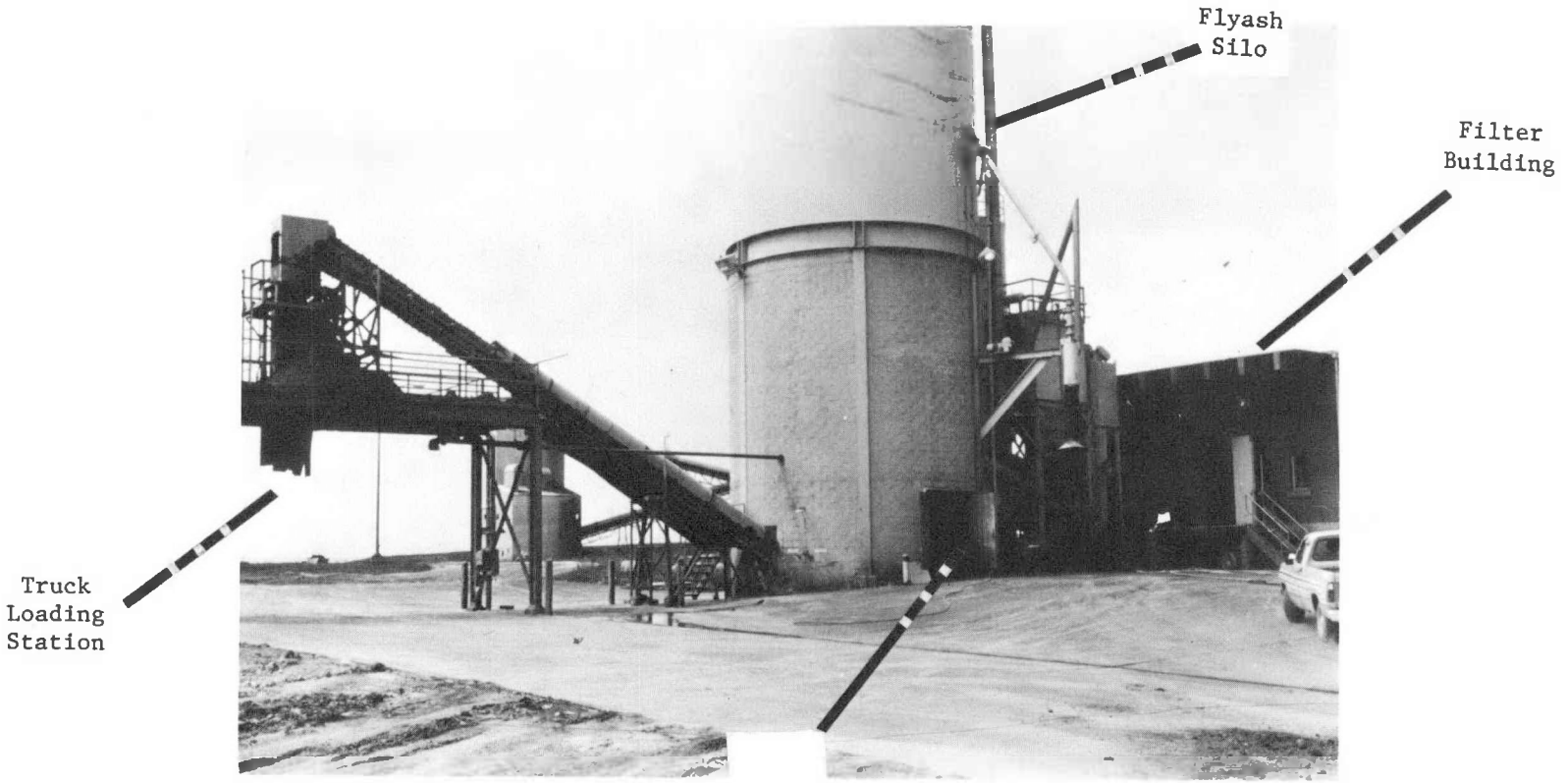


Figure 5-19. Sludge Processing Area
Southwest Plant, Springfield City Utilities



Figure 5-20. Sludge Landfill
Southwest Plant, Springfield City Utilities

SLUDGE PROCESSING/DISPOSAL	DRY DISPOSAL OPTION 5
Power Plant/Location	Conesville/Conesville, OH
Company	Columbus & Southern Ohio Electric Company
No. Boilers/MW on Scrubbers	2/800
New or Retrofit	New
Flyash Removal	ESP
SO_2 Removal	UOP Turbulent Contact Absorber^R
Scrubber Reagent	Lime

The Conesville Plant burns local coal which contains about 4.5% sulfur. The emissions first pass through 99.6% efficient electrostatic precipitators, then to the scrubbers. Each boiler is equipped with two scrubber modules. Lime is added to the recycle tank under each module to maintain the pH leaving the scrubbers at about 5.8.

The bleed stream from the scrubbers at 7 to 12% solids content is sent to two 145 ft thickeners. The underflow at about 30% solids is sent to the IU Conversion Systems' processing plant, where it can be further dewatered in a thickener or sent directly to vacuum filters. Solids content is increased to about 45-50% in the filters and the filter cake is conveyed to mixers where dry flyash and lime are added. The final product at 60% solids is then conveyed to the disposal area where it is allowed to stand for three to six days before being spread and compacted. The disposal area was previously used as an ash pond. It will be filled to grade, after which the fixed sludge will be mounded to a height of about 100 feet, covered and vegetated.

The sludge processing/disposal flow diagram is shown in Figure 5-21, the IUCS plant in Figure 5-22, and the sludge disposal area in Figure 5-23.

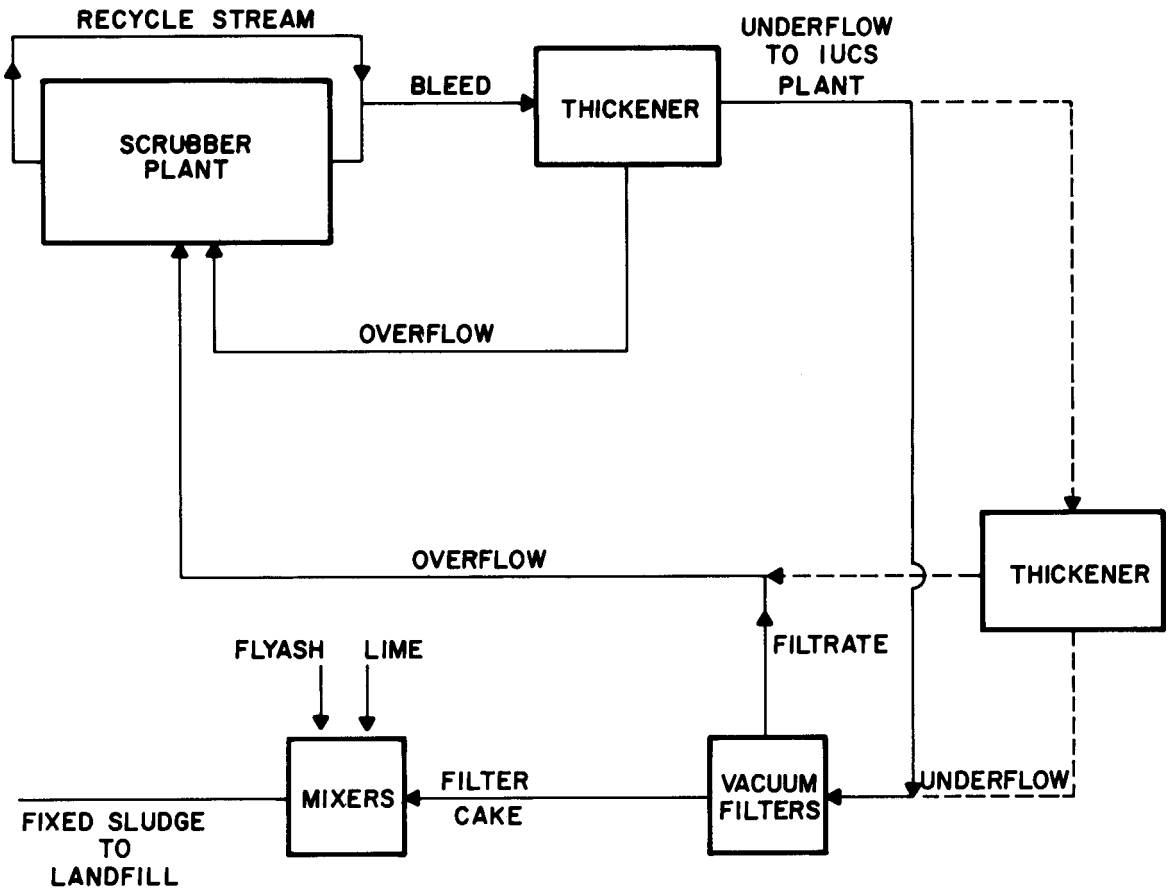


Figure 5-21. Flow Diagram for Dry Disposal Option 5
Conesville Plant, Columbus and Southern Ohio Electric Company



Figure 5-22. Sludge Processing Plant, Conesville Plant
Columbus & Southern Ohio Electric Company



Figure 5-23. Sludge Disposal Area, Conesville Plant
Columbus & Southern Ohio Electric Company

SLUDGE PROCESSING/DISPOSAL	DRY DISPOSAL OPTION 6
Power Plant/Location	Scholz/Sneads, FL
Company	Gulf Power Company
No. Boilers/MW on Scrubber	1/20
New or Retrofit	Retrofit, prototype
Flyash Removal	ESP
SO_2 Process	Chiyoda 101

The Chiyoda Thoroughbred 101^R process (CT-101) is one of three prototype systems tested at the Scholz Plant in a program initiated in 1972. The program conducted and results obtained in 1975-1976 are described in EPRI FP-713-SY, Volumes 1-3.

A simplified flow diagram is shown in Figure 5-24. The gas stream from 2-40 MW (equivalent) pulverized-coal boilers is normally passed through 99.5% electrostatic precipitators before discharge to the atmosphere. For the prototype tests, a slip stream of clean gas equivalent to about 20 MW, was processed by the CT-101 system. The gas passed through a fixed-throat venturi prescrubber for removal of flyash and chlorides. From there it flowed to a packed absorption tower where sulfur dioxide and sulfur trioxide were removed. The sulfurous acid produced was oxidized to sulfuric acid in an iron-catalyzed reaction in an oxidation vessel. The sulfuric acid was partially neutralized with limestone in a crystallizer to produce gypsum. The gypsum was separated from the partially neutralized acid by centrifugation to about 85% solids.

The product gypsum is shown in Figures 5-25 and 5-26. Almost the entire output from the last nine months of operation was sold for use as a soil amendment, providing calcium and sulfur for peanut growing in northwest Florida. Two hundred tons of the material was used in the demonstration production of wallboard in a commercial plant.

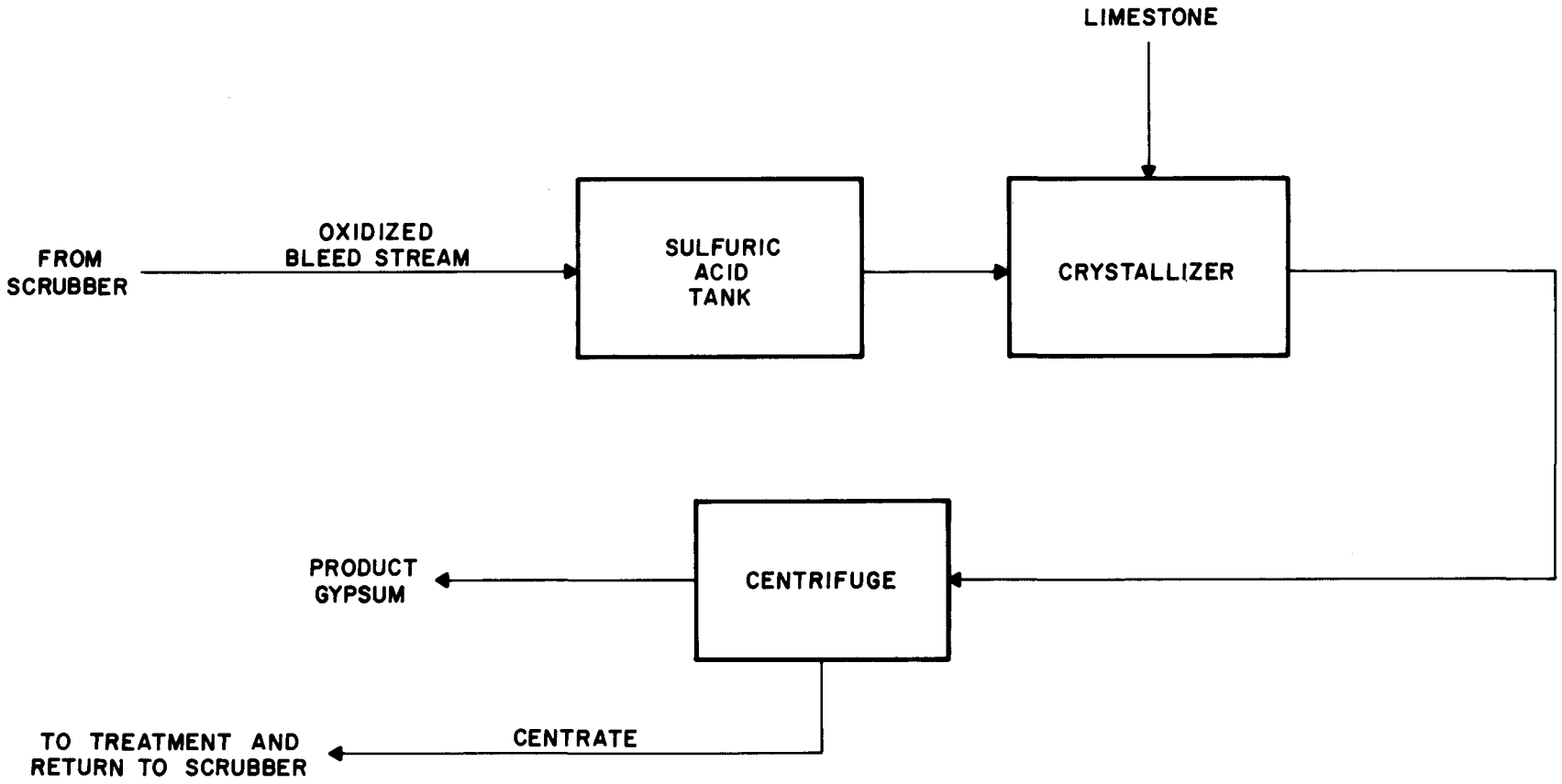


Figure 5-24. Simplified Flow Diagram for Dry Disposal Option 6
Scholz Steam Plant, Gulf Power Company

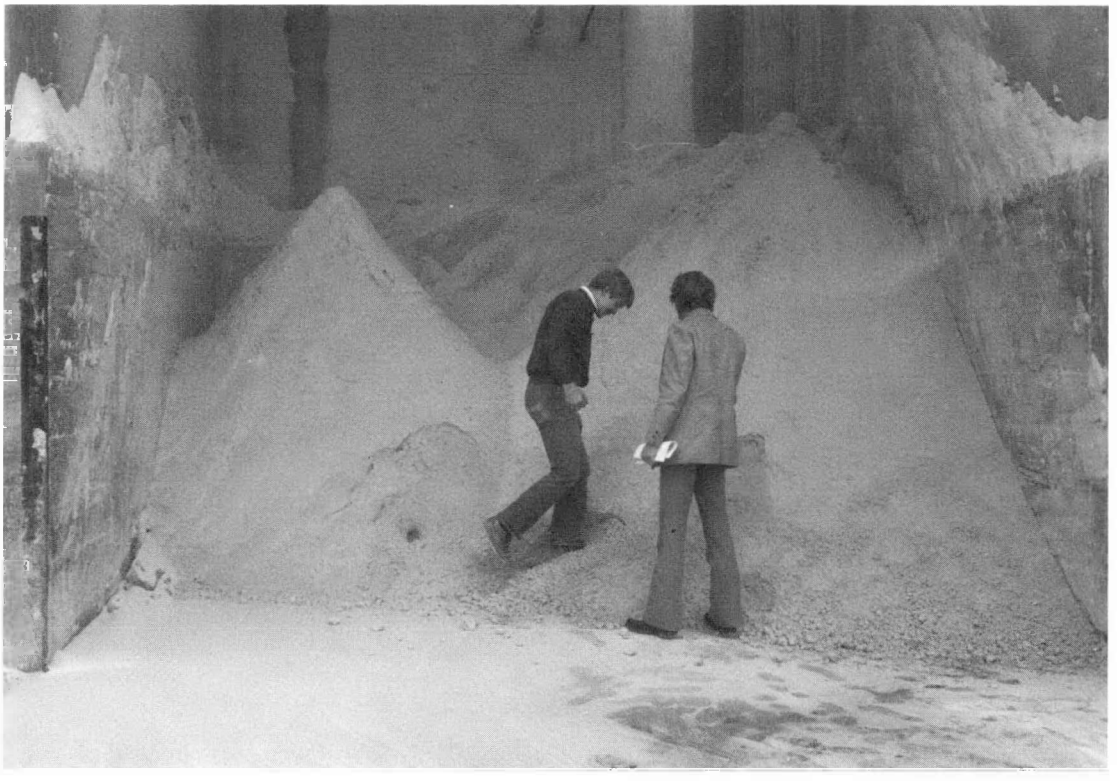


Figure 5-25. Gypsum from Chiyoda 101 Scrubber
Scholz Steam Plant, Gulf Power Company

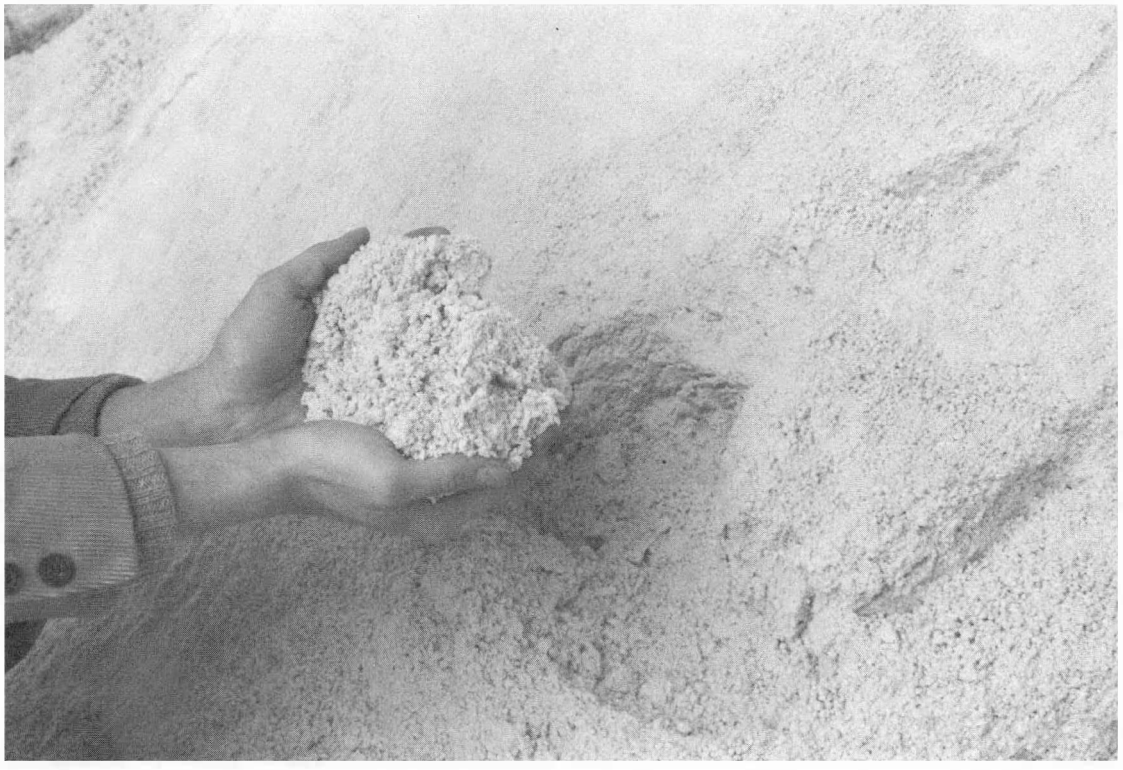


Figure 5-26. Close-up of Chiyoda Gypsum
Scholz Steam Plant, Gulf Power Company

SLUDGE PROCESSING/DISPOSAL	DRY DISPOSAL OPTION 7
Power Plant/Location	Scholz/Sneads, FL
Company	Gulf Power Company
MW on Scrubber	1/20
New or Retrofit	Retrofit, prototype
Flyash Removal	ESP
SO_2 Process	Chiyoda 121

The Chiyoda Thoroughbred 121 process^R (CT-121) and gypsum disposal by stacking were tested in 1978-1980 at the Scholz Plant under EPRI sponsorship, RP-536. As described for the previous CT-101 process, a 20 MW (equivalent) slipstream of ESP-cleaned flue gas was sent to the scrubber from the 2-40 MW boilers in the plant. A flow diagram of the scrubber and disposal process is shown in Figure 5-27.

The CT-121 process employs a Jet Bubbling Reactor^R, shown later in Section 10. The reactor has two zones: a jet bubbling zone and a reaction zone. The flue gas is sparged into the jet bubbling zone and forms a froth layer in which the sulfur dioxide absorption takes place. Limestone and air are introduced into the reaction zone where gypsum is formed. There is no slurry bleed or recycle. The entire process of absorption, oxidation and neutralization is accomplished in one vessel.

The waste gypsum stream was sent to stacking disposal by pipeline. As described in EPRI FP-713-SY, Volume 1, "stacking is a gypsum disposal method employed extensively by the phosphate industry. In the stacking operation, an earthen starter dike is constructed to form a pond in which the gypsum slurry is deposited. Once sufficient gypsum is deposited in the pond, it is dug out with a dragline and placed around the perimeter of the pond to form subsequent starter dikes." Supernatant liquor is drained into a ditch around the stack and returned to the scrubber plant. The Scholz pond is shown in Figure 5-28, the stack in Figure 5-29 and the drainage ditch in Figure 5-30.

A complete description of the Scholz stacking test is given in Section 16 - GYPSUM STACKING.

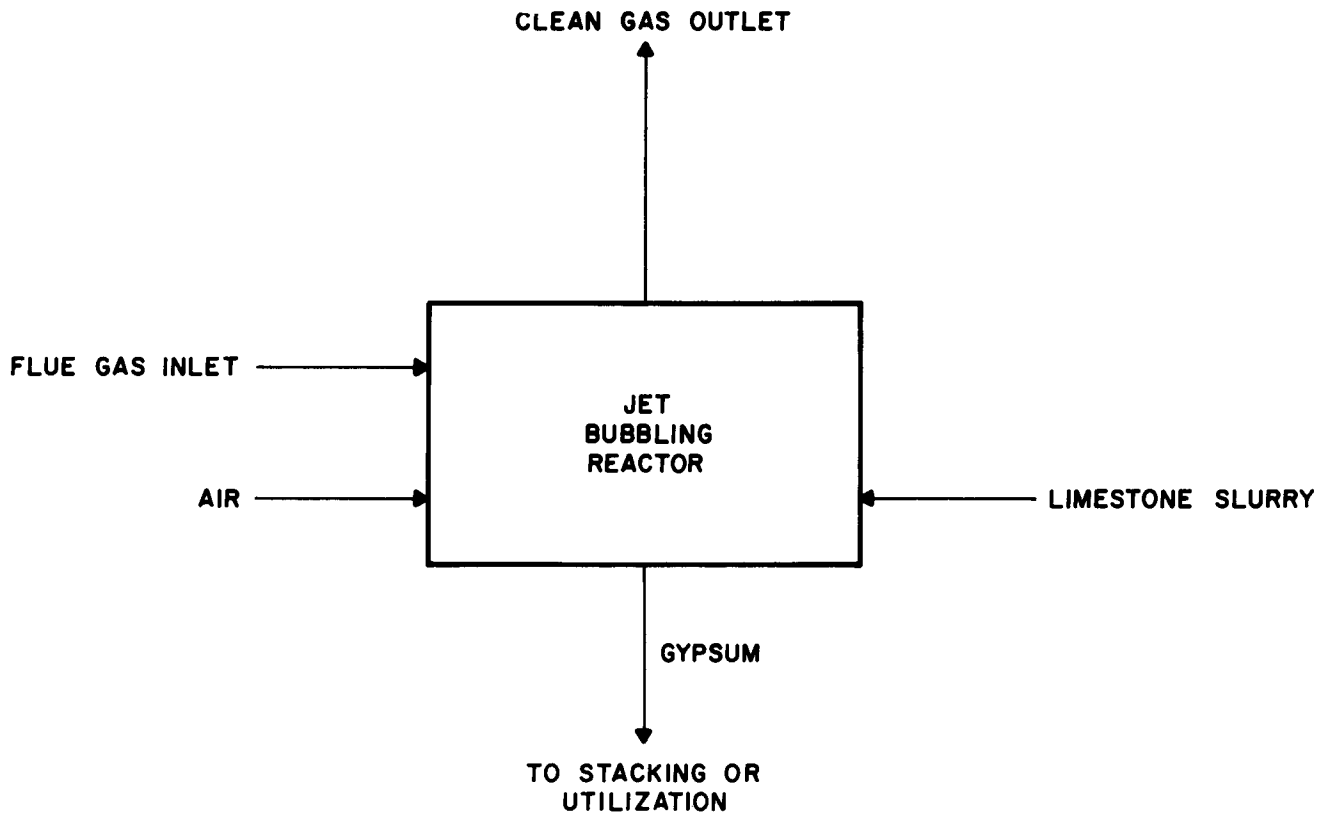


Figure 5-27. Flow Diagram for Dry Disposal Option 7
Scholz Steam Plant, Gulf Power Company



Figure 5-28. Gypsum Stacking Pond
Scholz Steam Plant, Gulf Power Company

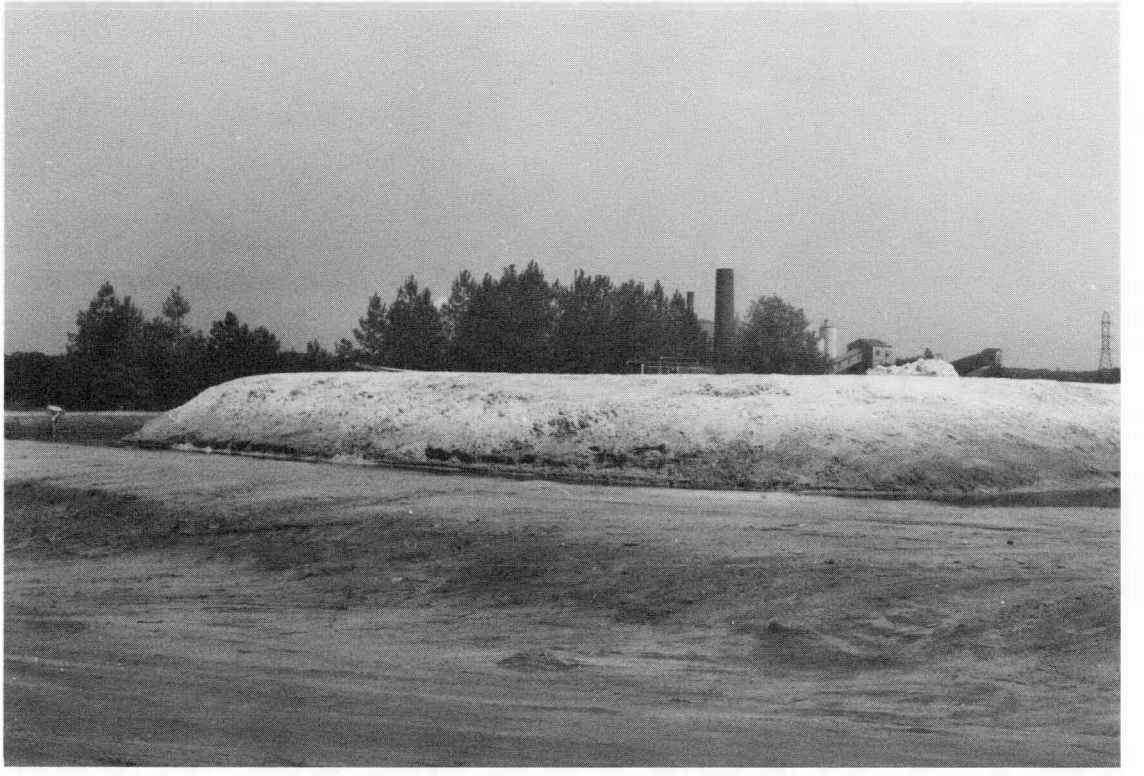


Figure 5-29. Exterior of Gypsum Stack
Scholz Steam Plant, Gulf Power Company



Figure 5-30. Drainage Ditch for Gypsum Stack
Scholz Steam Plant, Gulf Power Company

WASTE DISPOSAL	DRY DISPOSAL OPTION 7
Plant/Location	USS Agri-Chemical/Bartow, FL
Product	Phosphate Fertilizers
Waste	Phosphogypsum (Calcium Sulfate)

A narrative on this plant is presented because the waste product is very similar to oxidized scrubber sludge. The method of landfill disposal appears to have potential application to FGD sludge disposal.

As a step in making phosphate fertilizer, local calcium phosphate rock is reacted with sulfuric acid to form phosphoric acid. The waste product is an impure form of calcium sulfate. It is pumped as a 20% slurry to a diked, two-section pond. As one section is filled, it is taken out of service and the other section placed in service. The idle pond is allowed to drain and some evaporation occurs. When the waste is dry, it is pulled to the sides by a dragline to build up the dikes. A section of the pond is shown in Figure 5-31. This alternate ponding, drying and dike-raising continues until the desired height is reached, usually 100 to 150 feet. The waste piles are not compacted, have a recommended slope of 30% and do not appear to be subject to erosion. The material is dry, non-thixotropic and is reported to have cementitious properties. A nearly vertical, 25 ft cut had been bulldozed with no sign of slope failure, as shown in Figure 5-32. A crust forms on the surface, and dusting does not appear to occur unless the crust is disturbed. The slope of the completed phosphogypsum stack is shown in Figure 5-33.

Seepage from the pile is accumulated in a diversion ditch and returned to the plant. Run-off is directed to separate ditches and not mixed with the seepage. Discharge of run-off water is permitted by the state.



Figure 5-31. View of Drained Phosphogypsum Pond
USS Agri-Chemical Plant, Bartow, FL



Figure 5-32. Vertical Cut Through Phosphogypsum Stack
USS Agri-Chemical Plant, Bartow, FL



Figure 5-33. Side of Completed Phosphogypsum Stack
USS Agri-Chemical Plant, Bartow, FL

Section 6

SITE SELECTION

PURPOSE

This section points out the necessity for early and careful disposal site selection. This section also describes the site selection process and enumerates the various criteria for the choice, including engineering, environmental, legal and economic factors. Specific case histories in disposal site selection and permitting are discussed in Appendix C.

FUNDAMENTALS

Often one of the most critical questions facing the utility installing a scrubber is where to put the sludge. Finding a suitable and acceptable disposal site can be difficult and frustrating. In view of the complicated process of locating, permitting and developing a disposal site, the location of the site should be given very early consideration in the planning process. As shown in Section 4 - WASTE QUANTITIES, the amount of sludge generated in a scrubber is significant. Quite commonly, hundreds of acres of land are required for a suitable disposal site. Acquisition and public acceptance of such a large land area dedicated to a "non-productive" disposal site can be complex, difficult, time consuming, and costly. The difficulties can be minimized by proper planning and appropriate timing of the steps required to acquire the site. Acquisition and development of a new site can be expected to take from two to five years, so it is best to begin planning early.

In general, there are two cases with which to be concerned in selecting a site:

1. A new station at a previously undeveloped site which is required to have scrubbers
2. An existing station for which a disposal site must be found. This station may require a new site for any of the following reasons:
    - A new unit with a scrubber is being added to the existing station.
    - The existing station is being retrofitted with a scrubber.
    - The existing station is equipped with a scrubber for which the disposal area has been exhausted and a new area must be found.

For new stations, the sludge disposal area should be considered as part of the total area required for the plant. Locating the disposal site should be one of the primary factors considered in siting the plant. Under current regulations for plant siting and environmental impact statements in virtually all states, the disposal area must be considered part of the new plant. This is actually the best approach because it obviates the need for a special search for disposal sites after the plant site has been selected.

Ordinarily, but not always, the disposal area is part of the same parcel of land devoted to the generating station proper. This is advantageous because having the disposal area in close proximity to the scrubbers will minimize waste transport costs. However, including station buildings and the disposal area in the same parcel will considerably expand the amount of land area needed for the station, thereby increasing the difficulty of finding a suitable site. In these cases, off-site disposal (that is, disposal of sludge on property not contiguous with the plant property) needs to be considered. Off-site disposal, such as worked-out mines or quarries, may be advantageous and should be considered where such sites are available and appropriate. A detailed methodology for power plant siting is presented in Reference (1).

In the second case, which involves new and retrofitted units at an existing station, a different set of conditions applies. Due to the fixed location of the existing station, the scope of the search for a disposal site is much smaller than for a new power station. For these systems, it is usually most convenient and advantageous to expand the existing flyash or bottom ash disposal facilities, adapting them as appropriate to receive FGD sludge. While this solves the problem of sludge disposal for the short term, the greatly increased volume of waste material (sludge plus ash) is likely to exhaust the capacity of the disposal facility before the design life of the plant is ended. In this instance, the altered use of the ash disposal facilities should be considered an interim measure while plans are begun for selecting a sludge disposal site for ultimate use.

Once it has been determined that a new site must be found, either for present or future use, the best approach is to conduct an organized and comprehensive site selection study. The study process for a new disposal site is much the same as would be employed for any major site selection.

One of the critical questions in the site selection process is whether the sludge is to be disposed of wet (in a pond) or dry (in a landfill). Section 5 - DISPOSAL ALTERNATIVES discusses this question in detail. Ideally, the decision regarding wet vs. dry disposal should be made before initiating the site selection process so the type and size of site can be determined. Having made this decision at an early date simplifies the site selection process. However, it may not be possible or prudent to make this decision without knowing the types of sites which are available. In some cases, siting may be the deciding factor and it may be better to determine what sites are available for wet or dry disposal and then choose between the two methods.

SITE SELECTION PROCESS

The process of selecting a disposal site should be carried out at a level of detail which is appropriate for the situation. A rigorous search is preferable but not always necessary if the utility has a good knowledge of local conditions and potential sites through previous experience. The familiarity of the utility personnel with the area will be an important asset in initiating the siting process for a disposal site to serve an existing plant. Their experience at the plant has probably acquainted them with the potential disposal sites within the near vicinity of the plant.

The magnitude of the task of selecting a site is put into perspective by envisioning the quantities of sludge to be generated during the operating life of the power plant. This concept helps to underscore the importance of minimizing the distance between the disposal site and the power plant.

Properly carrying out the site selection process may require a multi-disciplinary team with competence in the fields of engineering and environmental science, as well as in socio-economics, political science and land-use planning. While this team should conduct the study in a cooperative fashion, each team member should perform his site evaluations independently.

The selection of each site will entail a procedure which will be determined largely by the individual characteristics of the generating station and its surrounding territory. However, the basic process of site selection will remain the same, even though the effort required for each step may vary appreciably from one case to another. Regardless of the size and complexity of the process, each step with the associated decisions and supporting reasons should be documented for the record. This record may prove to be quite useful if the utility's site selection is challenged by either the public or by the regulatory agencies. The principal steps of this process are as follows:

- Establishing the siting criteria. All the appropriate siting criteria are identified, including subjective as well as objective criteria.
- Weighing the relative importance of each criterion. Region-specific as well as site-specific concerns are utilized in assigning relative weights to the criteria.
- Establishing the area of study. Based on transportation economics and the general topography of the region, a maximum radius with its center at the plant site is determined. The circle of this radius encompasses the area of intensive search for a disposal site.
- Identifying potential candidate sites. Areas with unsuitable characteristics (e.g. dense population, inappropriate topography, undesirable geology or soils, floodplains, environmentally sensitive areas) are excluded from further evaluation. From the remaining territory within the study area, potential candidate sites are selected.
- Developing information about each site. Site-specific data are accumulated from various sources such as the electric utility (previous studies and general familiarity with the area), government agencies (federal, state, county, and local), and neighboring industries, colleges and universities.
- Applying the criteria to each site. Each site is evaluated in terms of each criterion. Where several sites are under consideration, a scoring system is utilized to quantify the results and document the basis of comparison.
- Selecting the candidate sites. After ranking the sites based on the evaluations, the low scoring sites are eliminated from further consideration.
- Reviewing the candidate sites in detail. A detailed field investigation is conducted to verify the data base used for each candidate site. In large part, this field investigation is geotechnically oriented and includes a detailed surface reconnaissance, subsurface exploration (core borings) and a hydrogeologic study.
- Evaluating the candidate sites. The previous evaluations are reviewed and the criteria are applied to each site in greater depth than the previous screening. The economic criteria, in particular, are applied such that estimates are developed for the capital cost as well as operation and maintenance costs for each candidate site.
- Selecting the site. The site which this procedure has isolated as being superior to the others is recommended for development.

SITING CRITERIA

Choice of an appropriate disposal site requires consideration of a large number of factors. It should be recognized that the relative importance of each of these factors varies from situation to situation. Each utility must decide for itself the magnitude and importance of each of these factors based on local conditions. Some general guidance, however, may be useful.

As shown in Table 6-1, there are four broad categories of factors (or criteria) which may influence the choice of a site: engineering; environmental; economic; and regulatory and political. These are all interrelated and to a certain extent, overlapping. Regulations currently proposed under RCRA incorporate some of the criteria from all categories except economic. These regulations are covered in detail in Appendix B.

It should be recognized that some of the criteria are fixed (rigid) while others are flexible. Rigid criteria are those which must be met. That is, if the criterion is not met, the site is definitely not suitable. For example, the site must meet a certain minimum size requirement. If it fails to meet this criterion, it is not considered advisable to locate the disposal area there.

Flexible criteria are those which involve more subjective reasoning. For example, it is desirable, but not mandatory, that the disposal area be close to the plant site. When evaluated and weighed, the flexible criteria collectively should be used to determine the relative ranking of the sites considered.

Engineering Criteria

Most of the engineering criteria are fundamental and fixed. That is, the site must meet these requirements or it is simply not suitable for development. Section 8 - DESIGN OF DISPOSAL AREA - discusses the criteria in detail. Principal engineering criteria are:

- Physical size--Acreage must be provided to accommodate the sludge and related facilities for the design period (usually the life of the plant). The required storage volume can be computed using the formulas shown in Sections 4 and 9. This volume can be related to the required acreage by assessing the average depth of sludge which depends on the disposal method, topography and soil conditions. Where possible, the active disposal area should be surrounded by at least 100 ft of unoccupied space which serves as a buffer zone between the site and the nearest human activity.
- Proximity--Select a site as close as possible to the scrubber facility to minimize the transportation costs.
- Site access--The site must be able to be made accessible for construction purposes as well as for delivery of sludge during operation. Where truck or rail transport of sludge is considered, the access route is especially important in relation to environmental factors such as safety, noise and fugitive dust emissions. The existing routes must be of adequate width and load capacity and traffic congestion should be avoided.
- Topography--With due consideration of the type of disposal operation, the site should be developable with a minimum of earthmoving activity by utilizing the natural contour of the land. Minimal

Table 6-1

SITE EVALUATION CRITERIA

ENGINEERING	ENVIRONMENTAL	LEGAL, REGULATORY AND POLITICAL	ECONOMIC
Physical Size	Surface Water	Legal and Regulatory	Transportation Costs
Proximity	Groundwater	Local	Property Acquisition Costs
Site Access	Air	State	Site Development Costs
Topography	Terrestrial and Aquatic Ecology	Federal	Processing Costs
Geology	Noise	Political and Public Acceptance	Closure Costs
Soils	Land Use		Salvage Value
	Scenic and Aesthetic Effects		
	Recreation		
	Cultural Resources		

site preparation should be required for diverting the surface drainage away from the active disposal operations. Small valleys and ravines may be advantageous since they are capable of receiving large volumes without extensive modifications to the natural topography. Section 8 - DESIGN OF DISPOSAL AREA - suggests some ways of taking advantage of natural topography as part of the disposal operation.

- Geology--Geotechnical hazard areas (such as those prone to slides and faults), as well as areas with underlying, adjacent, or interconnected mines, quarries, sinkholes or solution cavities should be avoided. The strength of the underlying strata should be capable of supporting any of the necessary surface structures such as dams or embankments.
- Soils--There should be an adequate depth of soil between the base of the disposal area and bedrock. Low permeability and a high renovative capacity are desirable soil characteristics. Availability of sufficient clay material for use as an impervious liner is also important. Suitable construction materials for dikes, berms and final cover should be available on site. The final cover material should be capable of inhibiting water flow and of developing a good stand of vegetation, if growing conditions permit.

Environmental Criteria

In general, the environmental criteria are not as rigid as the engineering criteria. There is considerably more flexibility in dealing with potential environmental problems than with potential engineering problems. It is often possible to make tradeoffs or to provide measures which mitigate adverse environmental impacts. This does not mean that environmental factors are less important in the decision-making process. Environmental factors are important and must be given full attention, especially since many of these factors are required to be addressed by regulation. Failure to do so could result in regulatory or public rejection of an otherwise suitable site.

A formal environmental impact statement is sometimes required for a new disposal site. For a new station, of course, an EIS is usually required and the sludge disposal site would be considered along with the station proper. However, it is often advisable to conduct a low intensity (inexpensive) environmental assessment of the short list of prospective sites just to determine that there are no critical or unique environmental factors (such as historic or archaeological sites) which would be lost by construction of a new disposal area. Environmental factors which should be considered are:

- Surface Water--The site should be located outside the 100-yr floodplain to prevent inundation. Surface water (rivers, creeks, ponds, swamps, wetlands, seeps and springs) should be avoided. Where total avoidance is not possible, surface water should be diverted

around the site. Minimizing the surface water on site will reduce the operational problems of leachate abatement and erosion control. Maximizing evaporation and recycling the pond overflow can be very advantageous since these measures substantially reduce and possibly eliminate the discharge of water which has been associated with the sludge.

- Groundwater--The potential impact of the site on the groundwater should be minimal. As discussed in Section 7 - LEACHATE, contamination of the groundwater by leachate should be prevented. Prevention is particularly important where the site overlies an aquifer which is either potentially or presently used as a water supply. Groundwater contamination is less likely to occur where there is sufficient depth between the bottom of the landfill and the historically seasonal high groundwater table. The potential impact on water supplies, both groundwater and surface water, should be considered in the site location. In addition, the site's impact on groundwater quantity and quality should be minimized by locating away from groundwater recharge areas.
- Air--Wind intensity and direction should be considered, particularly with regard to minimizing the effects of wind erosion of a dry disposal area and the impacts of fugitive emissions from dry transport and disposal.
- Terrestrial and Aquatic Ecology--The alteration of any unique habitat should be avoided. Detrimental effects on any rare or endangered species (resident or migratory) must be prevented.
- Noise--The local impacts from transportation (truck or rail traffic), construction and operation should be minimized.
- Land Use--Populated areas and areas of conflicting land use, such as parks, nature preserves, wilderness areas and airports, should be avoided. The use of potential farm and timber land should be minimized. The site should have the capability for beneficial land use at the termination of disposal operations. This consideration is particularly important around urban areas where the value of land is high.
- Scenic and Aesthetic Effects--Sites should be as visibly isolated as possible. Visual impact should be minimized by maintaining natural barriers such as a ridge of ground or a belt of trees. Presence of such natural barriers may preclude the need for the construction of artificial screening devices.
- Recreation--Areas of intense recreational activity, such as public parks or private resorts, should be avoided.
- Cultural Resources--Unique archaeological, historical and paleontological areas should be avoided.

Many of the criteria listed above can be satisfied by selecting a disposal site in an isolated area. Impacts related to fugitive air emissions, noise, land use and scenic and aesthetic effects can usually all be avoided by selecting a site and transportation route which are physically and visually isolated from population centers. The desirability of isolation, however, must be balanced aginst the increased cost (longer transport distance) often necessary to obtain isolation (2).

Economic Criteria

Project costs are always an important criterion which should be considered along with the other factors in evaluating alternative sites. As mentioned in the discussion of the site selection process, the major cost consideration is locating the disposal site as close to the power plant as possible so as to minimize the transportation costs. In addition to distance, the transportation costs are a function of the mode of sludge transport (truck, rail, pipeline) and the route of travel. The other principal cost factors relating to the disposal site are:

- Property acquisition costs--Consider actual land costs plus indirect costs such as legal fees, realtor costs and related items.
- Site development costs--Consider factors relating to site development and construction such as excavation, grading and new roads.
- Processing costs--Consider the cost of processing the waste (dewatering, stabilization, or fixation) to make transport or disposal easier and less costly.
- Annual costs--Compare the relative merits of high fixed annual charges and low operating costs or low fixed annual charges and higher operating costs.
- Closure costs--Consider the expense of the final covering of the site and preparing it for subsequent land use.
- Salvage value of the site--If the site is restored to a productive state, this may be considered as an asset to be realized upon termination of the disposal operation.

Because costs of disposal are significant, they are discussed in more detail in Section 14 - COSTS. It is important that all costs are considered and accounted for, both direct and indirect.

Political and Regulatory Criteria

Political and Public Acceptance. While similar, these two terms are not the same. Political acceptance means acceptance by local elected representatives such as county commissioners, town councils, local planning commissions, mayors and supervisors. These individuals often wield considerable influence locally and can stop projects by various means, both direct (such as refusing to grant a zoning variance, refusing to transfer property, or passing a non-disposal ordinance) and indirect (using personal persuasion and influence to block property transfer). Public acceptance means acceptance by the public at large, including special interest groups such as sportsmans clubs, nature clubs, and environmental groups.

In evaluating alternative sites, the utility should anticipate and avoid areas and issues which are locally sensitive. Many of these relate to the environmental

criteria mentioned earlier. It is important, for example, to avoid parks and recreation areas, unique historical and archaeological sites, and similar areas of local concern in order to gain political and public acceptance.

Political acceptance and public acceptance may not be the same thing. It is possible for elected officials to act in a manner which they perceive to be the public interest, allowing a project to proceed, while a sector of the public-at-large feels the project should not proceed because of a damage to their interest. It may not be possible to satisfy all these interests, for they are sometimes conflicting. However, in the site selection and evaluation process, it is best to anticipate what the opposing forces are likely to be. If these forces cannot be avoided, they can often be overcome at some increase in cost by implementing mitigating measures.

In many cases, it is necessary to conduct a public information and public relations program concurrent with the site selection process to win political and public acceptance of the project. Both are necessary in order to proceed effectively with the project.

Regulatory Requirements. Expansion of an existing site may be made without undue difficulty because the agencies (and the general public) have become conditioned to the presence of a disposal operation. However, a totally new site may present greater problems because of the intrusion of a new operation into a new area. Whatever the situation, it is generally advisable as a first step, to identify and contact the relevant regulatory agencies to determine permitting and monitoring requirements. It will be necessary for a new disposal area to meet permitting conditions eventually so these conditions should be determined early. Early contacts with agency people may also bring to light areas of concern which need to be addressed and overcome before the permits can be successfully processed.

The number and types of permits and certificates required will depend on the specific situation and the extent of the proposed action. It is not possible to list all the permits which must be obtained, because they vary widely across the country. However, some legal and regulatory hurdles may include:

Federal: Environmental Protection Agency (NPDES permit)
(RCRA waste disposal permit)
(Environmental Impact Statement)

Corps of Engineers (Section 404 permit)

State: Energy agency permit (for disposal operation)

Solid waste disposal permit (for disposal operation)

Health department permit (for sanitary facilities)

Stream encroachment permit (for rerouting streams or stream crossings)

Highway department permit (to relocate or build new roads)

Soil erosion and sediment control plan (for construction)

Dike and dam permits (for construction and safety)

Discharge permit (for pond overflow)

Local: County health department permit (for disposal operation and sanitary facilities)

Zoning variance (for construction and dumping)

Soil and water conservation district permit (for construction)

Building permit

The U.S. Environmental Protection Agency administers regulatory programs in the areas of water pollution control and solid waste management as authorized respectively by the Clean Water Act and the Resource Conservation and Recovery Act (RCRA). Both of these programs provide for the delegation of the permitting authority to the states. Under EPA's National Pollution Discharge Elimination System (NPDES), permits are required for all point source discharges of pollutants. The discharge from the waste disposal site may be included as one of the point sources on the NPDES permit for the entire power plant. In the case of a new power plant, issuance of the NPDES permit by the EPA may constitute a major federal action, thereby requiring an Environmental Impact Statement (EIS). In the case of a new disposal site at an existing power plant, it is less likely that an EIS will be required. Also, if it can be demonstrated that there will be no discharge from the site due to evaporation and sufficient flow reduction measures (e.g., recycling the pond overflow), an NPDES permit will not be required.

Regulations pursuant to RCRA are in various stages of completion; some are currently in effect while others are still awaiting final issuance. As is discussed more fully in Appendix B, FGD sludge is currently excluded from regulation as a hazardous waste under RCRA. However, since FGD sludge is included within the legal definition of a solid waste, it is subject to regulation as a non-hazardous waste.

EPA is currently sponsoring a detailed study which may culminate in detailed design standards for large volume utility wastes. In the interim period, states will likely continue to be the primary agencies issuing waste disposal permits. It is

anticipated that these permits will be modified versions of permits currently issued by the states, since many states are currently revising their existing programs to comply with RCRA requirements. Therefore, in general, the state agencies will continue to be the principal forces in determining whether or not a site is acceptable. The role of the EPA in the permitting of waste disposal facilities will be (1) to oversee the state permitting programs where state authorization has been granted and, (2) to issue the federal permits where such delegation has not occurred.

Of the permits required from state agencies, the solid waste disposal permit is potentially the most complicated, time-consuming, and controversial. The level of effort associated with the other required approvals (e.g., for sewage disposal, stream encroachment, highway construction or modification, soil erosion control, leachate or supernatant discharge) is also substantial and must be planned for accordingly. Some states have a coordinated approach to permit issuance from various agencies, while other states have a number of permitting authorities operating autonomously.

The level of information required in the permit applications is also quite variable; some states require only general information and conceptual design, while others require specific information and detail design. Actual utility experience in selecting sites and obtaining the various permits is depicted in Appendix C.

Regarding the local regulatory system, it should be pointed out that zoning maps can be obtained from the local planner's office. Local officials will likely prefer that sites be developed in areas currently zoned for non-residential use (e.g., heavy and light industrial and unproductive agricultural lands). Areas zoned residential, commercial and recreational should be avoided. In obtaining a zoning variance, proposing an ultimate beneficial use of the disposal area is likely to be advantageous.

Any one permit, federal, state, or local, can result in a disruption of the disposal site development if not properly considered. Therefore, in order to prevent unnecessary, unanticipated delays in plan implementation, it is best to determine the following information early in the planning process:

- number and type of permits required
- type of information to be reviewed by the agencies (e.g., conceptual or detailed design)
- anticipated duration of review period
- possibility of public hearings required as part of the review process

With this background accumulated, the permitting activities can be interfaced with the planning and design effort in the development of a comprehensive implementation schedule.

The strategy of when to bring in the key agency people for a review of the situation varies. No single approach is best in all cases. Some utilities favor open communication with regulatory agencies, bringing them in before the selection process begins, keeping them informed as the work progresses, and making them an integral part of the selection process. Other utilities favor leaving the agencies out of the selection process until they submit the permit applications and attempt to gain key agency approval. Which approach to use is a matter of judgment to be decided based on a knowledge of the individuals and agencies involved and other factors related to the situation.

It will probably be found that, at this time, many regulatory agencies and their personnel are not familiar with FGD wastes to the same extent they are with flyash or municipal refuse. Therefore, the utility should expect to provide information regarding the physical, chemical, and engineering properties of the waste, including information about leachate quantities and characteristics and the presence or absence of hazardous and toxic substances. The utility may also be expected to provide detailed information about and justification for design concepts and construction specifications.

MINE/QUARRY DISPOSAL

Disposing FGD sludge in mines and quarries represents a special case in site selection. Consideration of mines and quarries as potential disposal sites is limited primarily by transportation logistics. While mines serving mine-mouth plants are apparently the most viable disposal sites, other mines/quarries, abandoned as well as active, within a reasonable proximity to the power plant also merit consideration. The previously described siting criteria should be applied on the evaluation of such candidate sites. In addition, there are benefits and constraints specific to mine/quarry disposal which should be addressed in the evaluation.

The advantages of mine/quarry disposal, as related to the type of mine/quarry, are as follows:

- In the case of returning the sludge to the originating coal mine, routes (truck or rail) are already established for transporting the waste back to the mined-out portions of the mine. Transportation costs can, therefore, be reduced or eliminated. If the

sludge is hauled in empty coal vehicles, deadheading costs can be reduced.

- In all cases, land requirements are reduced. Use of otherwise productive land for waste disposal can be avoided. Land acquisition costs can be reduced.
- At surface mines, the FGD waste could be used for tailings amendment and in land reclamation. Of course, additional amendments such as fertilizers would be required to restore depleted soils to productive use. At active surface mines, mining regulations require re-contouring and reclamation of the disturbed land. The primary cost of disposal is, therefore, the cost of transporting the waste to the mine. Considerable savings could result from not having to develop a separate disposal area.
- In the case of deep mine disposal, proper filling may help control acid mine drainage by reducing oxidation of pyrites and/or reducing groundwater flow through the mine. In addition, the presence of $CaCO_3$ in the waste may tend to neutralize any acid already present.
- If fixed FGD wastes are utilized, deep mine back-filling may help reduce mine subsidence.
- Deep mine filling may also help prevent and/or control mine fires in a manner similar to that already demonstrated with flyash alone.

Problems and constraints to be evaluated when considering mine/quarry disposal include the following:

- The disposal operation must not interfere with or interrupt present or future mining operations. Such concerns may cause mine operators to be reluctant to incorporate waste disposal in their mine planning.
- Mine disposal has the potential for significant environmental impacts, particularly on ground and surface waters. The degree of impact is highly site-dependent being largely a function of sludge characteristics, disposal site geology, soils, hydrology, groundwater quality and pathways to surface waters. Adequate protection measures can be provided but may prove costly and outweigh the other cost advantages.
- For surface mine disposal, the material should be handled as a solid material. The cost of dewatering and/or fixation must, therefore, be considered in the system evaluation.
- If dry materials are shipped by rail, especially if shipped long distances and exposed to the elements, some difficulty in car unloading may result. In fact, it may not be possible to utilize the same cars for sludge handling as are used for coal handling. Similarly, separate trucks may be required for hauling sludge and coal.
- If wet sludge were shipped by rail, tank cars would be required, as well as some means of maintaining the sludge in suspension during transit. These difficulties, as well as the possibility of freezing problems in unloading and the cost of transporting and disposing of the liquor, all combine to make this means of transport unfeasible.

- Probably the most significant cost factor will be transportation. Disposal at a distant mine/quarry site must be justified by balancing the incremental transportation costs against the savings in site acquisition and development costs.
- For wet disposal in deep mines, economical placement, containment, and monitoring may be difficult. The viscosity and settling characteristics of the sludge must be carefully controlled in order to effect suitable disposal. Such disposal is feasible only where the mine and the generating plant are in close proximity.
- For disposal at unreclaimed, inactive surface mines, the available capacity for sludge disposal may be limited by ponded surface runoff that has accummulated in the abandoned strip pits. Such areas would have to be reclaimed at the conclusion of disposal operations and the necessary topsoil may not be readily available.
- For disposal in inactive underground mines, the mine voids may be difficult to locate and utilize for sludge placement due to inadequate mine maps and the unknown extent of caving.

The mine/quarry disposal concept has received consideration in a number of instances, but application has been limited. At the Milton R. Young Plant, a mine-mouth plant near Bismarck, North Dakota, FGD sludge is co-disposed in adjacent surface mines with bottom ash and flyash. At this site vacuum-filtered sludge is hauled by off-road trucks to mine pits where the lignite has been removed. After disposal of the sludge and ash, reclamation of the mined-out areas continues, with replacement of overburden, followed by subsoil, topsoil, mulching and seeding.

Recent research in this area has generated results which should be useful in considering mine/quarry disposal. In an EPA-sponsored program, A.D. Little, Inc. is evaluating the technical, environmental, and economic factors associated with mine disposal of FGD wastes through various laboratory and pilot-scale investigations. From an initial assessment, FGD sludge disposed in active coal mines was found to be promising (3). The mining categories which are expected to offer the greatest potential are:

- Active Interior and Western surface coal mines.
- Active Eastern and Interior room-and-pillar underground coal mines - particularly those above the water table.

Jones reports that Interior surface coal mines appear more favorable then Western surface-area coal mines (4). Interior and Western surface mines considered are much more favorable than Eastern surface contour mines, due to the latter having low FGD sludge capacity and waste placement being difficult. Western surface-area mines are less desirable than Interior surface-area mines because they may present

a greater groundwater contamination potential. In addition, most Western plants burn alkaline-ash coal which can result in greater concentrations of dissolved solids.

Eastern and Interior room-and-pillar coal mines were also found to be favorable. Those portions which have been mined out may be bulkheaded and filled with FGD sludge by pumping it down from the surface through boreholes in the mine roof. However, problems concerning viscosity and settling characteristics must be resolved in advance in order to optimize the operation.

In a current research project sponsored by the Bureau of Mines, Michael Baker, Jr., Inc. is evaluating the feasibility of disposing coal related wastes, including FGD sludge, in active underground coal mines located adjacent to power plants. The primary method being evaluated is the disposal of cemented backfill for the purpose of minimizing or eliminating mine subsidence.

In a separate study, Michael Baker, Jr., Inc. investigated the feasibility of underground coal mine drainage abatement and subsidence control using FGD wastes. In this study it was found that fixed or unfixed FGD sludges are generally compatible with an acidic deep mine environment and are capable of abating acid mine drainage. Further, mine subsidence control was found to be generally feasible by backfilling mines with fixed sludges (5).

In summary, mine/quarry disposal is a potentially viable concept which should be evaluated on a case-by-case basis. Based on limited full-scale demonstrations and available research, it appears that this concept will see greater application in the future.

OCEAN DISPOSAL

Because of the large proportion of the U.S. population located near the oceans, the possibility of ocean disposal of scrubber sludge from coastal power plants seems worthy of appraisal. The primary advantages of the concept are minimal incremental land use, no disposal site development costs, availability of relatively inexpensive existing transport facilities (barge), and similarity of chemistry between some FGD wastes and sea water.

Currently, there are no power plants utilizing this approach. To evaluate the prospects for full-scale application of this concept, EPA has sponsored a study which

is being conducted by A.D. Little, Inc. This study preliminarily concluded that disposal of soil-like sludges by pipeline or quick-dumping craft is not suitable on the continental shelf because of sedimentation and suspension impacts (3). The following disposal options were considered promising and recommended for further research:

- Dispersed disposal of untreated sulfate-rich sludges on the continental shelf.
- Concentrated disposal of treated brick-like sludges on the continental shelf.
- Concentrated and dispersed disposal of sulfate-rich sludges in the deep ocean.

Research to evaluate this second option has been conducted at the State University of New York at Stonybrook. These studies have been aimed at utilizing blocks of fixated FGD sludge in the construction of artificial reefs which would enhance biological productivity. Phase I of this program, which involved both laboratory research and in situ experiments, has shown that blocks of stabilized sludge retain their integrity and appear to have no significant adverse effects on the marine environment. The results of the pilot-scale testing suggest that the blocks of adequate durability could be fabricated successfully on a full scale basis (6). However, the economic feasibility has not yet been demonstrated. In addition, in view of the ocean dumping regulations promulgated under the Marine Protection, Research, and Sanctuaries Act of 1972, the regulatory acceptability of this disposal alternative appears uncertain at this time.

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Section 7

LEACHATE

PURPOSE

This section explains the origins of leachate which may emanate from FGD disposal areas, describes methods for estimating the expected quantity and quality, and discusses methods for control.

INTRODUCTION

According to a current EPA definition, "Leachate means liquid that has passed through or emerged from solid waste and contains soluble, suspended, or miscible materials removed from such wastes" (1). In FGD sludge, leachate originates as water used in sludge transport, interstitial water, precipitation, surface inflow, or groundwater inflow which has percolated through or permeated a body of sludge/ash. The resultant outflow from the side surfaces or bottom of a landfill or pond may contain soluble or colloidal species which have been removed from the sludge.

Leachate from FGD sludge disposal areas, whether pond or landfill, has been a matter of concern because of the potential for its entering either surface or groundwater. There is concern that the leached species may be deleterious to these waters, which in many cases are ingested by humans and animals and which may affect aquatic life. Pollution of groundwater is of particular concern. In many areas, groundwater is a naturally pure resource which is widely consumed without testing or treatment.

The pathways through which leachate may reach groundwater, and in turn enter water supply sources, are often indirect, difficult to observe, difficult to trace, and even more difficult to correct. Because groundwater moves slowly and with little mixing, groundwater pollution from leachate may not be detected for many years and, once detected and corrected, may continue to persist for long periods. Regulatory agencies, therefore, have been concerned with contamination of groundwaters from leachate. Fortunately, the species present in high concentrations in FGD sludge leachates are not hazardous. The primary concern is with trace elements present in varying concentrations as discussed in the subsections below.

REGULATORY REQUIREMENTS

Leachate and Hazardous Wastes

The primary legal statute relating to FGD sludges is the Resource Conservation and Recovery Act (RCRA) passed on October 21, 1976 (PL 94-580). As discussed in Section 1 - INTRODUCTION, RCRA regulates disposal of solid waste materials, including FGD sludges, with special emphasis on hazardous wastes.

Under RCRA, wastes can be categorized as either hazardous or non-hazardous. One of the criteria used in classifying a waste as hazardous is toxicity. This criteria is applied using EPA's Extraction Procedure (EP), to generate an elutriate from a representative sample of the waste. If the EP elutriate has a concentration of a substance which exceeds 100 times the EPA Interim Primary Drinking Water Standards, then the waste can be classified as hazardous. Table 7-1 shows these standards as well as the Proposed Secondary Drinking Water Standards. It should be pointed out that the May 19, 1980 regulations limited the parameters of concern to arsenic, barium, cadmium, chromium, lead, mercury, selenium, silver, endrin, lindane, methoxychlor, toxaphene, 2,4-D and 2,4,5-TP Silvex (2). As the criteria for identifying hazardous wastes are expanded, additional parameters may be added to this list. The Extraction Procedure is defined in detail in the May 19, 1980 regulations and is presented in summary form in Table 7-2.

It is important to note that FGD sludges and other large volume utility wastes have been specifically excluded from regulation as hazardous wastes. As such, the EP is not required for FGD sludges. However, this test may be used as a method of predicting leachate quality.

Groundwater Protection

With the exemption of FGD sludges from the hazardous waste regulations, these wastes become subject to EPA's non-hazardous waste regulations. These regulations require that a disposal facility must not contaminate an underground drinking water source beyond the solid waste boundary or an alternate boundary set by the state (1). In EPA's definition, a disposal facility "contaminates" groundwater if it causes the concentrations of certain pollutants in the groundwater to either:

- Exceed the maximum contaminant level (based on the primary drinking water standards) specified for that pollutant, or
- Increase at all where the background concentration of the pollutant already exceeds the applicable maximum contaminant level.

Table 7-1

EPA INTERIM PRIMARY AND PROPOSED SECONDARY
DRINKING WATER STANDARDS

PARAMETER	MAXIMUM LEVEL
A. Interim Primary	
Arsenic	0.05 mg/1
Barium	1.0 mg/1
Cadmium	0.01 mg/1
Chromium (VI)	0.05 mg/1
Fluoride	1.4 to 2.4 mg/1
Lead	0.05 mg/1
Mercury	0.002 mg/1
Nitrate (as N)	10 mg/1
Selenium	0.01 mg/1
Silver	0.05 mg/1
Endrin	0.002 mg/1
Lindane	0.004 mg/1
Methoxychlor	0.1 mg/1
Toxyphene	0.005 mg/1
2,4-D	0.01 mg/1
2,4,5-TP Silvex	0.01 mg/1
Radium	5 pCi/1
Gross Alpha	15 pCi/1
Gross Beta	4 millirem/yr
Turbidity	1 TU
Coliform Bacteria	1/100 ml
B. Secondary	
Chloride	250 mg/1
Copper	1 mg/1
Foaming Agents	0.5 mg/1
Hydrogen Sulfide	0.05 mg/1
Iron	0.3 mg/1
Manganese	0.05 mg/1
Sulfate	250 mg/1
Total Dissolved Solids	500 mg/1
Zinc	5 mg/1
Color	15 Color Units
Corrosivity	Non-corrosive
Odor	3 Threshold Odor Number
pH	6.5 to 8.5

Table 7-2

EPA EXTRACTION PROCEDURE
May 19, 1980

Equipment

1 - An agitator which while preventing stratification of sample and extraction fluid, also insures that all sample surfaces are continuously brought into contact with well-mixed extraction fluid.

2 - Equipment suitable for maintaining the pH of the extraction medium at a selected value.

Procedure

1 - Weigh a representative sample of the waste to be tested. Separate the sample into liquid and solid phases by filtration through 0.45 micron filter membrane. Refrigerate the liquid for further use.

2 - Grind the solid material, if necessary to pass through a 9.5 mm (3/8") standard sieve.

3 - The solid material plus 16 times its weight in deionized water is added to an extraction apparatus. The pH of the solution is then adjusted to pH 5.0 $\pm$ 0.2 using 0.5 N acetic acid. Samples are to be agitated during pH adjustment. No more than 4 ml of acid for each gm of solid are added. Once 4 ml of acid per gm have been added, complete the 24 hour extraction without adding any additional acid. Adjust pH of solution at 15, 30, and 60 minute intervals moving to the next longer interval if the pH did not have to be adjusted more than 0.5 pH units.

4 - Samples are to be maintained at room temperature during extraction. Samples are to be agitated for a period of 24 $\pm$ 0.5 hours. Final pH must be above 5.2 unless 4 ml of acid per gram of solid have already been added.

5 - At the end of the 24 hour extraction period, the solution is separated into solid and liquid phases as in Step 1. The resulting liquid phase is adjusted with deionized water to a specified volume. The liquid is combined with the original liquid phase from Step 1. This combined liquid is the Extraction Procedure Extract.

The EPA has defined an underground drinking water source as an aquifer currently supplying drinking water for human consumption or an aquifer in which the concentration of total dissolved solids is less than 10,000 mg/l. A more detailed discussion of the prevailing regulatory requirements is contained in Appendix B.

LEACHATE QUALITY

The primary question is: "What are the chemical characteristics of the leachate from FGD sludges and will this leachate be deleterious to water uses?"

Applicable Standards

There are two basic sets of criteria against which to judge the deleterious quality of leachate from FGD sludges:

1. Drinking Water Standards (3)
    a. Interim primary standards (health related)
    b. Proposed secondary standards
2. Irrigation Water (4)
    a. Short term use (under 20 yr)
    b. Continuous use (over 20 yr)

Primary drinking water standards are of importance in determining the level of protection required for underground drinking water sources. While not mandated by EPA, secondary standards such as those relating to total dissolved solids, chlorides, and sulfates are important because of the physiological effects such as unpalatable tastes, nausea, and laxative effects which they can cause.

Comparison to irrigation standards is also appropriate because groundwater is used extensively for irrigation purposes. Irrigation water limits which include agriculture, pasture, turf/landscape, and livestock watering uses, were prepared by the National Academy of Science and Engineering for the EPA (4).

Typical Values

As might be expected, leachate quality varies considerably as a function of all the various plant and scrubber system parameters mentioned previously (see section 3 - WASTE COMPOSITION). Measurements of the range of concentrations reported for the various major and minor constituents are shown in Tables 7-3 and 7-4, respectively. It should be noted that the values used in this comparative analysis represent the initial concentrations that would seep from the base of an untreated sludge pond or

landfill. As discussed in subsequent subsections, these concentrations can be expected to be reduced as time progresses. In effect, they represent a first flush or worst-case condition. In these tables, elutriate denotes water that has contacted and moved through the waste material.

Comparison to Drinking Water Standards

Table 7-5 lists observed ranges for the relevant species in scrubber liquors and elutriates; drinking water standards also are listed. Note that in every case except turbidity, the lower end of the range of concentration of constituents in sludge liquors is well below the maximum allowable level for the primary drinking water standards. Note also that except for lead and selenium, the upper end of the range of concentrations does not equal or exceed 100 times the maximum allowable level (which is the May 19, 1980 guideline used by the EPA for its extraction procedure). It should not be inferred from this that all FGD sludges should automatically be considered toxic under the EPA definition. Further analysis of the data shown indicates that only occasional values of these constituents exceed 100 times the drinking water standards (5,6). Although trace elements are not eliminated as a matter of concern for some sites, the indication is that, in most cases, the concentrations are quite low. These data indicate that the determination of whether a particular sludge is toxic under the EPA definition must be made on a case-by-case basis.

Examination of the secondary drinking water standards shown in Table 7-5 shows that chloride, sulfate, and total dissolved solids concentrations in leachates are nearly always well above the specified standards. The pH and other constituents are of concern only in some cases.

Comparison to Irrigation Water Standards

Table 7-6 lists observed ranges for concentrations of constitutents in FGD sludge liquors and elutriates; irrigation water standards also are listed. From the data given, the constituents fall into three categories:

1. Those which are consistently below the long-term maximum allowable level. The elements in this group are:

   Aluminum
   Arsenic
   Lead.

Table 7-3

RANGE OF CONCENTRATION OF MAJOR SPECIES IN FGD SLUDGE LIQUORS AND ELUTRIATES

SPECIES	AEROSPACE[a]				USEPA[b]	ALL SOURCES
	EASTERN COAL		WESTERN COAL			
	RANGE, mg/l	MEDIAN, mg/l	RANGE, mg/l	MEDIAN, mg/l	RANGE, mg/l	RANGE, mg/l
Alkalinity, as $CaCO_3$	--	--	--	--	41 to 150	41 to 150
Calcium	470 to 2,600	700	420 to ~45,000[d]	720	520. to 3,000	420 to ~45,000[d]
COD	--	--	--	--	60. to 390.	60 to 390
Chloride	470 to 5,000	2,300	1,700 to 43,000[d]	--	--	470 to 43,000[d]
Magnesium	--	--	--	--	3.0 to 2,750	3.0 to 2,750
pH	7.1 to 12.8	--	2.8 to 10.2	--	3.04 to 10.7	2.8 to 12.8
Potassium	--	--	--	--	5.9 to 32	5.9 to 32
Sodium	36 to 20,000[c]	118	1,650 to ~9,000[c]	--	14.0 to 2,400	14.0 to 20,000[c]
Sulfite	--	--	--	--	0.8 to 3,500	0.8 to 3,500
Sulfate	720 to 30,000[c]	2,100	2,100 to 18,500[c]	3,700	720 to 10,000	720 to 30,000[c]
TDS	2,500 to 70,000[c]	7,000	5,000 to 95,000[d]	12,000	3,200 to 15,000	2,500 to 95,000[c,d]
Conductance, mho/cm	--	--	--	--	0.003 to 0.015	0.003 to 0.015
Turbidity, JTU	--	--	--	--	<3 to <10	<3 to <10

[a]Source: Rossoff, J. and Rossi, R. C., Disposal of By-Products from Non-Regenerable FGD Systems: Initial Report, Aerospace Corporation, EPA 650/2-7-37a, May, 1974.

[b]Source: Bornstein, et al., Re-Use of Power Plant Desulfurization Waste Water, EPA 600/2-76-024, USEPA, Corvallis, OR, February, 1976.

[c]The highest levels shown reflect single measurements on an unwashed double-alkali filter cake.

[d]Levels of soluble chloride components in sludges are dependent upon the chloride-to-sulfite ratio in the coal. The highest levels shown are single measurements for a western limestone scrubbing system.

Table 7-4

RANGE OF CONCENTRATION OF TRACE ELEMENTS IN FGD SLUDGE LIQUORS AND ELUTRIATES

SPECIES	RADIAN CORPORATION[a]		AEROSPACE[b]		AEROSPACE[b]		USEPA[c]	ALL SOURCES
			EASTERN COAL		WESTERN COAL			
	RANGE, mg/l	MEAN, mg/l	RANGE, mg/l	MEDIAN, mg/l	RANGE, mg/l	MEDIAN, mg/l	RANGE, mg/l	RANGE, mg/l
Aluminum	--	--	--	--	--	--	0.03 to 0.3	0.03 to 0.3
Antimony	0.09 to 2.9	0.2	0.46 to 1.6	1.2	0.09 to 0.22	0.16	0.09 to 2.3	0.09 to 2.9
Arsenic	0.004 to 0.3	0.009	< 0.004 to 1.8	0.02	<0.004 to 0.2	0.009	<0.004 to 0.3	<0.004 to 0.3
Barium	--	--	--	--	--	--	--	--
Beryllium	0.0006 to 0.14	0.013	< 0.0005 to 0.05	0.014	0.0006 to 0.14	0.013	<0.002 to 0.14	<0.0005 to 0.14
Boron	0.9 to 46	--[d]	41	41	8.0	8.0	8.0 to 46	0.9 to 46
Cadmium	0.002 to 0.044	0.032	0.004 to 0.1	0.023	0.011 to 0.044	0.032	0.004 to 0.11	0.002 to 0.11
Chromium	0.005 to 0.4	0.08	0.001 to 0.5	0.02	0.024 to 0.4	0.08	0.01 to 0.5	0.001 to 0.5
Cobalt	0.1 to 0.7	--[d]	< 0.002 to 0.1	0.35	0.1 to 0.17	0.14	0.10 to 0.7	<0.002 to 0.7
Copper	0.002 to 0.6	0.20	0.002 to 0.4	0.015	0.002 to 0.6	0.20	<0.002 to 0.2	<0.002 to 0.6
Fluoride	0.7 to 3.0	1.5	1.4 to 70	3.2	0.7 to 3.0	1.5	--	0.7 to 70
Iron	0.02 to 8.1	--[d]	0.02 to 0.1	0.026	0.42 to 8.1	4.3	0.02 to 8.1	0.02 to 8.1
Lead	0.001 to 0.4	0.016	0.002 to 0.55	0.12	0.0014 to 0.37	0.016	0.01 to 0.4	0.001 to 0.55
Lithium	--	--	--	--	--	--	--	--
Manganese	0.007 to 2.5	0.74	< 0.01 to 9.0	0.17	0.007 to 2.5	0.74	0.09 to 2.5	0.007 to 9.0
Mercury	0.0004 to 0.07	<0.01	0.0009 to 0.07	0.001	<0.01 to 0.07	0.01	0.0004 to 0.07	0.0004 to 0.07
Molybdenum	0.07 to 6.3	--[d]	5.3	5.3	0.91	0.91	0.91 to 6.3	0.07 to 6.3
Nickle	0.005 to 1.5	0.09	0.03 to 0.91	0.13	0.005 to 1.5	0.09	0.05 to 1.5	0.005 to 1.5
Selenium	0.001 to 2.2	0.14	0.005 to 2.7	0.11	<0.001 to 2.2	0.143	<0.001 to 2.2	<0.001 to 2.7
Silver	0.005 to 0.6	--[d]	--	--	--	--	0.005 to 0.6	0.005 to 0.6
Tin	3.1 to 3.5	--[d]	--	--	--	--	3.1 to 3.5	3.1 to 3.5
Uranium	--	--[d]	--	--	--	--	--	--
Vanadium	0.001 to 0.67	--[d]	--	--	--	--	0.001 to 0.67	0.001 to 0.67
Zinc	0.03 to 2.0	0.18	0.01 to 27	0.046	0.028 to 0.88	0.18	0.01 to 0.35	0.01 to 27

[a]Source: Jones, B. F., et al., Evaluation of the Physical Stability and Leachability of Flue Gas Cleaning Wastes, Radian Corporation, EPRI FP 671, Volume 2, 1978,

[b]Source: Rossoff, J. and Rossi, R. C., Disposal of By-Products from Non-Regenerable FGD Systems: Initial Report, Aerospace Corporation, EPA 650/2-7-37a, May, 1977.

[c]Source: Bornstein, et al., Re-Use of Power Plant Desulfurization Waste Water, EPA 600/2-76-024, USEPA, Corvallis, OR, February, 1976.

[d]Sufficient data were not available for the meaningful calculation of a mean.

Table 7-5

COMPARISON OF CONSTITUENTS IN FGD SLUDGE LIQUORS AND ELUTRIATES TO DRINKING WATER STANDARDS OF 1975

PARAMETER	MAXIMUM ALLOWABLE LEVEL	RANGE IN SLUDGE LIQUORS
Interim Primary Drinking Water Standards[a]		
Arsenic, mg/l	0.05	< 0.004 to 0.3
Cadmium, mg/l	0.01	0.002 to 0.11
Chromium (VI), mg/l	0.05	0.001 to 0.5
Fluoride, mg/l	1.4 to 2.4	0.7 to 70
Lead, mg/l	0.005	0.0014 to 0.55
Mercury, mg/l	0.002	0.0004 to 0.07
Selenium, mg/l	0.01	< 0.001 to 2.2
Silver, mg/l	0.05	0.005 to 0.6
Turbidity, TU	1	< 3 to < 10
Proposed Secondary Drinking Water Standards[b]		
Chloride, mg/l	250	470 to 43,000
Copper, mg/l	1	< 0.002 to 0.6
Iron, mg/l	0.3	0.02 to 8.1
Manganese, mg/l	0.05	0.007 to 9.0
Sulfate, mg/l	250	720 to 30,000
Total Dissolved Solids, mg/l	500	3200 to 95,000
Zinc, mg/l	5	0.01 to 27
pH	6.5 to 8.5	2.8 to 12.8

[a]Other parameters considered in the primary drinking water standards besides those listed include: barium, nitrate, endrin, lindane, methoxychlor, toxaphene, 2,4-D, 2,4,5-TP, Silvex, radium, gross alpha, gross beta, and coliform bacteria. These parameters are either not relevant to FGD sludges or no data are available at present.

[b]Other parameters considered in the proposed secondary drinking water standards besides those listed include: foaming agents, hydrogen sulfide, color, corrosivity, and odor. These parameters are either not relevant to FGD sludges or no data are available at present.

Table 7-6

COMPARISON OF CONSTITUENTS IN FGD SLUDGE LIQUORS AND ELUTRIATES TO IRRIGATION WATER STANDARDS

PARAMETER (mg/l)	LONG-TERM MAXIMUM ALLOWABLE LEVEL	SHORT-TERM MAXIMUM ALLOWABLE LEVEL	RANGE IN SLUDGE LIQUORS
Aluminum	5.0	20.0	0.03 to 0.3
Arsenic	2.0	10.0	<0.004 to 0.3
Beryllium	0.1	0.5	<0.0005 to 0.14
Boron	0.75	2.0	0.9 to 46
Cadmium	0.01	0.05	0.002 to 0.11
Chromium	0.1	1.0	0.001 to 0.5
Cobalt	0.05	5.0	<0.002 to 0.7
Copper	0.2	5.0	<0.002 to 0.6
Fluorine	2	15	0.7 to 70
Iron	5	20	0.02 to 8.1
Lead	5	10	0.0014 to 0.55
Manganese	0.2	10	0.007 to 9.0
Molybdenum	0.01	0.05	0.07 to 6.3
Nickel	0.2	2	0.005 to 1.5
Selenium	0.02	--	<0.001 to 2.2

2. Those which may be greater than the long-term maximum but are below the short-term maximum. These elements are:

    Beryllium
    Chromium
    Cobalt
    Copper
    Iron
    Manganese
    Nickel.

3. Those which may be greater than the short-term maximum. These are:

    Boron
    Cadmium
    Fluoride
    Molybdenum
    Selenium.

Only those in the last category should be of significant concern. However, the same rationale applies to comparison of leachate compositions to irrigation standards as was expressed for the drinking water standards. The elements named cannot be expected to exceed the irrigation standards in every case.

PREDICTING LEACHATE QUALITY

Predicting leachate quality is important for several reasons. Prediction allows the utility to determine the potential for adverse environmental impact. It allows a determination of compliance with existing regulations. It is instrumental to the permitting process for a new power plant. It is instrumental to the selection and preparation of the disposal site, the necessity of a liner, chemical stabilization, leachate collection system, and/or the design of a groundwater monitoring system. Accurate prediction is important as substantial capital investment and future revenues are involved. Future liabilities resulting from the contamination of groundwaster can result in very expensive mitigation measures.

In order to predict leachate quality of FGD scrubber sludge from either a new coal-fired power plant or an existing one, one first needs to understand the important factors or variables affecting leachate quality. What are these variables and how do they impact the leachate quality? Next one needs to identify the alternatives for predicting leachate quality. In what situations are they applicable? What are the advantages, disadvantages, and limitations of the prediction methods? This section will attempt to provide an overview with references provided for more detailed discussions.

Important Variables

It is virtually impossible, a priori, to predict with certainty the composition of the leachate expected to result from an FGD sludge. As discussed in Section 3 - WASTE COMPOSITION, the primary contributors to sludge properties are:

- Reagent--type, quantity, purity
- Upstream flyash removal
- Coal characteristics
- Water--quantity and quality
- Extent of oxidation

These same factors also affect the properties of leachate that may result from sludge ponds or landfills. Some generalizations can be made in regard to the major constituents, but prediction of trace elements is not possible by present methods.

Reagent. The reagent, whether lime, limestone or double alkali, affects the leachate in several ways:

- Unreacted lime in thickeners or ponds will increase the pH of the leachate, thus affecting the solubility of major and trace species. Both Theis, et al. (7) and Mahloch, et al. (8) report that the concentrations of cadmium, lead, nickel, copper and zinc decrease as the pH increases from the 5-6 range typical of limestone scrubbers to a pH of 8-9, more typical of the lime scrubbers.
- Limestone scrubbers normally operate at a lower pH than lime scrubbers and therefore have a predominance of sulfate over sulfite. The solubility of calcium sulfate dihydrate (gypsum) is relatively unaffected by pH changes while that of calcium sulfite decreases significantly with pH increases. And, as noted in Section 3 - WASTE COMPOSITION, sulfate and sulfite sludges differ greatly in physical properties.
- Soluble sodium salts in the double-alkali process can be sent to waste in the filter cake. The high concentrations of sodium will increase the ionic strength thus affecting the solubility of many of the slightly soluble or immiscible chemical compounds, both major and trace. Significantly higher concentrations of sulfate are seen because of the complexing (ion-pairing) of dissolved sodium and sulfate.
- Both lime and limestone can contribute magnesium to the sludge. Magnesium will form a soluble complex (ion pair) with the sulfate, thus increasing the magnesium and sulfate concentration in the leachate.
- Finally, many minor and trace species present in the reagent may be dissolved and eventually enter the leachate.

Coal Characteristics. Coal characteristics are a major factor in leachate quality, both as the source of fly ash and as the source of volatilized elements. The volatile elements, primarily chlorine, lead, bromine, fluoride, selenium, and sulfur, will be scrubbed from the flue gas and included in the FGD sludge waste. Mercury, although volatile, is not significantly scrubbed.

Trace elements contained in the fly ash entrained in the flue gas will also be scrubbed and will affect the leachate quality. This effect will be dominating if no upstream fly ash removal is used in the air pollution control system. Even with upstream particulate control equipment such as electrostatic precipitators, baghouses and cyclones, fine particulates escape collection and enter the SO_2 scrubber system. The partition tendencies of trace elements found in the coal is summarized in Table 7-7 along with additional references.

Fly ash. Fly ash is the major source of trace elements in FGD sludge leachates when no upstream particulate removal occurs or the dry fly ash is blended with the scrubber sludge prior to disposal. It is also a significant source and can be the major source even with upstream removal especially with older, less efficient particulate removal equipment including cyclone and some electrostatic precipitators. With several trace elements, enrichment mechanisms are responsible for the higher concentrations of the trace element which are found in the fine particulate escaping collection in the precipitator. In most studies those elements which were reported to undergo enrichment in the smaller particulates of emitted flue gas include antimony, arsenic, bromium, copper, cadmium, chromium, chlorine, fluorine, gallium, iodine, lead, mercury, molybdenum, selenium, sulfur, and zinc (9,10,11,12,13,14,15,16,17,18, and 19). However, not all of the elements enriched in the fly ash will be sufficiently soluble to be found in either the scrubber liquor or leachate.

In the case of most western coals, fly ash is a major source of alkali-metals. This sodium and potassium, in addition to many of the trace elements associated with the scrubbed fly ash, will be present in soluble form in the liquor and will reach the sludge only in occluded water. As such, they will be found in the first few pore volume displacements and not thereafter. A pore volume is defined as the volume of fluid required to fill the pore space in a solid material. The more soluble major constitutents will also be among the early species displaced.

Table 7-7

TENDENCIES FOR VARIOUS ELEMENTS TO BE
PREFERENTIALLY CONCENTRATED IN COAL COMBUSTION RESIDUES

Group I Elements Concentrated Approximately Equally in Bottom Ash and Fly Ash						
Al	Ce	Fe	La	Rb	Sm	Th
Ba	Co	Hf	Mg	Sc	Sr	Ti
Ca	Eu	K	Mn	Si	Ta	

Group II Elements Preferentially Concentrated in the Fly Ash		
As	Ga	Sb
Be	Mo	Se
Cd	Pb	S
Cu		Zn

Group III Elements Tending to be Discharged to Atmosphere as Vapors	
Hg	Cl
S	Br

Source: Rossoff, J., et al., Disposal of By-Products from Non-regenerable Flue Gas Desulfurization Systems: Second Progress Report,: Aerospace Corporation, EPA 600/77-77-052.

Radian Corporation, Coal-Fired Power Plant Trace Element Study, 4 vols., Austin, TX, September 1974.

Water. Water, as the scrubbing medium and liquid component of the sludge, has a major effect on leachate properties. The quality of make-up water will be important in view of the large number of cycles of concentration, as high as 50 in some cases. The water which adheres to the sludge when it is discarded determines the quantity and type of dissolved solids in the first few pore volumes displaced from a pond or landfill.

Time Variability

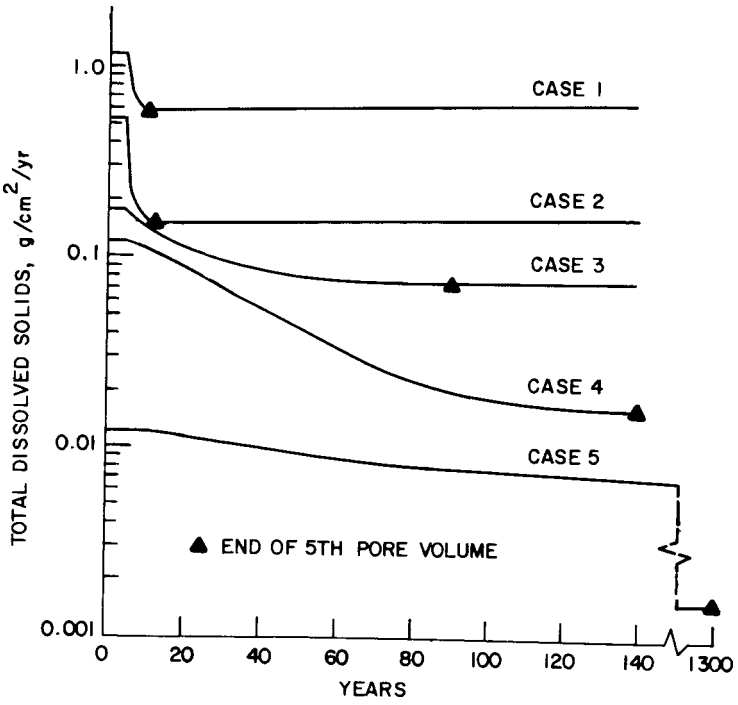
Leachate from laboratory tests with unfixed FGD sludge show total dissolved solids concentrations in leachate approximating those in the scrubber liquor which was retained in the sludge at the time of disposal. This liquor is displaced by infiltrating water, with the result that the interstitial liquor becomes more diluted with time. After about five pore volume displacements (PVD), the leachate TDS will have dropped to a stable level controlled by the solubility of major species, primarily gypsum. Thereafter, the concentration of the major ions, calcium and sulfate, will remain relatively constant in the leachate.

Figure 7-1 shows the mass loading of TDS expected to reach the subsoil after various periods of time. This shows the effect of treatment on sludge which is ponded with and without standing water and of treatment on sludge in a well-managed landfill. The data indicate that chemical treatment reduces the TDS in all cases, but that proper management of the area is more important. This is especially true in Case 5 where landfill of treated sludge extends the five PVD to an estimated 1300 yr (20). Table 7-8 shows the changes in the quality of leachate from treated and untreated sludge after 50 PVD.

In the simplest sense, the process of leachate release from scrubber sludges should be considered as occurring in two phases:

1. Displacement of interstitial or occluded liquor
2. Solubilization of sludge solids.

The first of these will contain the high concentrations of TDS normally found in scrubber liquors. Depending on the quantity of dilution water and the rapidity of PVD, the concentrations of the various species can vary widely and unpredictably.



Sludge Disposal Modes

Case 1 - Ponded, untreated, standing water
Case 2 - Ponded, treated, standing water
Case 3 - Ponded, untreated, no standing water, graded with landscape
Case 4 - Ponded, treated, no standing water, graded with landscape
Case 5 - Treated landfill, 10% of normal recharge by maximizing runoff

Figure 7-1. Mass Loading of TDS to Subsoil for Various Disposal Modes of Treated and Untreated FGC Wastes.

Source: Rossoff, J., et al., Disposal of By-Products from Non-Regenerable Flue Gas Desulfurization Systems: Second Progress Report, Aerospace Corporation, EPA 600/7-77-052.

Table 7-8

CHEMICAL CONSTITUENTS IN LEACHATE FROM
UNTREATED AND CHEMICALLY TREATED FGD WASTE AFTER
1 and 50 PORE VOLUME DISPLACEMENT CONCENTRATIONS IN mg/l

CHEMICAL CONSTITUENT	UNTREATED WASTE		TREATED WASTE	
	1st PVD	50th PVD	1st PVD	50th PVD
Arsenic	0.02	0.004	0.015	< 0.004
Beryllium	0.01	< 0.004	0.008	< 0.002
Cadmium	0.015	0.002	0.02	0.002
Chromium	0.045	< 0.003	0.06	0.003
Calcium	0.045	0.010	0.025	0.005
Lead	0.25	0.010	0.15	0.03
Mercury	0.0005	< 0.00005	0.0007	0.0002
Selenium	0.055	0.006	0.040	0.008
Zinc	0.65	0.04	0.27	0.03
Chloride	2600	100	600	75
Fluoride	4.0	0.8	1.1	0.4
Sulfite	50	30	35	20
Sulfate	6500 **	1200	3500	450
Total Dissolved Solids	10,000 **	2200	6000	1000
Chemical Oxygen Demand	10	6	7	4
pH	6.6	5.5	6.8	8.0

Source: Rossoff, J., et al., Disposal of By-Products from Non-Regenerable Flue Gas Desulfurization Systems: Second Progress Report, Aerospace Corporation, EPA 600/7-77-052.

** These values may be in error. The 6500 mg/l sulfate concentration is not consistent with a TDS concentration of 10,000 mg/l. This sulfate ion alone represents 9150 mg/l.

Following the first three to five PVD, the dominant factor in predicting leachate quality will be the solubilization of the relatively insoluble sludge components. All throwaway-type sludges will contain some calcium sulfate, which is normally soluble to the extent of about 2,000 mg/l, and this will account for most of the TDS in the second phase. Less than 100 mg/l of sulfite, if present, will be soluble under the pH conditions exiting in disposed sludge.

As shown in Figure 7-1, the time for five PVD has been estimated to vary from under 20 yrs for ponded sludge with standing water to over 1300 yrs for treated sludge in a managed landfill. Such widely varying periods add to the difficulty of predicting leachate quality.

Prediction Methods

If it is not possible to predict expected leachate characteristics from theoretical considerations, how then is it possible to determine what the leachate characteristics will be? Available alternatives are:

1. Assume that your sludge will be similar to that derived from an existing installation employing similar conditions of coal source, boiler type, flyash collection, scrubbing system, and disposal operation to that planned at your installation. Data derived by this method should be considered only a first order estimate. There are always important differences between sites which will make your leachate different from a similar operation elsewhere.
2. Conduct bench-scale and/or pilot testing to simulate actual operating conditions and generate a sludge which approximates that to be expected from the new scrubber. However, simulating a waste material can be very difficult, especially if coal ash is to be included. Generally, waste derived from an existing installation as described above will more closely approximate the leaching characteristics of the expected waste than laboratory produced waste.
3. Laboratory leaching experiments may be conducted on the waste or a simulated waste as in 1. or 2. and the resultant leachate quality compared to state and federal guidelines. A suitable disposal scheme can be planned depending on whether the waste will be designated as toxic or not.
4. All or a combination of the above methods.

Making the effort to determine leachate properties with certainty is well worth the effort. In fact, it is a necessity to plan well ahead for sludge disposal because large volumes of waste are involved and state and federal regulations govern disposal. The waste disposal method chosen affects many factors of plant operation, including scrubber design and particulate collection.

Leachate Tests

In evaluating the leachability of FGD scrubber sludges, two distinct concepts can be used. The batch leaching process is a relatively quick, inexpensive, and simple test which is highly reproducible within a single laboratory and can be easily standardized. The second concept, that of column leaching and some sequential batch leaching, makes use of much more intensive and sophisticated studies of the solid leaching characteristics.

The standardized batch tests such as EPA's EP test, procedures currently under consideration by ASTM, and many of the standardized tests use test parameters that are not necessarily specific for the particular type of solid residue being evaluated nor indicative of actual conditions of the disposal site. Nonstandardized simple batch leaching tests can, if properly designed and interpreted, provide initial screening and give an indication of leaching characteristics of the solid. The intensive study is designed to determine the leaching characteristics of a particular solid residue in an unique disposal situation. Testing conditions can be selected to provide a more realistic, applicable and appropriate leaching environment for evaluating the FGD scrubber waste.

There are a number of chemical and physical parameters which affect the leachability of FGD wastes when using batch leaching procedures. The chemical parameters are associated with the type of extracting solution used, and include:

- pH
- complexation
- ionic strength
- redox potential

The physical parameters which affect the leachability of the solid waste are associated with sample preparation and the extraction procedure. These variables include:

- sample preparation (grinding, drying, filtration)
- solids content of FGD scrubber sludge
- the relationship of mass of leached solid with volume of leachate
- contact time between leaching phase with scrubber sludge solids
- method of solid-liquid separation
- method of agitation, i.e., mixing between solid and liquid phases (batch tests only)
- sequential (secondary) versus single step extraction (batch tests only)

The pH of the extracting phase is one of the more important parameters controlling the quantity of a given element extracted from the solid phase. The pH strongly influences the solubility of many of the trace elements, and it may also determine the surface charge of the solid substrate, which in turn influences subsequent sorption of trace elements to the available surface of the residual solid particles. The pH of many of standardized procedures including EPA's EP test and others, are maintained or buffered at a fixed pH which may or may not be representative of actual conditions. The pH of the scrubber sludge will be largely determined by the scrubbing process chosen. The typical limestone throwaway process will produce a pH of approximately 5 to 7. The typical lime throwaway process will produce a higher pH of approximately 8 to 9. Deionized or distilled water is a more appropriate eluant with respect to pH than buffered leaching solution.

Possible complexation (or chelation) between ions contained in the extraction or leaching solution and species present in the solid is another important factor. For example, the citrate ion used in the solution A of the California Extraction Procedure is an excellent complexing agent for many metallic elements, which means that the solubility or extractability of ions within the solid waste will be enhanced by the presence of the citrate ions. On the other hand, the deionized water procedure of the Texas Department of Water Resources contains no complexing agent. Any complexing agents found in the leachate medium at a solid waste disposal site would have been derived from previous leaching of the solid waste. The deionized water or a simulated rainfall water would provide a more realistic environment with respect to potential complexation in typical disposal techniques employed for FGD waste.

Ionic strength is another parameter which may have an effect on the leaching tendency of many constituents in utility wastes. At moderate values, an increase in ionic strength will lead to increased solubility of a constituent due to a decrease in the activity coefficient in the liquid phase. However, in the higher ranges of ionic strength an increase in activity coefficient can occur with increasing ionic strength. This would have the effect of reversing the above phenomenon. Also, related common ion effects can be an important controlling influence on constituents which are present in the liquid phase at solubility controlled levels. All of these possible effects illustrate the importance that the ionic atmosphere of the extracting phase can have on leachability. In disposal of utility wastes, ionic strength of the leaching environment will be largely determined by the operation of the scrubber as well as the chemical characteristics of the scrubber liquor. Ionic strength effects will be particularly important with the dual alkali scrubber and when magnesium is used in conjunction with the lime or limestone scrubber.

The oxidation-reduction potential of the extracting phase can exert a significant influence on the leachability of many species. For example, particularly important in this regard are the transition metals which may have more than one positive oxidation state. For such polyvalent species, dissolution is often a function of which solution state exists. For example, an oxidizing atmosphere could lead to the conversion of trivalent chromium to the more soluble and toxic hexavalent form. This parameter is typically not controlled with most batch leaching techniques and may or may not be adequately controlled with column leaching studies.

Physical parameters also determine the leachability of the solid waste. For example, certain aspects of sample preparation such as filtration, grinding, and drying are important. Grinding can increase specific surface area and increase the surface area of a given mass of material in contact with the leaching phase. It could also mobilize otherwise encapsulated constituents contained within a nontoxic, insoluble matrix. However, on the benefit side, grinding coupled with sieving can produce a waste material of more uniform particle size distribution allowing for better correlation of surface area with leaching tendency. Grinding which produces a uniform particle size is also conducive to obtaining more reproducible results and obtaining a more representative chemical sample.

The drying of a solid waste prior to extraction may introduce error by changing the chemical phase of a component. For example, the drying of gypsum at temperatures in excess of 60-80°C can result in the conversion of calcium sulfate dihydrate to calcium sulfate hemihydrate or anhydrous calcium sulfate, having different solubilities. Additional risks are associated with the stripping of volatile compounds from the solid waste.

The solid-to-liquid ratio utilized in the batch tests and the volume of eluant percolated through a given mass of solids in a column study can significantly influence the concentration of species in the liquid phase. The very soluble chemical species such as sodium or chloride are not solubility limited, consequently, their concentration will depend upon the mass of solid used and the volume of the water. If the volume of water is increased while keeping mass constant, the concentration will tend to decrease, such that the mass leached is still the same but solution concentration is reduced. On the other hand, species which are limited due to the solubility of some slightly soluble phase will tend to have a constant concentration in the liquid phase no matter what the solid-to-liquid ration. However, at very low solid-to-liquid ratios the solubility limited concentration can be affected by common ion effects and solution non-ideality. The solid-to-liquid ratio typically found in

utility solid waste landfills is 2:1 on a weight basis. A typical solid-to-liquid ratio for ponded sludge with no recycle is 1:3. With recycle, the solid-to-liquid ratio can be increased to approximately 1:1. The batch extraction procedure chosen to screen utility waste should use a solid-to-liquid ratio representative of that proposed in the solid waste disposal methodology. The volume of leachate collected in column studies will depend upon such factors as the rainfall infiltration rate, permeability of the wastes, regulation, climate, and disposal site characteristics.

Contact time is important in that it can allow a parameter to reach "steady state" between the solid phase and liquid phase or it can be used to study the release kinetics from the solid phase. The selection of the contact time is often arbitrary. However, the batch test should be long enough to allow species rapidly distributed between solid and liquid to approach steady state, yet short enough to minimize biological growth and provide results in a practical amount of time. Finally, the test duration should be chosen to be as convenient as possible to satisfy schedule and budget constraints. The contact time of the leachate with the solids in the column should be long enough to approach actual disposal conditions but should be short enough to provide meaningful data within the program schedule and budget. The degree of compaction during preparation of the columns and the water head pressure used during leaching are major variables affecting the contact time or residence time of the leaching solution with the sludge in the column. Compaction effort will reduce the voids in the sludge and will decrease the permeability which in turn will increase the contact time.

The agitation technique used in the batch tests should be chosen to maximize solid/liquid contact without causing particle or container abrasion. Agitation is needed to avoid concentration gradients in the leachate in contact with the waste. Reciprocal shaking, wrist-action shaking, or circular shaking are suitable techniques which provide adequate mixing and are gentle enough that they do not promote abrasion.

The method of the solid/liquid separation at the end of each of the leaching periods is important in that inefficiency in separation can result in artificially high numbers for a given element. For example, the use of a filter paper with a medium filtering speed is only efficient at retaining medium size particles above the 5-10 micron range. Unfortunately, many of the fly ash particles and some of the scrubber sludge particles are in the size range less than 5-10 microns. Therefore, the smaller particles which frequently contain higher concentration of trace elements, would not be filtered and would appear in the filtrate and be analyzed as dissolved species. A 0.5 micron or more efficient filter would be more appropriate for evaluating fly ash and scrubber sludge.

A single batch test while providing screening data does not model the effects of time. For example, it does not provide information about how the leachate changes as it moves through a landfill coming in contact with fresh solids nor does it model the effect of fresh water coming into contact with previously leached solids. These types of information can be indicated by sequential batch leaching tests and column studies.

Several reports have been written recently which provide an excellent overview and/or evaluation of batch leaching parameters and tests. These reports include but are not limited to studies by the Mitre Corporation (21) and the University of Wisconsin (22).

Column leaching studies have been conducted by a number of laboratories. The U.S. Army Engineer Waterways Experiment Station has made a number of column tests on various sludges and mixtures, in which the water was allowed to flow by gravity through a column of the sludge or mixture. Samples were collected after once-through flow and analyzed (8). Still a different type of leaching test has been made by the Aerospace Corporation on cores taken from the test ponds at the TVA Shawnee Steam Plant. Water was passed through segments of cores under five psi pressure (23). The same organization has contacted sludge with water under both aerobic and anaerobic conditions. These tests involved as many as 50 PVD (24).

In a companion project (RP 786-2, Task 2) to the preparation of this Manual, Radian Corporation performed a number of leachate tests (25). Two procedures were used: (1) a sequential batch leaching test for high strength relatively impermeable stabilized sludge involving the equilibration of 100 g of crumbled test specimen with 400 ml distilled water for 48 hr and (2) column studies with the low strength and highly permeable FGC sludges. In (1) the slurry was filtered, the solids discarded and the liquid equilibrated with another 100 g of crushed specimen. This procedure was repeated four times. Analysis of the liquid was intended to give worst-case results. In (2) column leaching studies were performed on materials with low strength and relatively high permeabilities. These studies showed that the concentrations of major species decreased within the first three to five pore volumes of displacement. Concentrations after the first five PVD were dictated mainly by the solubility of gypsum. The concentrations of trace metals were within or below the range set by drinking water or irrigation standards. Typical column leaching behavior of major species is shown in Figure 7-2.

In summary, the general advantages of batch leaching tests are: simplicity, ease of performance, low cost, reproducibility, and brief duration of the test. The major

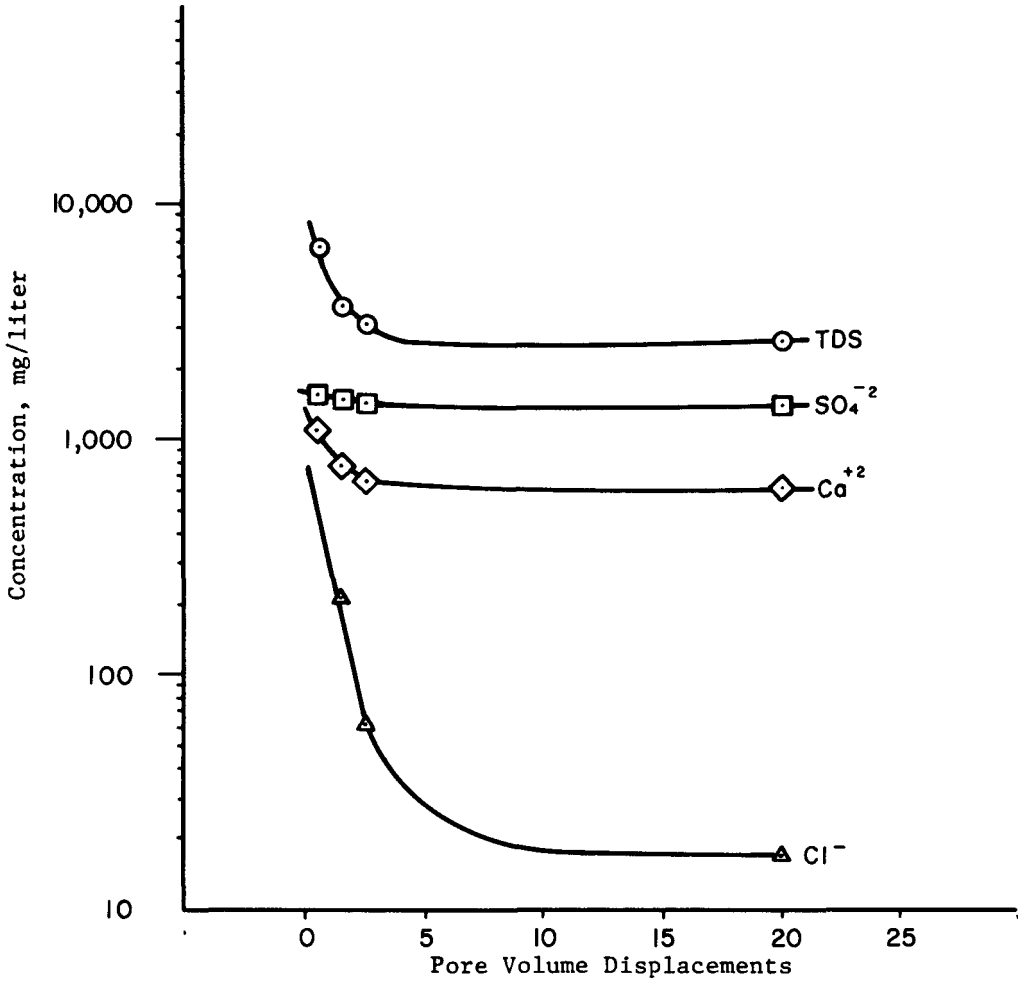


Figure 7-2. Concentration of Major Species in Leachate from Shawnee Forced Oxidized Scrubber Sludge.

disadvantage is that they do not model the dynamic flow regime found in actual disposal conditions. Column studies have an advantage over batch leaching studies in their ability to simulate the flow regime and vertical segregation of materials occurring in an actual landfill or pond disposal site. Laboratory columns can be constructed either to simulate ponding of wastes or landfilling of wastes. However, column studies are subject to the following disadvantages: complexity of operation, expense, interpretive difficulties, poor reproducibility, and lengthy time duration for testing. However, laboratory columns can be operated successfully to provide reproducible and meaningful data on leaching tendencies of solids, and attenuation capacity of various soils or other geologic substrates. However, highly trained personnel with acquired experience in the operation of columns are essential if meaningful data are to be obtained. Consequently, for many laboratories the batch extraction tests are used more successfully to acquire screening data.

LEACHATE QUANTITY

Influencing Factors

Estimating leachate quantity is perhaps the most important step in designing a disposal system. The quality of the leachate may be unimportant if flow of the leachate from the site is greatly restricted. Such a condition would exist if the disposal site is lined, contains low permeability waste, is a graded landfill or if evaporation exceeds precipitation. Finally, if a waste is designated toxic by a regulating agency then the flow of leachate from the site becomes very important.

Factors which are important in determining leachate quantity include

- permeability of the soil under the site as well as permeability of the sludge
- whether the site is a landfill or a pond
- climatic effects
- site design and management practices

Many of these variables will be fixed once the disposal method and site have been selected. The permeability of the FGD sludge can be estimated in the laboratory.

Permeability. Permeability of the sludge as well as that of soils under the disposal site, is probably the most important parameter in determining leachate quantity. Permeability values reported for FGD sludges and for various soils and engineering materials are expressed in standard soil mechanics terminology, defined as the discharge velocity through a unit area under a unit hydraulic gradient. The units of velocity are commonly expressed as centimeters per second (cm/sec) or feet per year (ft/yr). One ft/yr is approximately equal to 1×10^{-6} cm/sec.

Reported permeability values for FGD sludges vary between 10^{-4} to 10^{-7} cm/sec. The range of values reported for soils is considerably greater varying from 30 cm/sec for clean gravels to 10^{-9} cm/sec for some clays. Typical values of permeability for various natural soils are presented in Figure 7-3. The finer particles of the soil are the most important portion with regard to permeability as illustrated in Figure 7-4. Stratification of natural soil deposits can also markedly affect permeability. Many soil deposits are 100 to 1000 times more permeable when parallel to bedding planes rather than perpendicular to them. Stratification of FGD wastes deposited in ponds may also occur with the coarser particles settling nearest the sludge discharge point. If the quantity of leachate generated will be affected by such stratification, adjustments for its influence should be included in seepage estimates.

In addition to stratification of soil or sludge deposits, other factors which can affect the permeability are density, trapped air pockets, and dissolved salt content of the percolating water. Because the measured permeability is sensitive to a number of variables, several tests have been devised to measure permeability, each designed to reflect a specific set of conditions. Only one test method has been standardized by ASTM: D 2434-Permeability of Granular Soils (Constant Head). Unfortunately, this test is best suited for sand, gravel and aggregate and is not generally applicable to FGD sludges and fine-grained soils like silts and clays.

An alternate method for fine-grained materials is the falling head permeability test. Though not standardized by ASTM, the method is commonly used and the test apparatus is commercially available.

The typical apparatus for a falling head permeability test is shown in Figure 7-5. A sample of the material to be tested is placed in the large cylinder at the bottom and a smaller diameter standpipe is attached to the top of the cylinder. The standpipe is filled with water and the drop in water level with time is measured. Knowing the dimensions of the apparatus these data can be used to calculate the permeability of the sample in the cylinder using the equation:

$$\text{Permeability, } K = \frac{2.3aL}{A\,dt} \log_{10} \frac{h_o}{h_1}$$

Where: a = cross-sectional diameter of the top cylinder

L = depth of the soil sample

A = cross-sectional area of soil sample

h_o = height of water in the column at time = 0

h_1 = height of water in the column at end of the measured time period

dt = time taken for water column to decrease from h_o to h_1

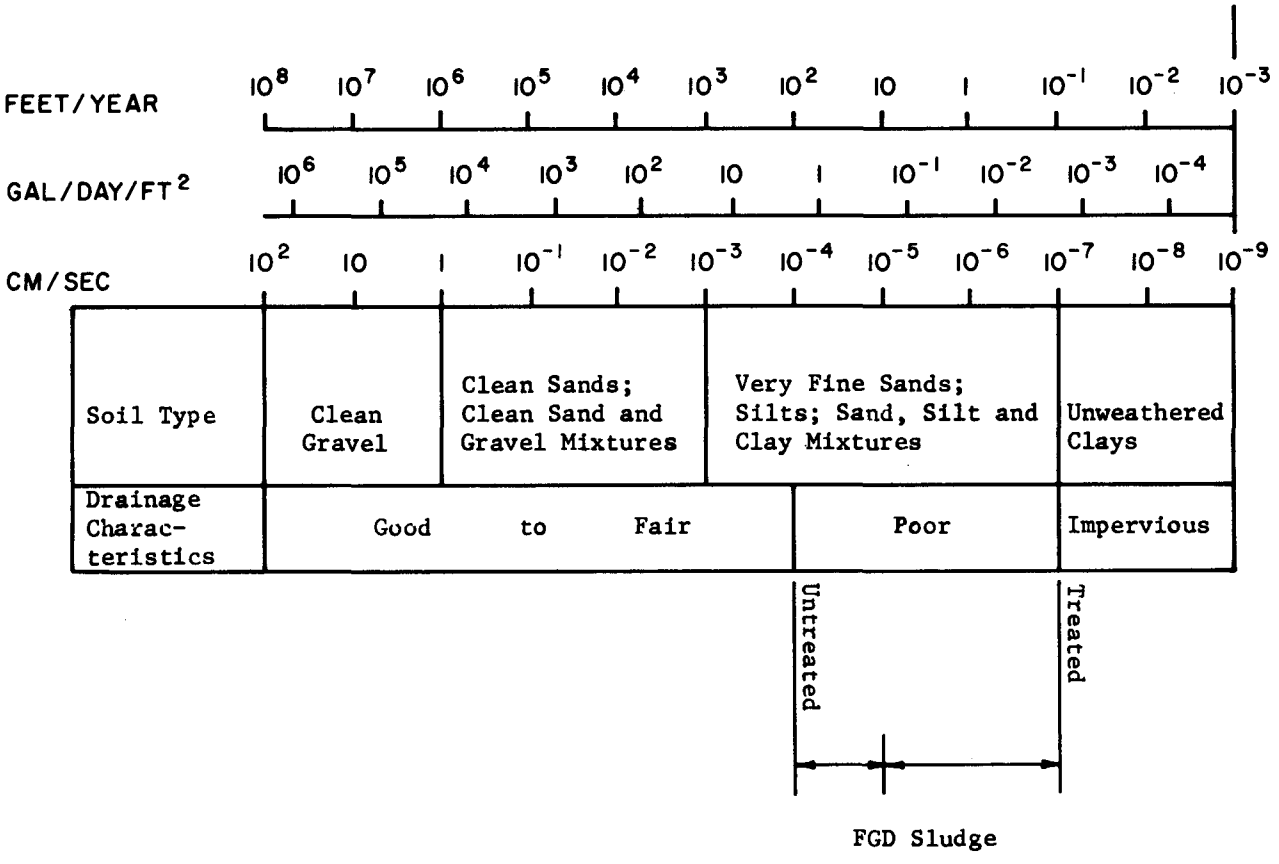


Figure 7-3. Coefficient of Permeability for Different Soil Types at Unit Gradients.

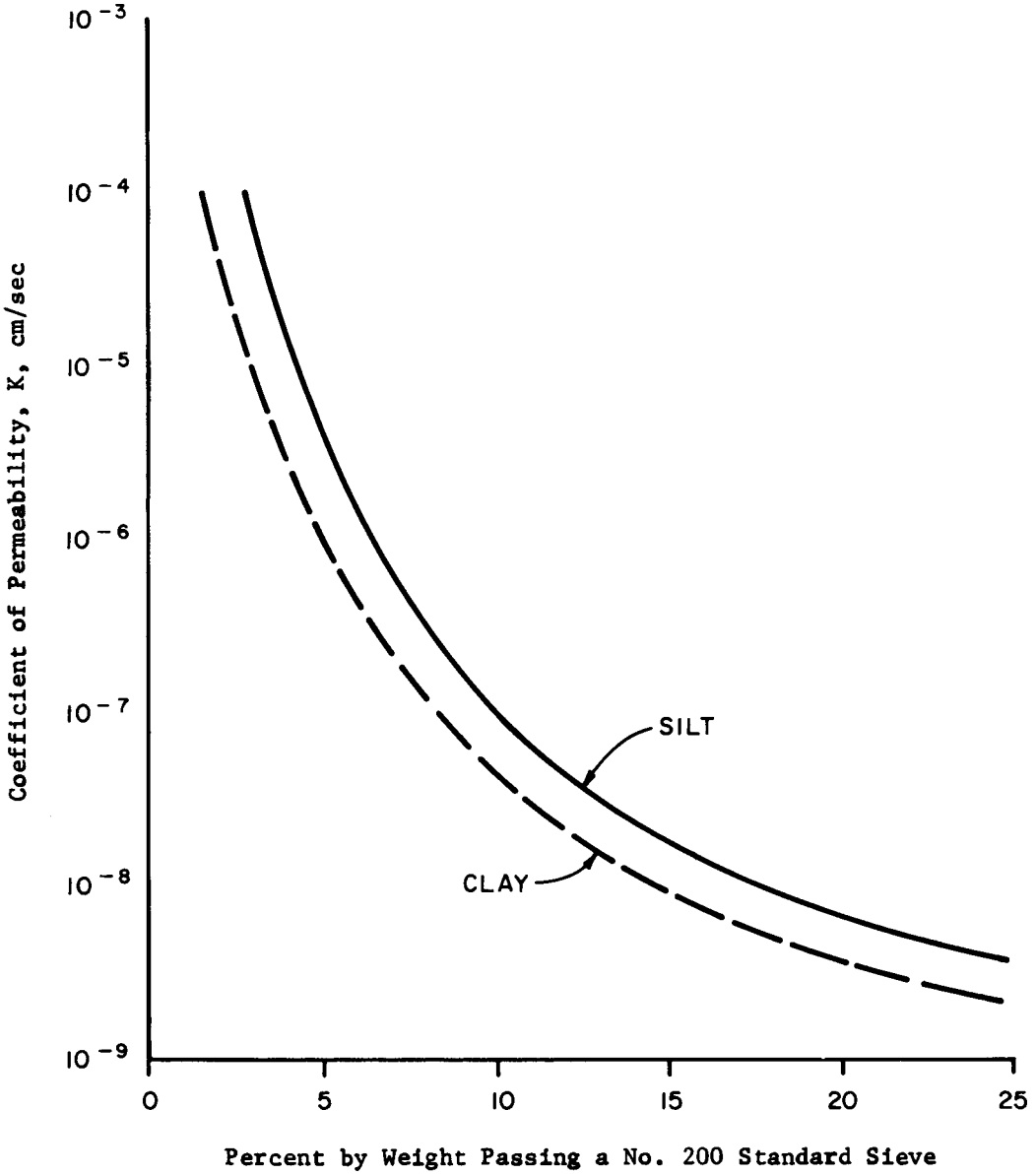


Figure 7-4. Effect of Fine Fraction on Soil Permeability.

Source: Design Manual - Soil Mechanics, Foundations, and Earth Structures, NAVFAC DM-7, March, 1971, Department of the Navy.

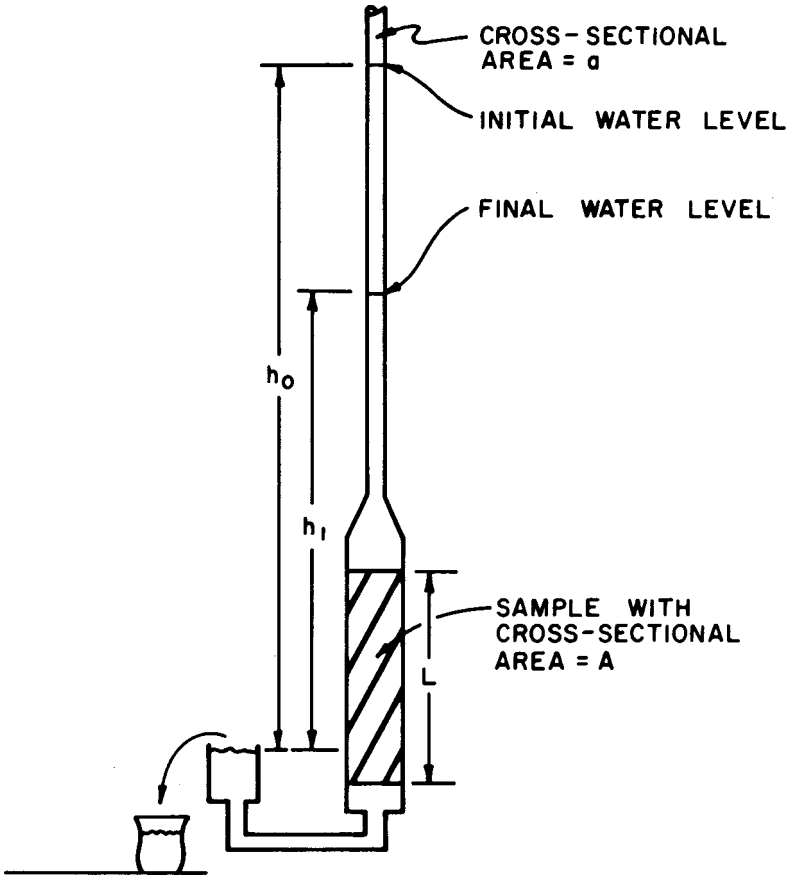


Figure 7-5. Falling Head Permeability Apparatus.

Deaerated, distilled water is commonly used in conducting the test. The water is deaerated to prevent the formation of air bubbles in the pores of the sample. Should bubbles form, they tend to block flow through the sample and give erroneously low permeability readings. Distilled water is used to avoid problems with ion exchange between the soil and the water. Variations in permeability of several hundred cm/sec have been observed between tests using water containing several hundred parts per million of mixed dissolved salts, and distilled water or water containing high concentrations of sodium salts. The reactions are thought to involve calcium and sodium ions. Since both of these species are likely to be present in large quantities in sludge liquors, testing with both distilled water and actual or synthesized sludge liquor may be advisable for design of FGD sludge disposal areas. In fact, since the relative concentrations of sodium and calcium ions change after extended leaching of FGD sludge, tests with simulated long-term leachate may also be warranted.

Permeabilities of sludge mixtures can also be measured using a constant head permeameter. This is especially useful for materials with low permeabilities, because high pressures can be used to force the water through a test specimen. The effluent volume is measured as a function of time. The permeability coefficient is then calculated from the water head, area of the test specimen, height of the test cylinder and time by the following correlation:

$$\text{Permeability, K (cm/sec)} = \frac{\text{volume of water (cm}^3\text{) x height (cm)}}{\text{time (sec) x water head (cm) x area (cm}^2\text{)}}$$

Radian used the apparatus in Figure 7-6 to obtain permeabilities of ash/sludge mixtures ranging from 10^{-5} to 10^{-10} cm/sec (25). To achieve a greater head pressure, pressurized nitrogen was used instead of a constant water head.

As previously noted, the permeability of natural soils may vary considerably in different directions due to stratification of the deposits. Obtaining samples which do not disturb the structure of the soil and will enable accurate determination of the soil permeability by laboratory testing is extremely difficult. Some limitations also result from the difference in size between the sample and the actual soil deposit. Therefore, while laboratory testing may be suitable for sludges and liner materials which will be disturbed during construction or operation of the disposal facility, field testing of site soils is preferred and advisable.

As with laboratory tests, no standardized ASTM method has been developed for field testing of permeability. In fact, a large number of methods have been developed,

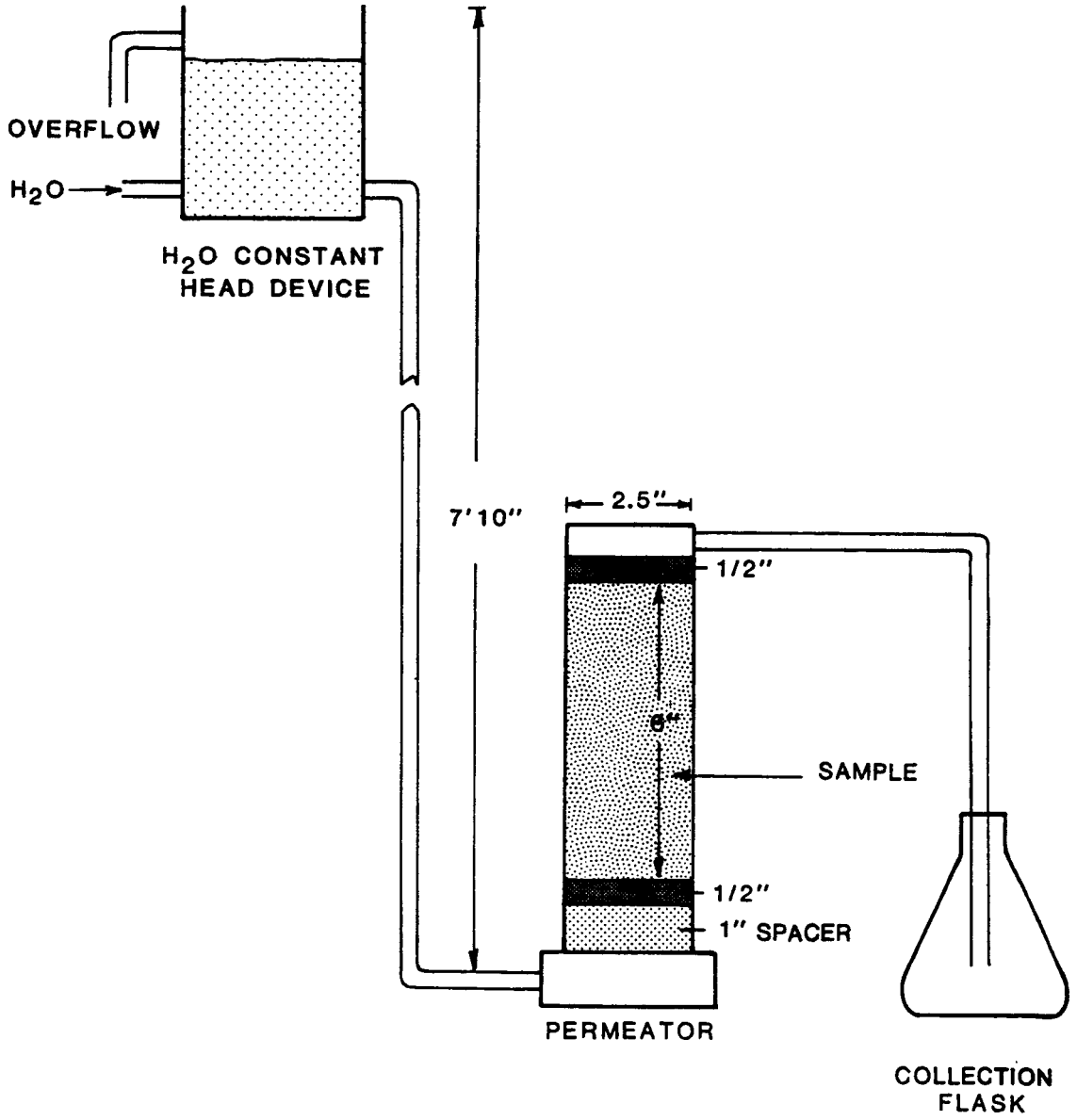


Figure 7-6. Constant Head Permeameter.

Source: Jones, B. F., et al., Chemical/Physical Stability of Flue Gas Cleaning Wastes, EPRI RP-671, Vol. 2, January 1979.

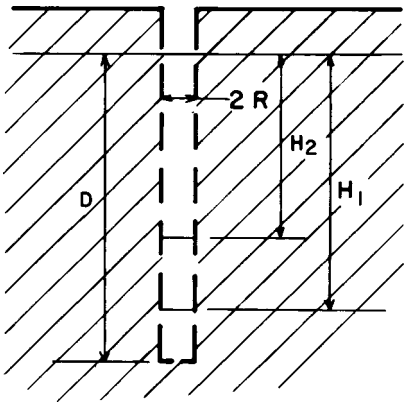
each to reflect a particular set of subsurface conditions. A number of these methods have been developed for use in boreholes, and are suitable for inclusion with other tests during a detailed site investigation. Cedergren gives a detailed description of several methods and references (26). Two simple methods are illustrated in Figure 7-7. A well planned site investigation will include borings so located that they are suitable for determining soil conditions, conducting permeability tests, and serving as monitoring wells by installation of permanent casings.

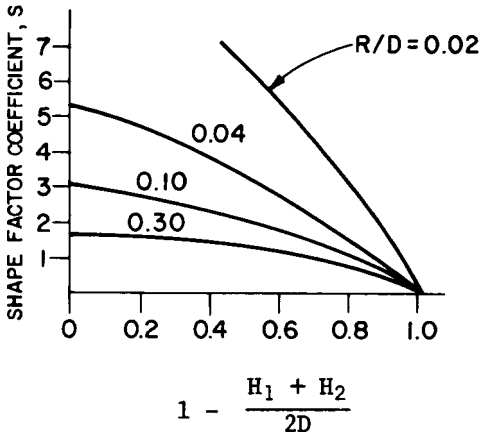
Disposal Method. Another important factor in determining the quantity of leachate generated is whether the sludge will be ponded or landfilled. Other things being equal, a pond will generate considerably more leachate than a landfill. This was pointed out graphically in Figure 7-1. In a pond, the pool of standing water above the sludge serves as a permanent hydraulic head continually forcing leachate through the sludge. In contrast to this situation, water only percolates into a well-constructed and managed landfill during periods of precipitation and snowmelt. The hydraulic head forcing the water into the fill is also less than in the case of a pond since precipitation and snowmelt do not accumulate to any significant depth. Methods of estimating leachate quantities for both ponds and landfills are contained in a subsequent part of this section.

Local Climate. Another major factor influencing the quantity of leachate generated by a disposal site is the local climate. The relative balance of precipitation and evaporation, or evapotranspiration, vary considerably throughout the U.S. as shown in Figure 7-8. The water balance for ponds will depend on the annual average evaporation as well as the precipitation. More detailed information for specific areas can be obtained from the local office of the National Weather Service.

Climatic effects also have a significant impact on long-term planning of disposal areas. As illustrated by Figure 7-8, the eastern U.S. is an area of excess precipitation while in most of the western U.S., evaporation exceeds rainfall. Thus, site closure for ponds in the western part of the U.S. may merely involve allowing the supernatant to evaporate, followed by covering and revegetation. While in the east, provisions for disposing of supernatant, maintaining the site in a drained condition and creating a stable surface may be necessary. Continued monitoring may also be advisable. In general, leachate quantities are likely to be less in the western part of the country due to the reduced amounts of precipitation and excess of evaporation.

Type 1 - Uncased Hole (for $\frac{D}{R}$ <50)





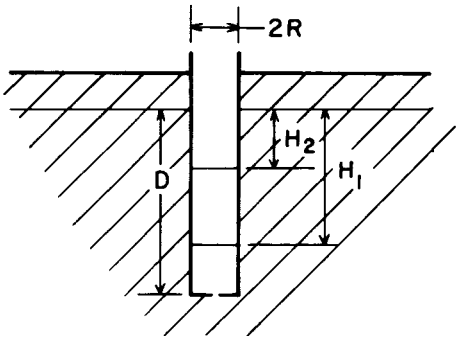
$$\text{Permeability } K = \frac{R}{16DS} \quad \frac{H_2-H_1}{t_2-t_1}$$

NOTE: 1. Hole is bailed to depth H_1 at time t_1; water level is recorded at depth H_2 at time t_2.

2. Values for S from chart above.

3. For homogeneous soils.

Type 2 - Cased Hole (for 6" $\leq$ D $\leq$ 60"



$$\text{Permeability } K = \frac{2\pi R}{11(t_2-t_1)} \ln \frac{H_1}{H_2}$$

NOTE 1. This method is most accurate for situations where the water level is allowed to rise rather than fall.

Figure 7-7. Field Permeability Tests Conducted in Boreholes.

Source: Design Manual - Soil Mechanics, Foundations, and Earth Structures, NAVFAC DM-7, March, 1971, Department of the Navy.

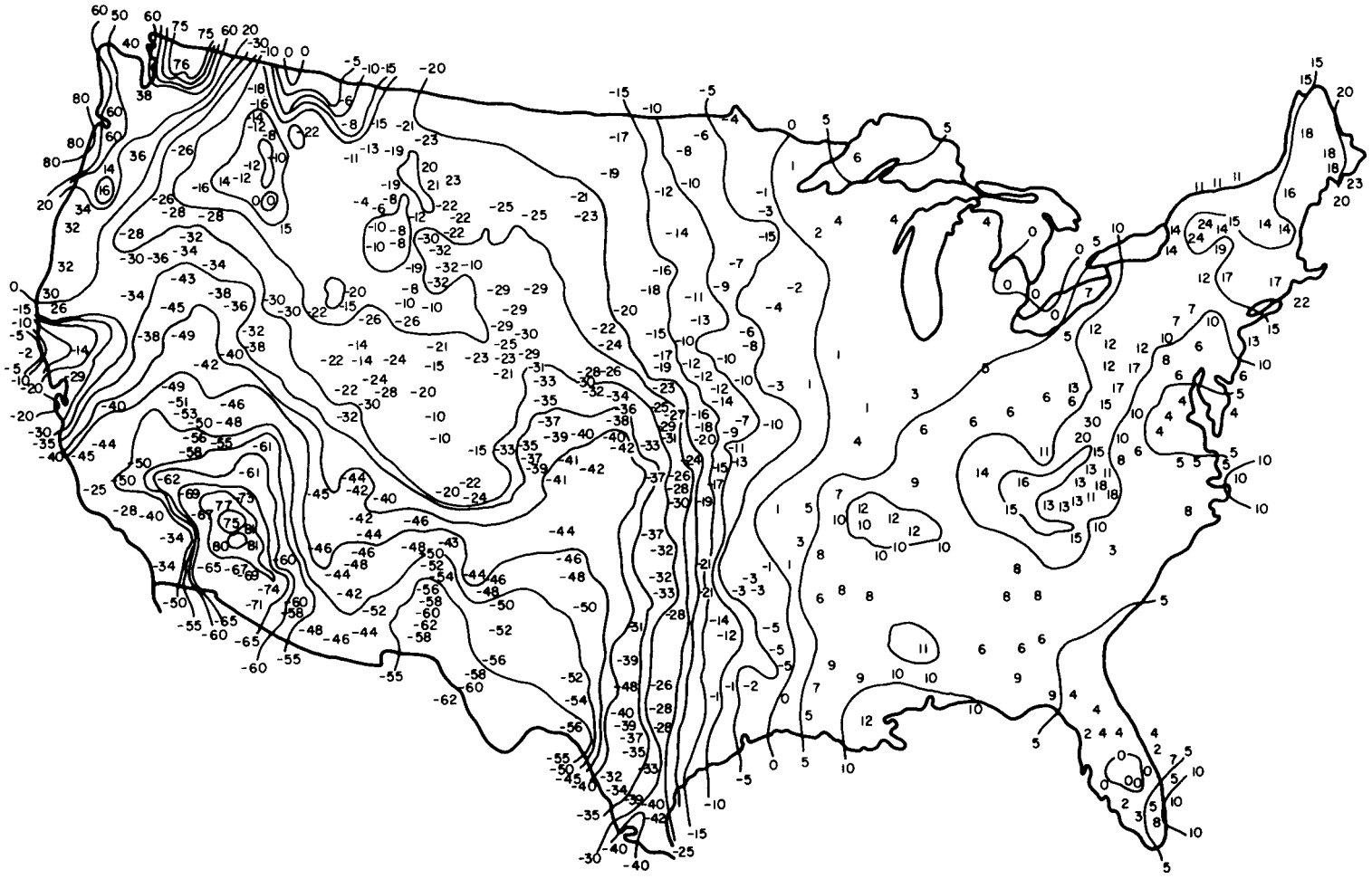


Figure 7-8. Average Net Precipitation in the United States. (Figures represent difference in inches between precipitation and evaporation.)

Source: U. S. Weather Bureau

Site Management. An additional factor influencing the quantity of leachate produced is disposal site management. When construction and operation of the disposal area are planned to maximize runoff and minimize both surface and groundwater infiltration, leachate quantities will be reduced. Details of site design and management are contained in Section 8 - DESIGN OF DISPOSAL AREAS.

PREDICTING LEACHATE QUANTITY

Prediction Methods

Of particular interest in considering any potential problem dealing with leachate from sludge disposal areas, is an estimate of the quantity of leachate that will be generated. Unless the quantity is estimated, the relative effectiveness of various control measures and whether or not their use is justified cannot be determined. In fact, methods of estimating the quantity of water seeping into or out of a pond or landfill is a problem that has received considerable attention. Seepage quantities are an important consideration in the design of reservoirs, dams, irrigation systems, sanitary landfills and infiltration facilities, as well as FGD sludge disposal areas. Field and laboratory tests, physical and mathematical models, and monitoring of actual installations have all been performed with the intent of increasing the accuracy of predictive methods. In spite of all the work which has been devoted to this subject and no matter how sophisticated the method of analysis used, the inability to accurately define the permeability of the site soil affects the accuracy of the results. In many cases, the permeability of the soils at a proposed disposal site are only known within an order of magnitude. If this is the case, the quantity of leachate can only be estimated to within an order of magnitude.

When permeability and other physical factors are only generally known, simple methods of analysis which will give order of magnitude estimates of leachate quantities are satisfactory for defining the magnitude of the potential problem. Analysis at this level of detail is sufficient to determine what control and corrective measures are appropriate. Simple methods of estimating leachate quantities for ponds and landfills are given below. More detailed methods of analysis, suitable when permeabilities and other physical factors are well known, are referenced. It is important to reiterate that for most cases only extensive field and laboratory testing can accurately define the permeability of subsurface soils and the properties of the waste material in the disposal site. For most situations, the accuracy of estimating leachate quantities will depend on the accuracy of permeability estimates, no matter how sophisticated the method of analysis used.

Landfills

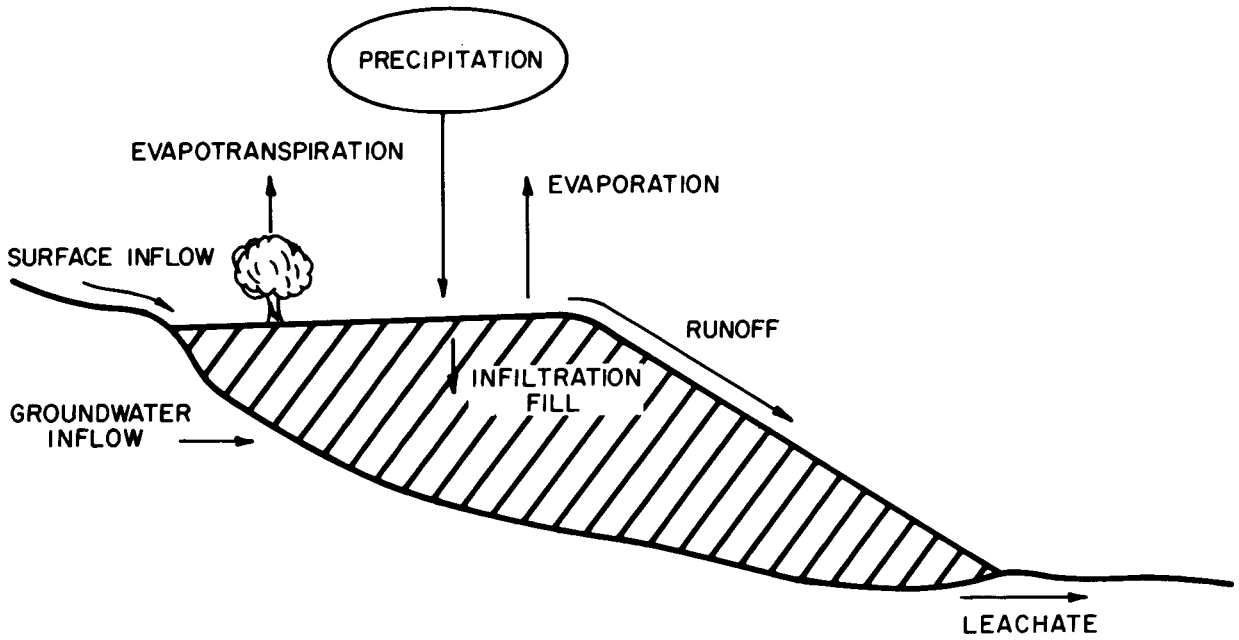
Figure 7-9 shows the water balance for a landfill. Of the precipitation that falls on the site, a portion runs off, some is lost as evaporation or evapotranspiration (loss of water through uptake in vegetation) and the remainder percolates through the fill. Water percolating through the fill will eventually leave as leachate unless it is permanently trapped in the pores of the fill. In some cases, water entering the fill can and will chemically react with the fly ash and/or sludge. Since the amount of pore space in the fill is limited, water that percolates through the fill will eventually leave the fill as leachate, once the pores of the fill are saturated.

The proportion of precipitation which runs off or is evaporated may vary considerably from one site to another, depending on site-specific conditions. Important influencing factors include steepness of slopes, types of vegetation cover, permeability of the surface and subsurface soils, climate variables and disposal site management procedures. A method of computing leachate quantities which considers these variables is contained in a recent ASCE publication (27).

A simpler, although less precise, method of estimating leachate quantities from landfills is to assume that the net infiltration rate is 20% and that the overall permeability of the fill is a limiting condition. These assumptions give a reasonable order of magnitude approximation of leachate quantities and have been used to prepare the curves shown in Figure 7-10. To illustrate the use of Figure 7-10, two cases are examined in the following paragraphs:

In Case A, the annual precipitation rate is 22 in./yr and the permeability of the fill is greater than 3.2 by 10^{-7} cm/sec. In this case, if 20% of the annual precipitation percolates through the fill, average leachate quantity generated will be 300 gal/day/ac.

In Case B, the annual precipitation rate is 40 in./yr and the permeability of the fill is 5×10^{-7} cm/sec. In this case, the total leachate quantity of 450 gal/day/ac is controlled by the permeability of the fill. Therefore, the permeability of the fill is low enough relative to the precipitation rate that the fill will eventually become saturated and reduce the infiltration rate to less than the 20% assumed. An infiltration rate of 20% of the precipitation that falls on the site is a reasonable estimate for many situations. However, the actual rate of infiltration may be more accurately known, particularly if field testing on the site or similar sites has



Precipitation + Surface Inflow + Groundwater Inflow
- Evaporation/Evapotranspiration - Runoff - Leachate = 0

NOTE: Water loss to pores in fill is neglected.

Figure 7-9. Water Balance for Landfill.

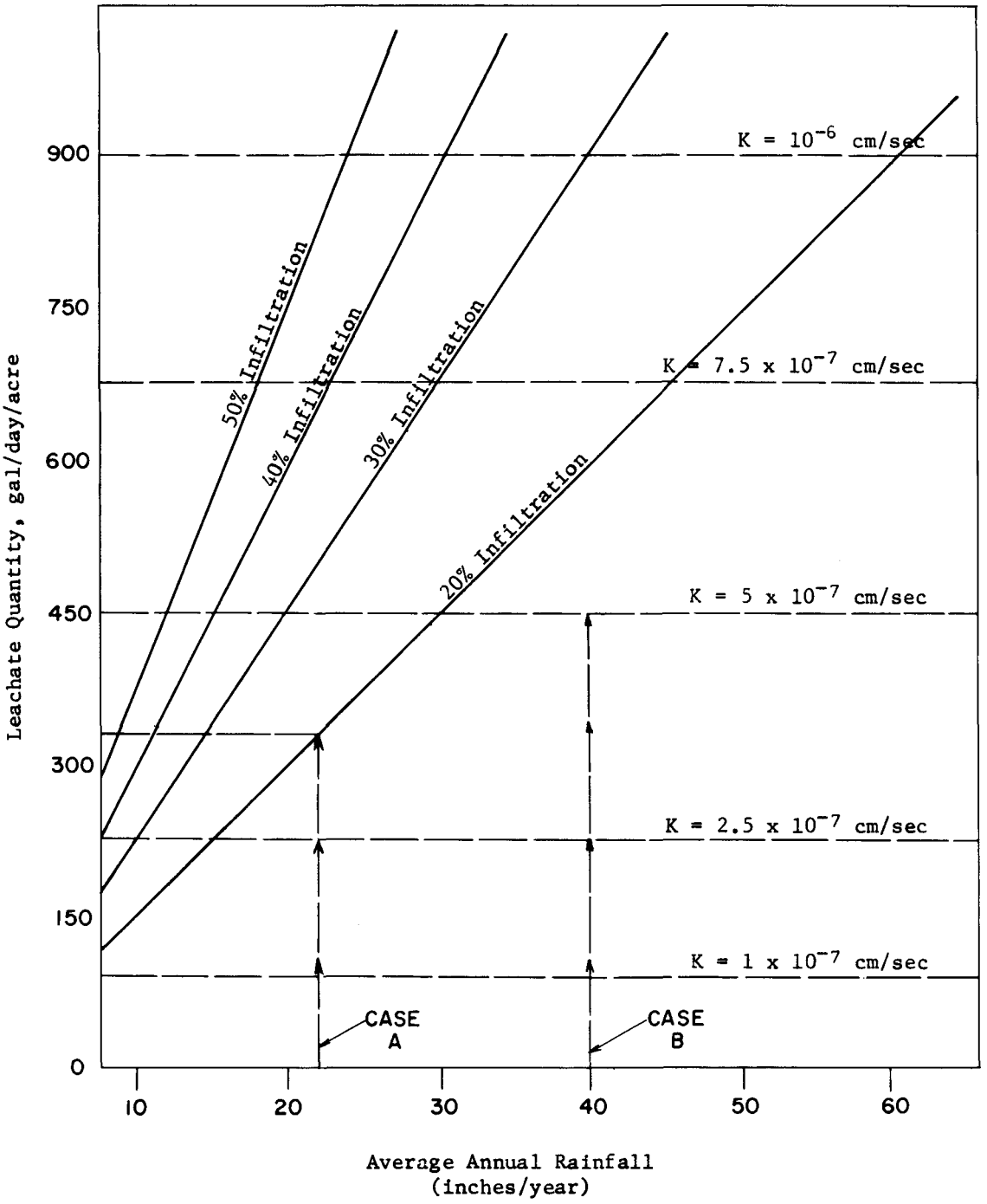


Figure 7-10. Quantity of Leachate from a Landfill

been performed. If such information is available, the limit lines for 30%, 40% and 50% net infiltration shown in Figure 7-10 may be more appropriate.

Examination of Figure 7-10 shows an interesting relationship between precipitation rate, fill permeability and leachate quantity. The majority of the continental U.S. experiences annual precipitation rates between 10 and 60 in./yr. In this range for a net infiltration rate of 20%, the permeability must be reduced to 10^{-7} to 10^{-6} cm/sec., respectively, to control leachate quantities from landfills. For example, if the annual average precipitation rate is 30 in./yr, the permeability of the fill must be reduced to below 5×10^{-7} cm/sec before leachate quantity is reduced. Alternately, for a 20% net infiltration rate, treatment methods which only reduce sludge permeability to 10^{-6} cm/sec are ineffective in reducing leachate quantities from landfills unless the annual precipitation rate exceeds 60 in./yr.

For annual precipitation rates less than 60 in./yr. the quantity of leachate will be controlled by the availability of precipitation and not the permeability of the fill. For 60 in. of annual precipitation and a net infiltration rate of 20%, only when the landfill permeability is reduced below 10^{-6} cm/sec does fill permeability become the controlling factor determining leachate quantity.

Also shown on Figure 7-10, the scale for average annual precipitation is not extended below eight in./yr. At rainfall rates this low, investigations have shown no net infiltration of precipitation (28). This situation is unusual and occurs in only limited areas of the U.S. For very low precipitation rates, up to about 15 in., Figure 7-10 will give somewhat conservative results, overestimating seepage quantities.

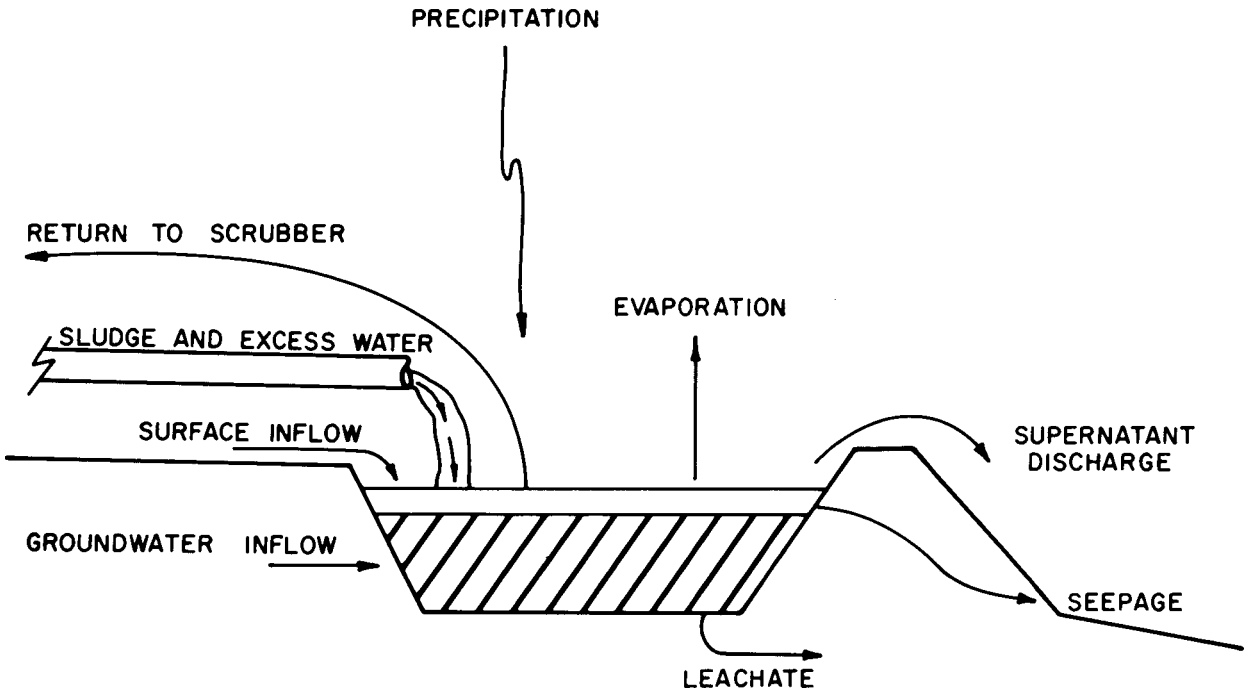
Another assumption inherent in Figure 7-10 is that the permeability of the subsoil exceed that of the fill. Similar conditions would occur if an underdrain system were present at the base of the fill. If the base soil is less permeable than the landfill or if a liner exists, then the flow of leachate from the fill will be retarded. In this case, the quantity of leachate would likely be reduced and some would leave the fill in an uncontrolled manner as seeps along the side slopes. A detailed seepage analysis taking into account the specific configuration of the fill would be required to estimate quantities. Slope stability problems are also likely to result from uncontrolled seepage and should be reviewed. To prevent stability problems and collect leachate, drainage blankets or underdrains are sometimes installed at the base of landfills.

An alternate approach to reducing leachate quantity which may be more effective is to reduce infiltration by placing a zone of low permeability near the top of the fill and reducing the infiltration rate. For example, if the landfill is constructed so that a low permeability layer is placed near the surface, infiltration and downward percolation of water will be controlled by this layer, regardless of the permeability of the remainder of the fill. Thus, a landfill constructed of wastes with a permeability of 10^{-5} cm/sec, but capped with a low permeability layer of 10^{-7} cm/sec material, would generate a quantity of leachate similar to that produced if the entire fill were constructed of low permeability material. Control of water trapped by the low permeability layer, by near-surface drains or some similar approach would be required. Figure 7-10 can also be used to estimate the effectiveness of low permeability layers in reducing precipitation infiltration into landfills.

Ponds. Figure 7-11 shows the water balance for a wet disposal system where the waste is ponded. In wet systems, water is added as excess water used to transport the sludge, as precipitation, as groundwater inflow, and as surface runoff into the pond. Water leaves the system as return water to the scrubbing system, evaporation, supernatant discharge (if permitted) and as seepage. One important distinction between ponds and landfill systems, insofar as leachate is concerned, is the supernatant. With ponds, the supernatant is constantly present to serve as a source of recharge for leachate generation. In landfill systems, recharge occurs only during and immediately following periods of precipitation or snowmelt.

The quantity of seepage from a pond will be influenced by the permeability of the sludge and site soils, the dimensions and configuration of the pond, and the boundary conditions of the entire system. Figure 7-12 can be used to estimate seepage quantities. In this case, it is assumed that since the soil beneath the pond is more permeable than the sludge, the depth of supernatant is small compared to the sludge depth. If the permeability of the soil is less than the sludge or the depth to an impervious layer beneath the pond is not much greater than the pond depth, the seepage quantities will be less than predicted by Figure 7-12. Alternately, if the depth of pond supernatant is significant, seepage quantities will be increased. However, for estimating seepage from sludge ponds without complex subsurface conditions, Figure 7-12 is useful in obtaining an approximate estimate. As shown, if the permeability of the sludge is 10^{-5} cm/sec, the volume of leachate generated is 9000 gal/ac/day.

A method of estimating seepage quantities for cases with more complex boundary conditions than those assumed in Figure 7-12 has been developed (29). This method is



Precipitation + Surface Inflow + Groundwater Inflow + Excess Water
- Evaporation - Leachate - Seepage - Supernatant Discharge - Return Water = 0

Figure 7-11. Water Balance for Disposal Pond.

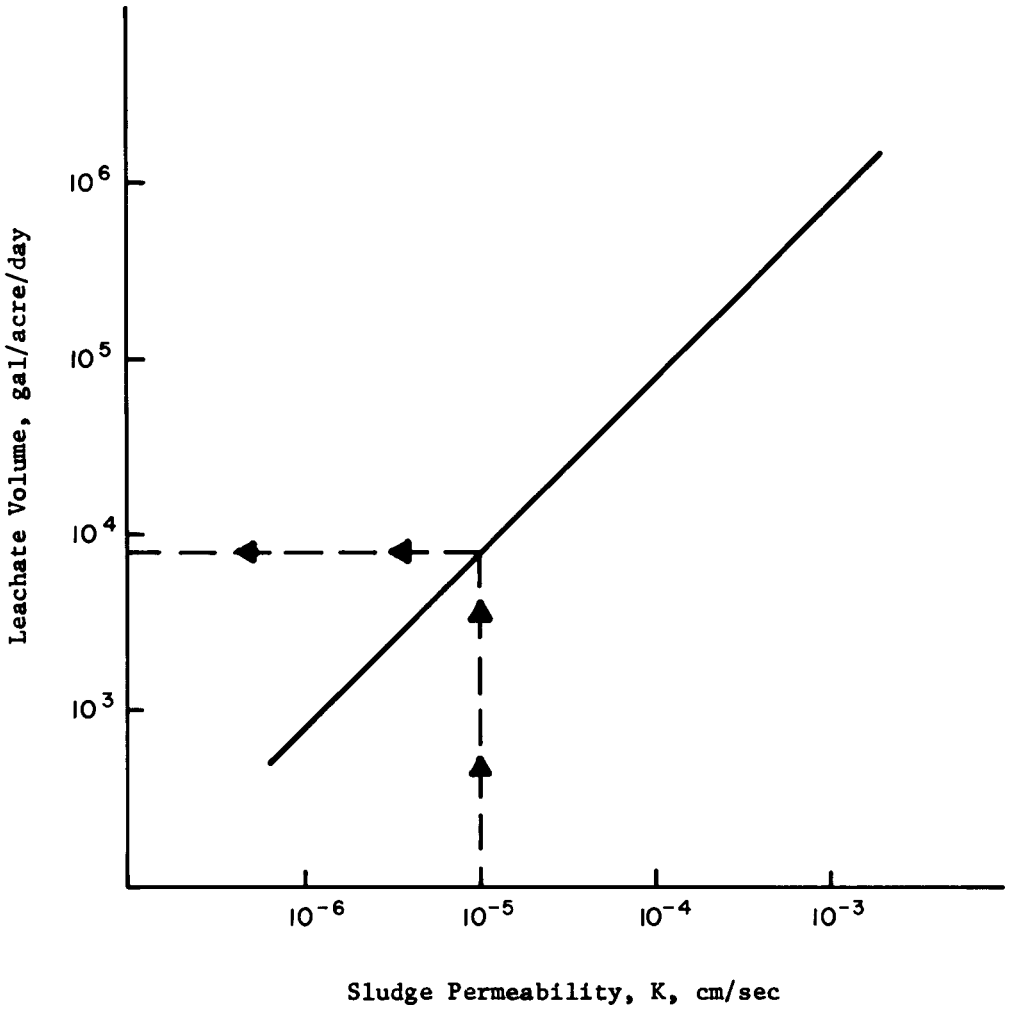


Figure 7-12. Effect of Sludge Permeability on the Volume of Leachate from a Pond.

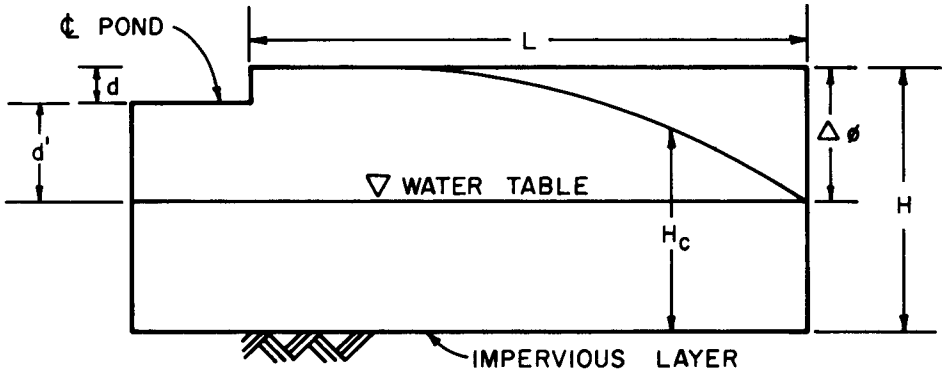
based on seepage studies performed with a finite element computer model which was used to produce the graph in Figure 7-13. As a first step in estimating seepage quantities with this method, it is necessary to know or estimate the following parameters shown in Figure 7-13:

d'	depth to the water table
d	pond depth
H	depth to an impervious layer
L	length of the flow domain
$\Delta\phi$	drop in hydraulic head

The first three parameters are relatively easy to obtain since they can be measured. The last two parameters require some judgment, and are determined by the selection of the flow regime boundary. The drop in hydraulic head, $\Delta\phi$, will equal the difference in elevation between the free water surface in the sludge pond and the elevation of the groundwater table. The depth to the groundwater table can be determined by actual borings or estimated by observation of existing features such as streams, springs, ponds or wells.

The length of the flow regime, L, is more difficult to predict but can be estimated from Figure 7-14. This chart is based on empirical data obtained in field tests of natural soils, and relates the length of the flow regime, L, to the permeability of the subsurface soils. As shown in Figure 7-14, a sandy site soil with a permeability of 10^{-1} cm/sec will have a flow regime of about 1000 ft. This value is for difference in hydraulic head of 10 ft and should be adjusted proportionately for other head differences. Therefore, if the drop in hydraulic head, $\Delta\phi$, is 20 ft, the length of the flow regime would be about 2000 ft for soil with a permeability of 10^{-1} cm/sec.

Two example problems illustrating the use of Figures 7-13 and 7-14 are included in Table 7-9. In Case 1, a small sludge pond 100 ft by 200 ft in plan and 10 ft deep is located on a river floodplain. The pond is underlain by sandy alluvial soils 30 ft deep overlying impervious bedrock. The water table is controlled by the river elevation and is 15 ft below the ground surface. A sketch of the pond and the parameters from Figure 7-13 are included in the example. The length of the flow regime, L, from the pond through the sandy alluvial soils is 1500 ft. Since the distance to the river is less than this value, the drop in hydraulic head on the side of the pond nearest the river will be more abrupt and seepage quantities on this side will be greater. In Step 3 of the example, the total seepage quantity from the pond is calculated. The estimated quantity is compared to Figure 7-12 to see if the estimate is reasonable. Figure 7-12 relates seepage quantity to sludge permeability, and for



Sketch Illustrating Definition of Critical Height, H_c

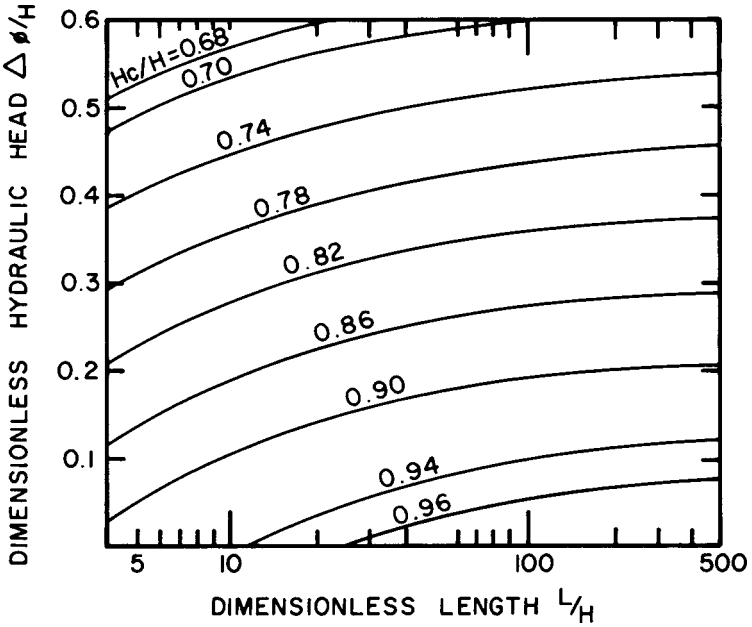


Chart for Estimating Critical Height, H_c/H

Figure 7-13. Factors in Predicting Seepage Rates.

Source: Witherspoon, P. A., and Narasimhan, T. N., "Seepage from Recharge and Landfill Ditches," Specialty Conference on "Agricultural and Urban Considerations in Irrigation and Drainage," April, 1973, Colorado Section of ASCE.

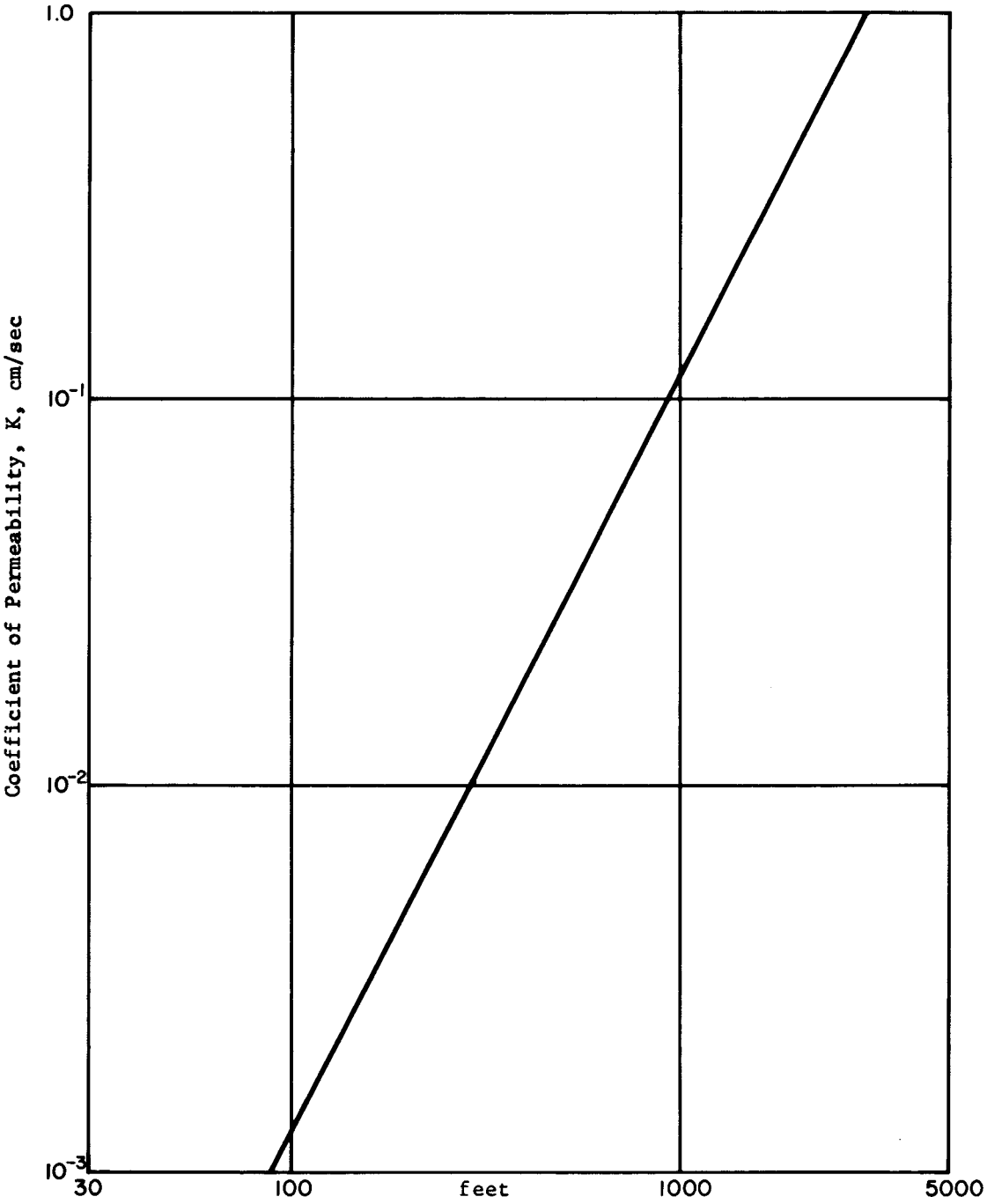
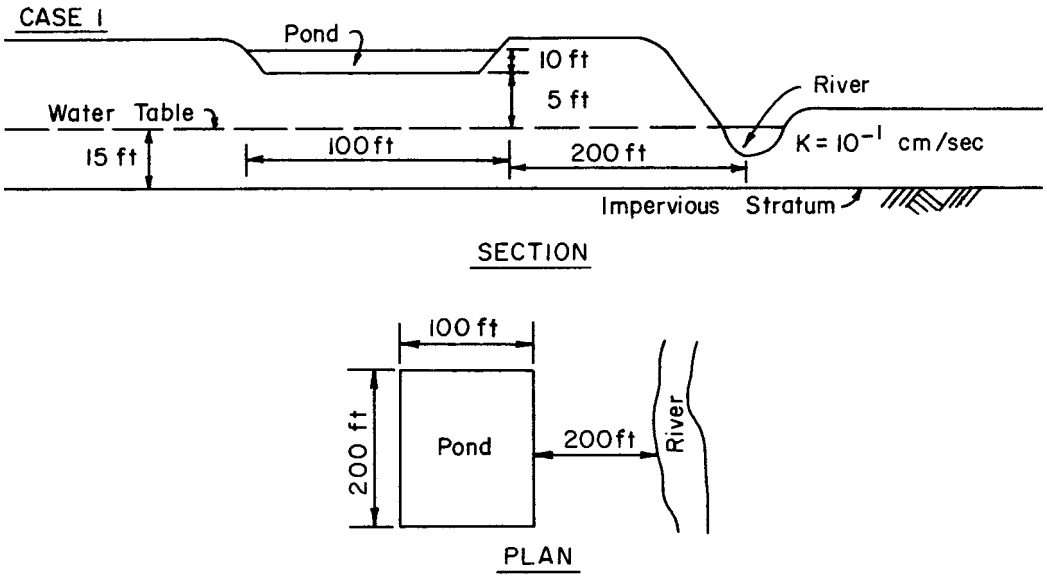


Figure 7-14. Length of Flow Regime, L, for Difference in Hydraulic Head of 10 feet.

Source: Foundation Engineering, Edited by G. A. Leonards, McGraw-Hill Book Company, Inc., New York, NY (1962).

Table 7-9

EXAMPLE CALCULATION OF POND SEEPAGE RATE



CASE 1

Step 1: Parameters as shown in Figure 7-11 and 7-12

$d = 10$ ft

$H = 10$ ft + 15 ft + 5 ft = 30 ft

$L = 1000 \text{ ft} \times \frac{15 \text{ ft}}{10 \text{ ft}} = 1500$ ft

Since the distance to the river is 200 ft, which is less than L, use 200 ft on side nearest river.

$\Delta\phi = 10$ ft + 5 ft = 15 ft

Step 2: $L/H = 1500/30 = 50$

L/H on river side = 200/30 = 6.66

$\Delta\phi/H = 15/30 = 0.5$

$H_c/H = 0.74$ (Figure 11)

H_c/H on river side = 0.70

Table 7-9 (Cont.)

Step 3: Seepage rate, Q, = Flow rate per unit length of perimeter

$Q = KIH_c$

where $I = \Delta\phi/L$

$K = 10^{-1}$ cm/sec = 300 ft/day

$I = 15/1500 = 0.10$

$I = 15/200 = 0.075$ on river side

$Q = 300$ ft/day x 0.010 x 0.74 x 30 x 400 ft (perimeter)

$= 27{,}000$ ft^3/day

Q (on river side) = 300 ft/day x 0.075 x 0.70 x 30 x 200 (perimeter)

$= 96{,}000$ ft^3/day

Total Seepage = 27,000 + 96,000 = 123,000 ft^3/day

$\simeq 1 \times 10^6$ gal/day

Since the pond area is about ½ ac

Seepage rate $\simeq 2 \times 10^6$ gal/day/ac

To determine if this rate is reasonable, from Figure 7-10 a seepage rate of 2×10^6 gal/day/ac corresponds to a sludge permeability of $>10^{-3}$ cm/sec, which is not a reasonable value for sludge. Therefore, the sludge permeability will control. Referring to Figure 7-10, if K is 5×10^{-5} cm/sec, the seepage rate is ~50,000 gal/day/ac. If the sludge permeability were reduced, leachate quantity would be reduced.

CASE 2

Assume the same conditions as in CASE 1, except

$K = 10^{-3}$ cm/sec

Pond side = 1000 ft x 1000 ft

Step 1: d = 10 ft

H = 30 ft

L = 150 ft

Since L is less than the distance to the river, the boundary condition of the river does not control

$\Delta\phi = 15$ ft

Step 2: $L/H = 150/30 = 5.0$

$\Delta\phi/H = 15/30 = 0.5$

$H_c/H \simeq 0.69$ (Figure 11)

Table 7-9 (Cont.)

Step 3: $Q = KI\frac{H_c}{H} \times H$

where $I = \Delta\phi/L = 15/150 = 0.10$

$K = 10^{-3}$ cm/sec = 3 ft/day

Q = 3 ft/day x 0.10 x 0.69 x 30 x 4000 ft (perimeter)

= 24,000 ft^3/day ≃ 200,000 gal/day

Since the pond area is about 25 ac

Seepage rate ≃ 8000 gal/day/ac

From Figure 7-10, the equivalent sludge permeability is about 8×10^{-6} cm/sec. However, even for more permeable sludges, the leachate quantity is not appreciably increased, since it is controlled by site conditions and not by sludge properties.

seepage to equal that predicted in the example, the permeability would have to be greater than 10^{-3} cm/sec. This value is too high for most FGD sludges. Therefore, a more accurate estimate is based on Figure 7-12, indicating that leachate quantity is controlled by sludge permeability. For the case in the example, leachate quantity would be reduced by reducing sludge permeability. This result is often the situation with small ponds and sites with permeable subsoils.

In the second example, Case 2 of Table 7-9, the pond is somewhat larger and the natural soils are less permeable than in Case 1. In Steps 1 and 2, the controlling physical parameters are estimated by Figures 7-13 and 7-14. Because the site soil is less permeable than in the previous case, the length of the flow regime, L, is reduced. In Case 2, the river is no longer within the flow regime and is not a boundary condition. In Step 3, the total leachate quantity is estimated and compared to that predicted by Figure 7-12. In this case, the result is equivalent to that expected from a sludge with a permeability of 5×10^{-6} cm/sec, a reasonable figure for stabilized sludges. However, in this case, the leachate quantity is as predicted by Figures 7-13 and 7-14 and is, therefore, controlled by site geometry and conditions. Therefore, even if the sludge were more permeable, leachate quantities would not be expected to increase substantially.

METHODS OF LEACHATE CONTROL

Exclusion

Exclusion of all water inflow to a disposal area is impossible. As previously stated in this section, the sources of water are:

- sludge transport (sluice water)
- interstitial water
- precipitation
- surface and groundwater inflow

Because of these various sources, only an approach toward exclusion can be made. That is, the contributions from these sources can only be minimized, not eliminated. Ways to minimize water entering the disposed site are discussed below.

Transport Water. Sludge transport water is a factor only in ponding. Therefore, one way to eliminate transport water is to elect dry disposal and keep most of the scrubber bleed at the plant. However, if ponding is preferred, the effects of transport water can be minimized by:

- Reducing the quantity of sluice water by preliminary sludge dewatering at the scrubber plant before pumping the slurry to the pond. This will not only reduce the leachate potential but will reduce the quantity of water to be returned. (See Section 5 - DISPOSAL ALTERNATIVES for further discussion.)
- Keeping the standing water on the ponded sludge at the lowest possible level to reduce the hydraulic head. The greater the head, the higher the driving force will be toward causing leachate flow.
- Providing pond underdrains with return of the seepage to the scrubber system. This will aid in minimizing the pond supernatant and in reducing precipitation effects. A recent EPA report recommends such drains for reducing leachate and adding structural stability to the sludge, thereby aiding in reclamation and eliminating the need for a pond liner (30). On-going EPA programs will evaluate this technique.

Interstitial Water. Interstitial water (sludge liquor) is a factor in both ponding and landfills. Reduction of this water content can favorably affect leachate quality by reducing the quantity of high TDS water that will eventually be displaced from the sludge. Steps that can be taken to reduce the quantity of this water include:

- Dewater the sludge to the maximum possible before disposal. Methods would include the use of thickeners, vacuum filters and centrifuges.
- Chemically treat (fix) the sludge so that the cementitious reactions will involve or encapsulate the water.
- Oxidize the sludge to the sulfate form. The crystalline form of calcium sulfite is such as to hold water and impart a pseudothixotropic nature to the sludge. Oxidizing to the sulfate form would be of significant assistance in dewatering.

Surface and Groundwater Inflow. Surface inflow can affect both ponds and landfills. It can result from precipitation runoff from surrounding areas, uncontrolled surface flow from springs or streams and flood conditions in streams. Means for control are:

- Construct and maintain diversion channels so that the surface water is prevented from flowing on, in or across disposal sites.
- Provide drainage pipes in landfill site preparation to collect and direct existing groundwater discharge points.
- Alter stream channels, if possible, or provide dikes to control any anticipated flood condition.

Fixation/Stabilization

Fixation is of value in leachate control from both ponds and landfills through several mechanisms. As described in Section 12 - FIXATION/STABILIZATION, both commercial

and non-commercial methods of fixation employ cementitious reactions involving alkaline and/or pozzolanic materials. The resulting products have improved disposal properties because some of the sludge constituents are combined into less-soluble types and some of the interstitial water and sludge solids are encapsulated by the cementitious compounds. These effects are illustrated in two ways:

- The data in Figures 7-15 and 7-16 show that the TDS concentration in ponds of fixed material was initially about 1/2 of that of the sludge liquor. Also, as previously shown in Figure 7-1, the expected leachate quality from fixed sludge continues to be greatly improved over that from raw sludge for an indefinite period of time.
- The effects of encapsulation are shown in permeability test results, where untreated sludges and flyash disposed of separately have typical values of 10^{-4} to 10^{-6} cm/sec. Commercially fixed sludge is shown to have values on the order of 10^{-5} to as low as 10^{-7} cm/sec.

Physical stabilization is of advantage in controlling leachate in landfill disposal only. As discussed in Section 12 - FIXATION/STABILIZATION, physical stabilization is a dewatering process in the context of this Manual. The dewatering is accomplished by mechanical means--the use of one or more of thickener, vacuum filter, centrifuge--with or without the addition of dry flyash. Since the solids content is increased to the range of 60 to 80%, leachate control is accomplished in two ways:

- Reduction of the water content leaves less adherent water for displacement after disposal, thus improving leachate quality.
- Reduction in permeability from free draining to approximately 10^{-5} cm/sec represents some improvement.

Attenuation

Attenuation of leached species by the soils beneath ponds and landfills takes place through the natural geochemical processes of:

- ion-exchange
- sorption
- precipitation
- filtration
- dispersion
- dilution

This natural process has received much attention in regard to sanitary landfills (31, 32,33). It has received less attention as applied to FGD sludge landfills, but the mechanisms are much the same. Clays and soils containing hydrated manganese and

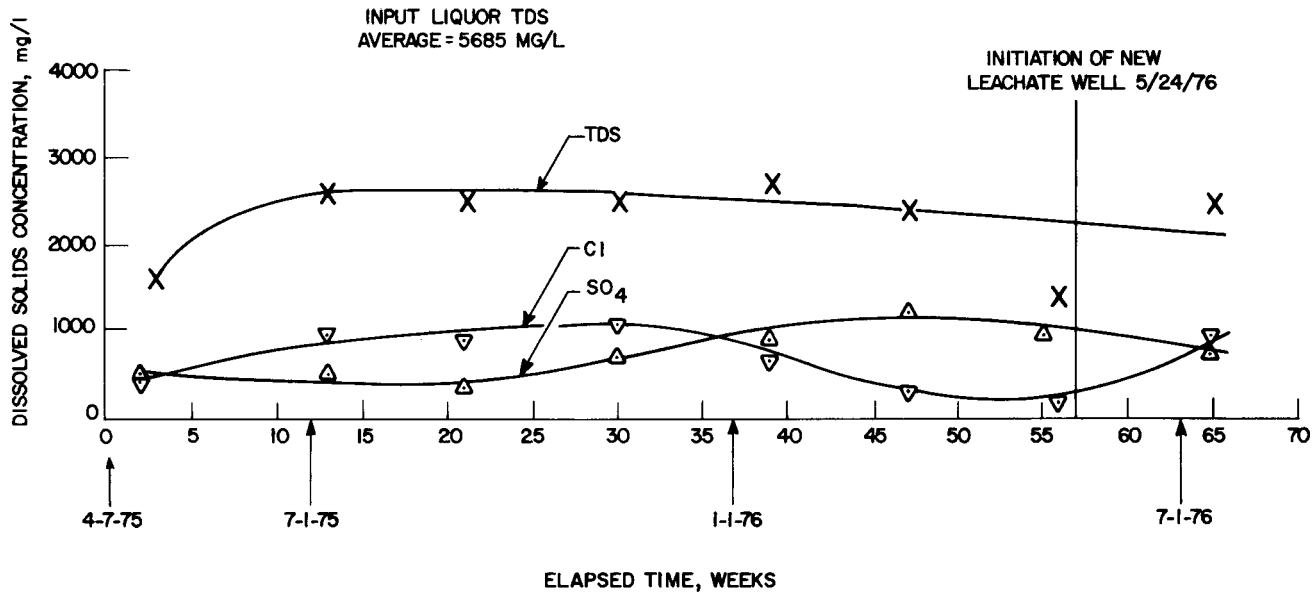


Figure 7-15. Dissolved Solids from Calcilox-Treated Material at TVA Field Test.

Source: Fling, R. B., et al., Disposal of Flue Gas Cleaning Wastes: EPA Shawnee Field Evaluation - Second Annual Report, Aerospace Corporation, EPA 600/7-78-024, February, 1976.

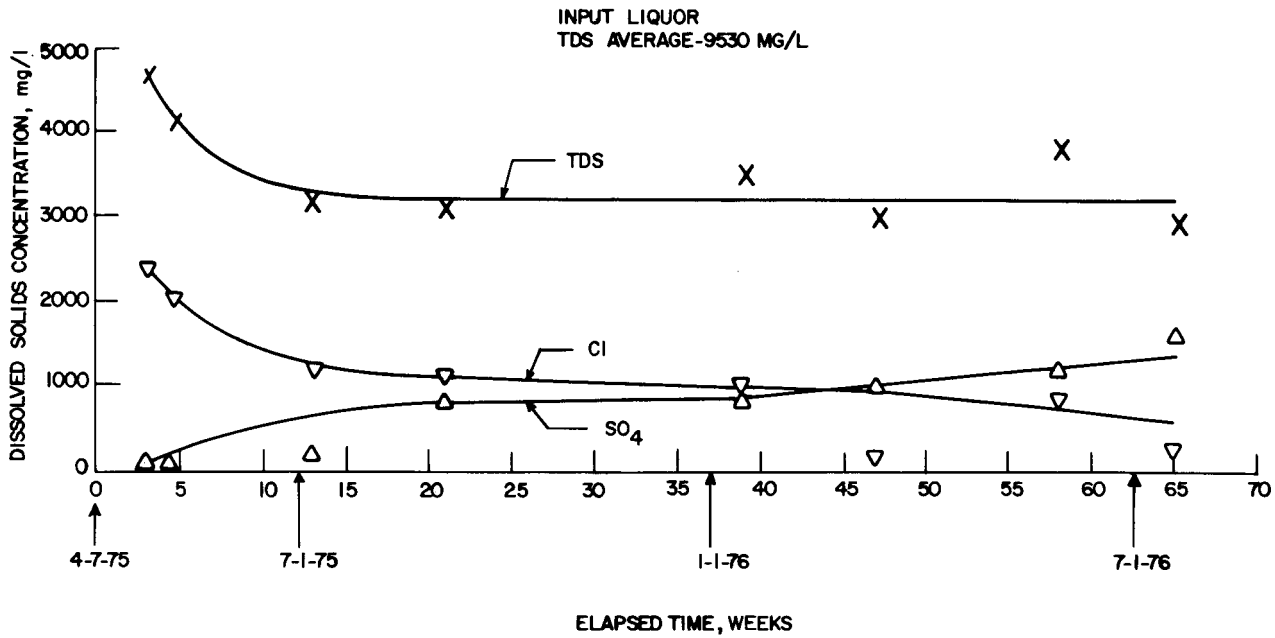


Figure 7-16. Leachate Dissolved Solids from POZ-O-TEC at TVA Field Test.

Source: Fling, R. B., et al., Disposal of Flue Gas Cleaning Wastes: EPA Shawnee Field Evaluation - Second Annual Report, Aerospace Corporation, EPA 600/7-78-024, February, 1976.

iron oxides and organic material are the best attenuating agents. The processes are described below.

Ion-Exchange. Ion-exchange is a process usually associated with clays and their ability to exchange cations. The capacity for such exchange, termed the Cation Exchange Capacity (CEC), is a measurable property expressed in milliequivalents/100 grams. A test procedure for determining CEC is given in Table 7-10. Soils with high CEC values are not necessarily the best for attenuation; the higher numbers indicate high clay content. If the clay content is so high as to result in an impermeable material, the leachate movement will be lateral rather than downward, and ion exchange cannot occur.

The ion-exchange characteristic can be a disadvantage when considering the calcium compounds in FGD sludges. The naturally occurring cation in clay is sodium, which is exchanged for the calcium in the sludge. There are two effects: the resultant sodium salts are much more soluble than the calcium, and the calcium-base clay is less effective when used as a liner. This is discussed in a following subsection.

Sorption. Sorption includes several mechanisms for retention of soluble species by a soil or attenuating medium. These processes occur on the microscopic level at the surface of the attenuating solid. One example would be the electrostatic attraction of ions by the charged surface of a solid particle. The surface charge of solid particles depends on the pH and ionic strength of the solution and the mineralogy of the solid (34). A second type of sorption commonly occurs on surfaces of hydrated manganese and iron oxides. These metal oxides can control the solubility of many trace elements in the leachate if they are present in significant amounts in the soil (35,36).

Precipitation. Precipitation describes one method a species may cross the boundary between liquid and solid phase. In this sense, ion-exchange and sorption may be considered as precipitation reactions. However, they were mentioned separately here because of their importance in natural soils. At neutral pH and above, direct precipitation of trace metals as hydroxides or carbonates may become the predominant mechanism of removal. The solid metal hydroxides can then be removed by natural filtration.

Filtration. When metallic species are precipitated, the filtration mechanism is effective in removing them from leachate. The efficacy of filtration is determined by the pore size, which becomes progressively smaller as the precipitating action proceeds, resulting in still finer particles being removed.

Table 7-10

PROCEDURE FOR DETERMINING CATION EXCHANGE CAPACITY

(1) Approximately five gm of the soil of known moisture content is weighed and transferred to a 50 ml centrifuge tube.

(2) 33 ml of 1N sodium acetate at pH = 8.2 is added, the tube stoppered and shaken for five min, washed down and then centrifuged, and the clear supernatant discarded.

(3) Step 2 is repeated three times.

(4) 33 ml of 95% ethanol is added, to remove excess soluble salts, shaken for five minutes, centrifuged, and the clear supernatant discarded.

(5) Step 4 is repeated two times.

(6) Na is displaced by adding 33 ml of 1N ammonium acetate, shaken, and centrifuged as above, and the decantate is collected in a 100 ml volumetric flask.

(7) Step 6 is repeated two times, using the same volumetric flask.

(8) The solution is made to volume, mixed, and the Na^+ determined by atomic absorption spectrophotometry.

(9) Cation exchange capacity is expressed as milliequivalents (of exchange) per 100 gm of 105°C - dry soil.

Source: Holland, W. F., et al., The Environmental Effects of Trace Elements in the Pond Disposal of Ash and Flue Gas Desulfurization Sludge, Radian Corporation, EPRI Report No. 202, September, 1975.

Dispersion. Dispersion acts to spread leachate flow over an area, rather than having what amounts to a number of point sources. This "spreading" action is of benefit in promoting greater contact for the preceding mechanisms to be effective.

Dilution. Dilution of dissolved components occurs by the water retained in the soil and at the interface between the soil and groundwater. The latter is a slow-acting mechanism since there is no turbulent mixing.

Radian conducted a study on the attenuation by soils of trace elements leached from coal ash and FGD sludges (37). The study concluded that typical soils gave some degree of protection to groundwater. For example, laboratory results indicated that 40 feet of clay soil will remove over 95% of the selenium and chromium from pond leachate after 10 years of continuous flow. Soil with a high percentage of sand provided the least protection. However, 50 feet of even this type of soil will remove over 95% of copper, arsenic or zinc after 10 years flow.

Those trace elements leached from ponded ash or sludge which exceed proposed standards can be controlled to a large extent by careful selection of a pond site underlain by soil with sufficiently high sorption capacity.

A second study on this subject was conducted by the U.S. Army Materiel Command, Dugway Proving Center (38). Tasks in the study were:

1. Physical and chemical characterization of wastes and preliminary screening tests with a variety of United States soil types,
2. Leachate studies in columns with the wastes applied to two selected (best and worst) soil types,
3. Long-term permeability tests with selected clays, and
4. Interpretation of data from the tests in (1) and (2) to identify soil attenuation mechanisms and to develop empirical attenuation coefficients for specific chemical substances.

Results are to be presented in a report to be published.

Liners

As in the consideration of attenuation, much attention has been given to the subject of liners in the sanitary waste field (31,32,33). It has also been of interest in the areas of hazardous waste, reservoirs and canals (39,40). In addition, the subject has been investigated in regard to FGD sludge disposal ponds (24,41). The reaction of liners to scrubber sludge can be completely different from that to other

materials, and experience or information gained in one field cannot be indiscriminately applied in another. The Waterways Experiment Station, U.S. Army Engineers, has been conducting tests specific to the use of liners with scrubber sludge (42). In addition, EPRI, under RP-1457 is funding research on liner compatability using utility wastes.

The purpose of a liner is to create a barrier through which water cannot pass, so that sludge liquors and elutriates cannot come into contact with the subsoil or groundwater.

There are many different types of liners including those formed from natural and sometimes indigenous clay, those manufactured through various admixtures, and thin film synthetic membranes. For lining scrubber sludge disposal areas (primarily ponds) barriers formed by existing natural clay have been the prime choice in practically all cases. A second choice has been the construction of liners from onsite or local clays. These have been choices based on economics, but, depending on transportation costs, some synthetics may be competitive with imported clays. For small basins and temporary holding facilities or interim ponds, synthetic liners are sometimes more practical.

The subject of liners is discussed more thoroughly in the following sub-section.

LINERS

Introduction

The purpose of a pond liner is to retain leachate and drainage from pond and landfills of FGD sludges to the greatest extent possible for the longest time at the most reasonable cost. This is a severe set of requirements which entails consideration of the following criteria:

Impermeability. This characteristic implies that a minimum quantity of leachate will be permitted to leave the impounded area to enter the sub-soil. No material is completely impermeable; however, the aim in examining candidate liner materials has been to find one which will impede leakage to the extent that the potential for pollution will be minimized. Concrete has a permeability of about 10^{-8} cm/sec; clay can range from about 10^{-5} to 10^{-8} cm/sec; raw scrubber sludge is considered to be free draining, as is sand. (A permeability of 1×10^{-6} cm/sec is equal to about 1 ft/yr.)

As described previously, permeability is determined in the laboratory by means of a permeameter.

Life. The effective life of the available linings in contact with FGD sludges is as yet unknown. This is a new application, and few installations have been made. The life of clay lining, which is the only type to receive serious consideration, can be greatly influenced by the type of impounded material. Synthetic membranes of some types have been guaranteed for periods of up to 20 yrs, but these have been the more expensive types that would not be practical for long term containment of scrubber sludge. The conclusion must be that, at this stage of development, no prediction can be made of the effective life of any liner with any particular sludge.

Cost. Figure 7-17 shows the installed costs of selected liners as of the report year of 1977 (20). Some of these lining materials as well as more recent costs will be discussed later. The table shown is of use for a general level comparison of different materials. It will be noted that an 18 inch clay liner can vary from about $1.50/sq yd installed to as much as $4/sq yd. Transportation would be the big determinant in this case. Only polyethylene (PE) is shown as being cheaper, but there are a number of disadvantages to that material. As previously stated only indigenous (or local) clay has been seriously considered or used for FGD sludge ponds. The various liner materials have been categorized into several general types by a number of investigators (31,38). For the purposes of this Manual, they will be listed and discussed as:

- Synthetic membranes
- Admixtures
- Clay

Only the more promising materials in each category will be discussed. Most emphasis will be placed on the use of clay.

Synthetic Membranes

Polyethylene. PE is shown as the lowest cost material in Figure 7-17. The low cost is counterbalanced by poor abrasive resistance, susceptibility to sunlight, and stiffness along with poor performance when creased. The poor resistance to sunlight requires a protective covering of soil, as do most of the membranes. Great care is required in preparing the surface before placing the PE because of the poor abrasive resistance and tendency to puncture. A thickness of greater than eight mils is difficult to handle because of the stiffness.

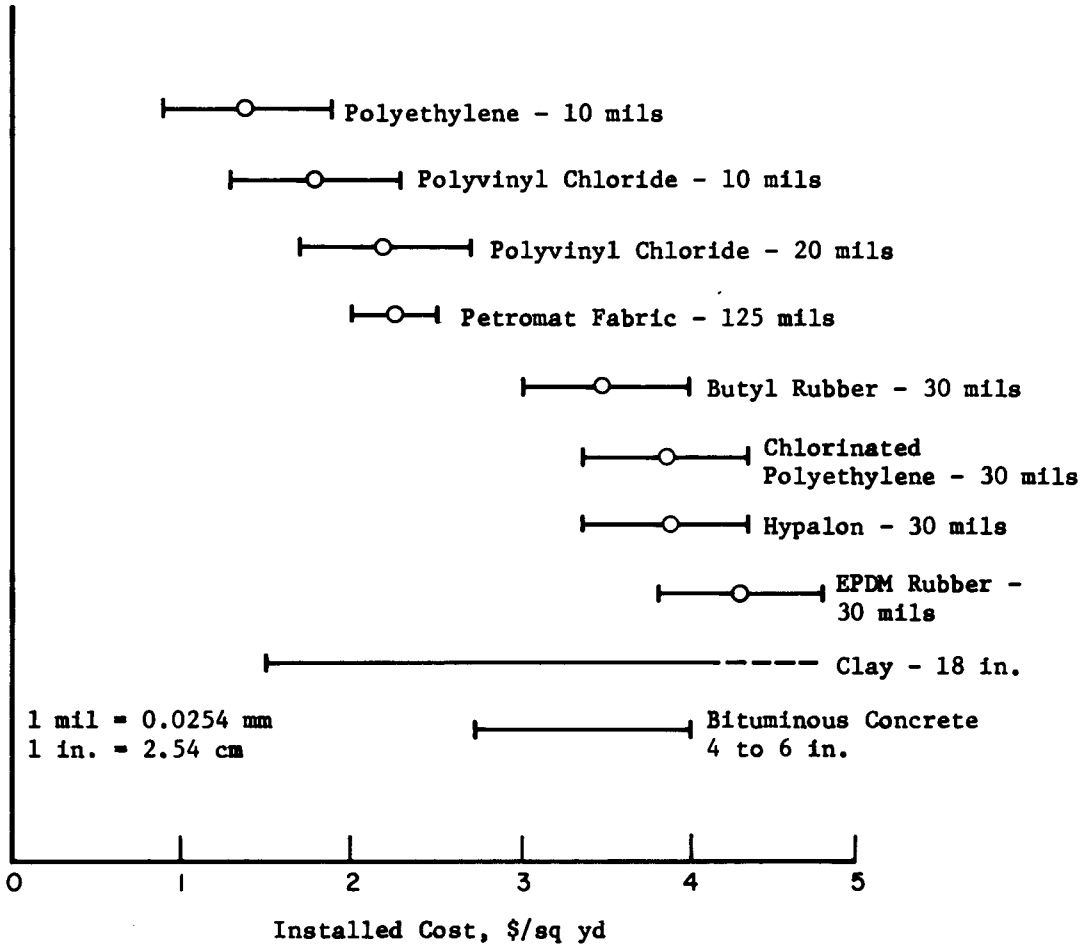


Figure 7-17. Installed Liner Costs.

Source: Rossoff, J., et al., Disposal of By-Products from Non-Regenerable Flue Gas Desulfurization Systems: Second Progress Report, The Aerospace Corporation, EPA 600/7-77-052, May, 1977.

Polyvinyl Chloride (PVC). PVC, a widely used material, is shown to be the next lowest cost membrane. This material is generally better than PE except in susceptibility to aging and sunlight. However, that particular fault makes repairs difficult after several years exposure. If the weathering effect is minimized by a protective blanket, PVC is generally satisfactory when its thickness is over 10 mils.

Hypalon. Hypalon is one of the new liner materials. Pinholes and shrinkage have been the primary faults found with this membrane. Curing proceeds during storage and after installation and this may cause problems. Heat sensitivity is greater during the early stages of curing. Seam sealing requires different techniques at different points in the curing process. It is second to PVC in the number of applications.

Admixtures

Concrete. This material does not appear to be a viable answer to the liner problem. The necessity for replacement, problems with cracking during curing, and necessity of expansion joints with subsequent leaks are all disadvantages.

Asphalt. Asphalt, as such, is not currently used to any extent in hydraulic lining. However asphalt concrete and asphalt panels are seeing limited use. Asphalt concrete is more flexible than cement concrete and is used in a blanket thickness of 1-1/2 to 3 in. It is often used for erosion control above the normal water level. Asphalt panels of 1/2 in. thickness have proven successful after original development problems were solved. The cost of these liner systems is too high for consideration in most FGD sludge applications.

When asphalt has been used, it has been a hot spray-on application, either with or without fabric reinforcement. There have been many problems with this type liner, not the least of which has been pinholes. Uniform application is also a problem.

Soil Cement. This liner material is made from a mixture of soil, cement and water. Soils must be easily pulverized and contain less than 50% silt and clay (39). Laboratory tests are required to determine the amount of cement required. The mix, made on site or at a batch plant, is placed in a six inch compacted layer. At this thickness, the cost is competitive with other liners classed as impermeable. However, curing cracks occur, and this prevents soil cement from being considered impervious.

Soil Asphalt. This liner type has been tested as a sanitary landfill liner (43). The soil or aggregate and asphalt are mixed in place, spread and compacted. The

resulting liner is reportedly more flexible and resistant to cracking than soil cement or asphalt concrete and has good aging characteristics in the absence of light. MC-type liquid asphalts are not recommended because evaporation of the kerosene diluent could leave voids.

Chemically-Treated Scrubber Sludge. Some applications of IU Conversion Systems' (IUCS) Poz-O-TEC^{R} as basin liners have been made and will be closely watched. This material is a mixture of FGD scrubber sludge, flyash, bottom ash, lime and other additives. The permeability of the mix is reported to be 10^{-6} - 10^{-8} cm/sec after curing. An evaporation pond at the Four Corners Station of the Arizona Public Service Company was lined with 18 in. of the compacted material in 1974. In 1977, three wastewater ponds (two - 61,000 gal and one - 324,000 gal) at the Cheswick Power Station of Duquesne Light Company were lined with Poz-O-Tec using materials brought in from another station. Use of this liner was approved by the Pennsylvania Department of Environmental Resources. Use of chemically treated scrubber sludge as a liner is particularly attractive because the prime ingredients, sludge and flyash, are available on site. A utility can therefore manufacture its own liner.

Clay

The best known form of clay is bentonite with the largest deposits in Wyoming and South Dakota. It is in the montmorillonite mineral group, and some deposits are noted for a high swelling index. This characteristic is of especial advantage in oil well drilling, which is the largest outlet for the clay. The index is defined as the ratio of the increased volume when wetted in distilled water to the original dry volume. Values for the index in bentonite range from negative (shrinks when wet) to over 2,000% (39). However, a high value is not necessary to obtain low permeability. All high index clays have low permeability, but many low index clays have the same property.

Since large deposits of bentonite are not widespread, many local clays have been used for lining ponds, including those used for FGD sludge. Transportation cost is a major part of the installed cost for clay liners. As an example, in 1974, the cost of an installed 18 inch liner of local clay in the mid-west was estimated at \$1.50/yd^2; the same clay when transported 30 mi was estimated at \$9/yd^2 (24).

Methods of Placement. Although clay can be placed either wet or dry, only the latter method is used for FGD sludge ponds. For sludge ponds, one type of application is to spread and compact the clay in six-inch layers to the thickness found necessary.

The final layer is then covered with soil for protection. Another type of dry application involves mixing the clay with the top three in. of the pond base and then compacting and placing the protective earth covering (39).

Clay Properties and Tests. The following properties affect the suitability of a clay when placed as a dry liner:

- Swelling index has been discussed previously. An index of 50% is said to be the minimum for good sealing.
- Layer permeability is the water loss in ft/day through a loosely packed clay layer of 0.6-in. thickness under a starting water head of 52 in. The loss should be no more than 0.005 ft/day.
- Colloidal yield involves the dispersion of a sample in 1000 ml of distilled water with sodium tripoly-phosphate as a dispersant. After 24 hr, the degree of suspension is determined with a hydrometer. The clays which seal best show a colloidal yield above 40%.
- Grit content indicates the sand fraction in the clay. A value of 30% is preferred for sealing coarse or rocky soil; for other soils, 10% or less is desired.

All these tests require the use of distilled water. It should be noted, however, that results with high TDS scrubber liquor can be completely different. Also, as previously noted, clays have cation exchange capacity. A clay that is high in sodium can be changed to a calcium clay and be less effective as a sealant if the contained liquor permeates the clay.

Surface Preparation. Correct and careful preparation of the pond surfaces prior to clay placement are necessary. The sides and bottom should be smooth and free of vegetation and debris. Side areas above the expected water line should be protected against erosion; wave action can be a problem.

Attenuation. Although clay liners are used for impermeability, it is of interest to consider their attenuating properties because of the clay content in underlying soils. This subject was discussed previously to some extent in this Section.

A recent report on landfill leachate gives a ranking for attenuation of three different clays (44). The clays and their attenuating capacity were given:

montmorillonite > illite > kaolinite

The first clay listed attenuates approximately four times better than illite and five times better than kaolinite. The degree of attenuation was credited to cation

exchange capacity. The clays used were calcium-saturated with respect to the exchangeable cations. Calcium, iron and manganese were not attenuated. The order of element attenuation by the three clays were:

$$Cl < CO_3 < Na < NH_4 < K < Mg < Si < Cd < Zn < Pb \simeq Hg$$

These results are of interest in regard to scrubber sludge because of the inclusion of some of the major soluble components, e.g., Cl, Na, Mg. Also the presence of some of the trace elements is of interest, e.g., Cd, Zn, Pb and Hg.

The ranking of trace elements is also given in another recent report (37). In this study, the attenuation of 12 soils was determined. Six of the soils were natural, and six were controlled mixtures of sand, silt and clay. The leachates tested were made from ash and scrubber sludge samples from five different power stations. Attenuation ranking was:

$$\text{Ash} - F < Cr \leq Se << Cu << As$$
$$\text{Sludge} - Cr < F < Hg < Zn < Cu$$

Costs

Costs of various lining systems have been reported by the Aerospace Corporation (20, 41). The 1977 figures are shown in Figure 7-17, referred to previously. An additional update has been published by the same organization (45). The most recent information is based on the reference conditions shown in Table 7-11; the costs are shown in Table 7-12 for clay and Table 7-13 for 20-mil PVC.

As previously noted, the only pond lining that has been used for FGD sludge is clay, and that is the only material that seems at all economically feasible. Table 7-12 shows that the total capital pond cost as of July, 1977, for a 1000 MW unit burning coal of 3.5% S, 14% ash and 12,000 Btu was $12,477,300 or $12.48/kW. Average annual cost was estimated at $4.89/t of dry sludge or 0.54 mills/kWh. This compares to a total capital pond cost of $13,757,200 or $18.76/kW and an average annual cost of $7.25/t of dry sludge or 0.80 mills/kWh for 20 mil PVC. That is, the costs, both annual and operating, for PVC are approximately 1-1/2 times those for indigenous clay.

Table 7-11

REFERENCE CONDITIONS FOR LINER COST ESTIMATES

Dollar base:	July, 1977
Plant and disposal site lifetime:	30 yr
Annual average operating hours:	4,380 hr/yr (30-yr avg)
Average annual capital charges, 30-yr avg:	18% of total capital investment
Cost of land used for disposal:	$5,000/ac, all land assumed purchased initially; sludge depth, 30 ft
Land depreciation:	Total depreciation in 30 yr, straight-line basis
Coal burned:	3.5% sulfur, 12,000 Btu/lb, 14% ash
SO_2 removal:	Limestone absorbent, 90% removal, 80% limestone utilization
Sludge generated:	2.5×10^5 short t/yr (dry) (disposed waste assumed to contain 50% solids for 500 Mw plant

Source: Leo, P. P. and J. Rosoff, Controlling SO_2 Emissions from Coal-Fired Steam-Electric Generators: Solid Waste Impact, Aerospace Corporation, EPA-600/7-78-044b, March, 1978.

Table 7-12

ESTIMATED COSTS FOR DISPOSAL OF
UNTREATED FGD WASTE IN PONDS WITH INDIGENOUS CLAY SOIL

Unit Size MW	CAPITAL INVESTMENT		AVERAGE ANNUAL COSTS	
	$	$/kW	$/ton(dry)	mills/kWh
1000	12,477,300	12.48	4.89	0.54
500	7,796,300	15.60	6.07	0.70
25	572,913	22.92	14.76	1.87

Table 7-13

ESTIMATED COSTS FOR
PONDING UNTREATED WASTES WITH FLEXIBLE 20-MIL PVC LINER

UNIT SIZE, MW	CAPITAL INVESTMENT		AVERAGE ANNUAL COSTS	
	$	$/kW	$/ton(dry)	mills/kWh
1000	18,757,200	18.76	7.25	0.80
500	11,901,200	23.80	9.01	1.02
25	768,533	30.74	17.30	2.19

Source: Leo, P. P. and J. Rosoff, Controlling SO_2 Emissions from Coal-Fired Steam-Electric Generators: Solid Waste Impact, Aerospace Corporation, EPA-600/7-78-044b, March, 1978.

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Section 8

DESIGN OF DISPOSAL AREAS

PURPOSE

This section of the text presents procedures to be used for the design of new FGD waste disposal facilities. It addresses the design of impoundments for the disposal of wet scrubber sludges as well as landfills for the disposal of dry, processed power plant wastes. The purpose of this Section is to provide the utility industry a common understanding of what is involved in the design of disposal areas and to provide specific guidance in the design of these facilities.

BACKGROUND

The design procedures described are not significantly different in principle from those traditionally used to design water impoundments or construct landfills. Dominating these designs and, therefore, those described here, are the properties of the construction materials used and the geologic and hydrologic characteristics of the disposal site. Primary emphasis in this section of the text has been placed on the design of long-term, structurally stable disposal facilities. Discussions include the various alternative pond and landfill disposal configurations commonly used, geotechnical design considerations and methods of site investigation, the criteria, procedures and methods necessary for the design of disposal ponds and landfills, the importance and techniques of monitoring the disposal operation, and the design of the abandonment of the disposal site.

ALTERNATIVE DISPOSAL CONFIGURATIONS

Once the basic type of FGD sludge disposal system has been selected, either ponding of wet sludge or landfilling of dry sludge, there are a number of disposal configurations that are commonly used for each system.

Pond Configurations

Diked Pond. Probably the most common form of wet disposal is the diked pond. A diked pond is a pond contained within a perimeter embankment or dike. Figure 8-1 shows a typical installation. This form of pond construction requires a level or nearly level site. The dike may be constructed of materials excavated from below the existing grade at the pond site as shown in Figure 8-2, or it may be constructed above-grade from borrow sources as shown in Figure 8-3. At some potential pond sites, excavation below the existing ground surface may be difficult due to shallow depths to groundwater or bedrock. In these cases, above-grade construction will probably be necessary.

Incised Pond. An incised pond is a pond contained in an excavation entirely below the existing ground surface level as shown in Figure 8-4. This type of facility is attractive where groundwater and bedrock will not be encountered during excavation, where there is limited space for dike construction or when the excavated materials are either unsuitable for dike construction or valuable for some other purpose. For example, the disposal pond at the Louisville Gas and Electric Cane Run Station was excavated into an aggregate-grade sand deposit. The sand was stockpiled for future sale.

Existing Basins. A variation of incised ponds constructed for FGD sludge disposal is the use of existing basins such as abandoned surface mines and quarries. If available within a reasonable distance from the plant and approval can be obtained from the appropriate regulatory agencies, abandoned surface mines and quarries may provide suitable disposal sites. (See Section 6 - SITE SELECTION for more discussion of mine/quarry disposal).

Side-Hill Pond. This type of pond configuration lends itself to hilly terrain where a level site is not available for either diked or incised pond construction. The side-hill pond configuration takes advantage of the local terrain to provide one or two sides of the pond. An example of this type of construction is shown in Figure 8-5. Depending upon the steepness of the natural slopes at the prospective pond site, it may be difficult to construct a large pond using side-hill construction unless the pond is long and narrow or the down hill dike is relatively high.

Cross-Valley Pond. A cross-valley pond is created by constructing a dam across a portion of a natural valley between the two valley walls. This type of pond configuration, similar to a typical water impounding dam, impounds both the natural drainage



Figure 8-1. Typical Diked Pond Installation.

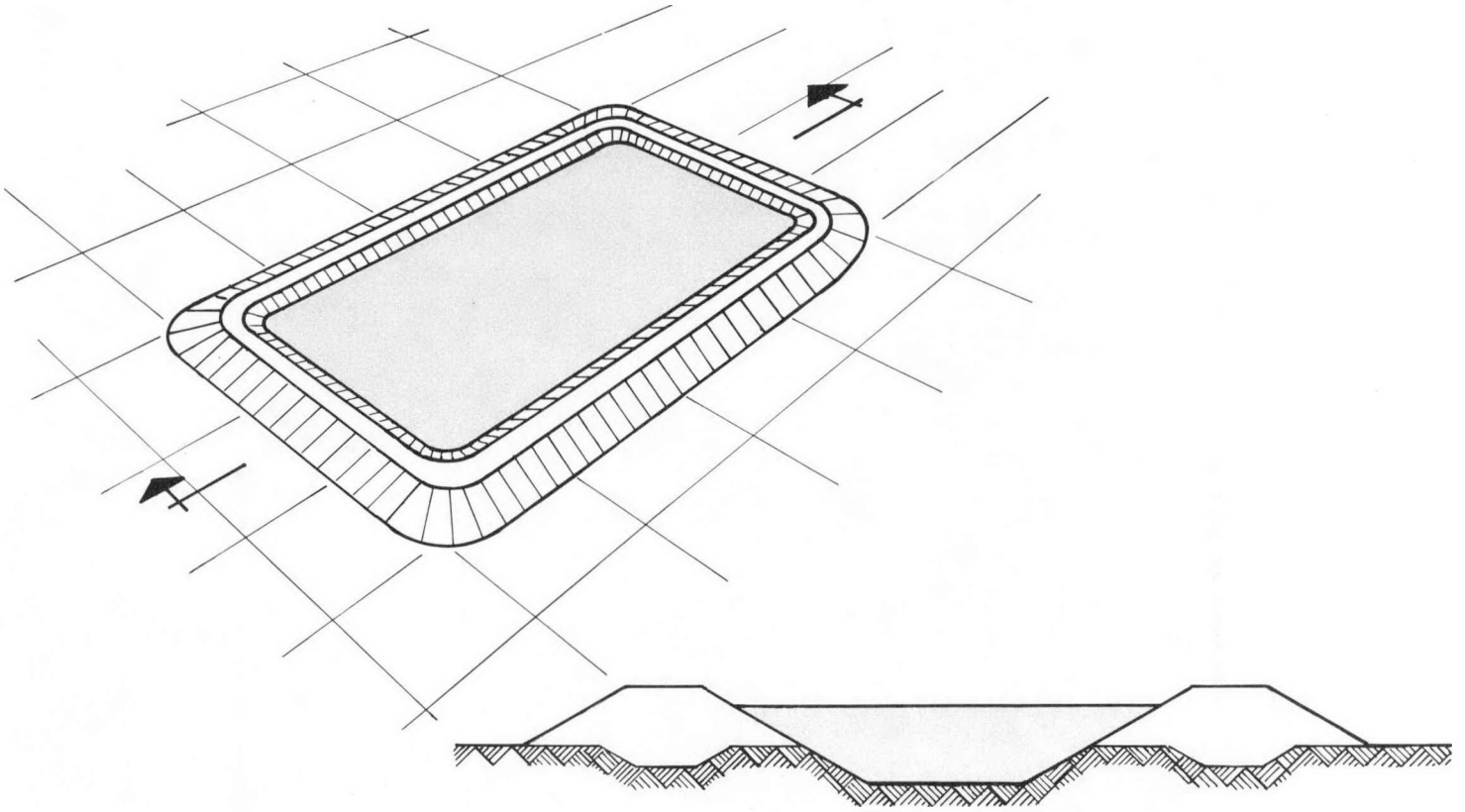


Figure 8-2. Diked Pond Partially Excavated Below-Grade.

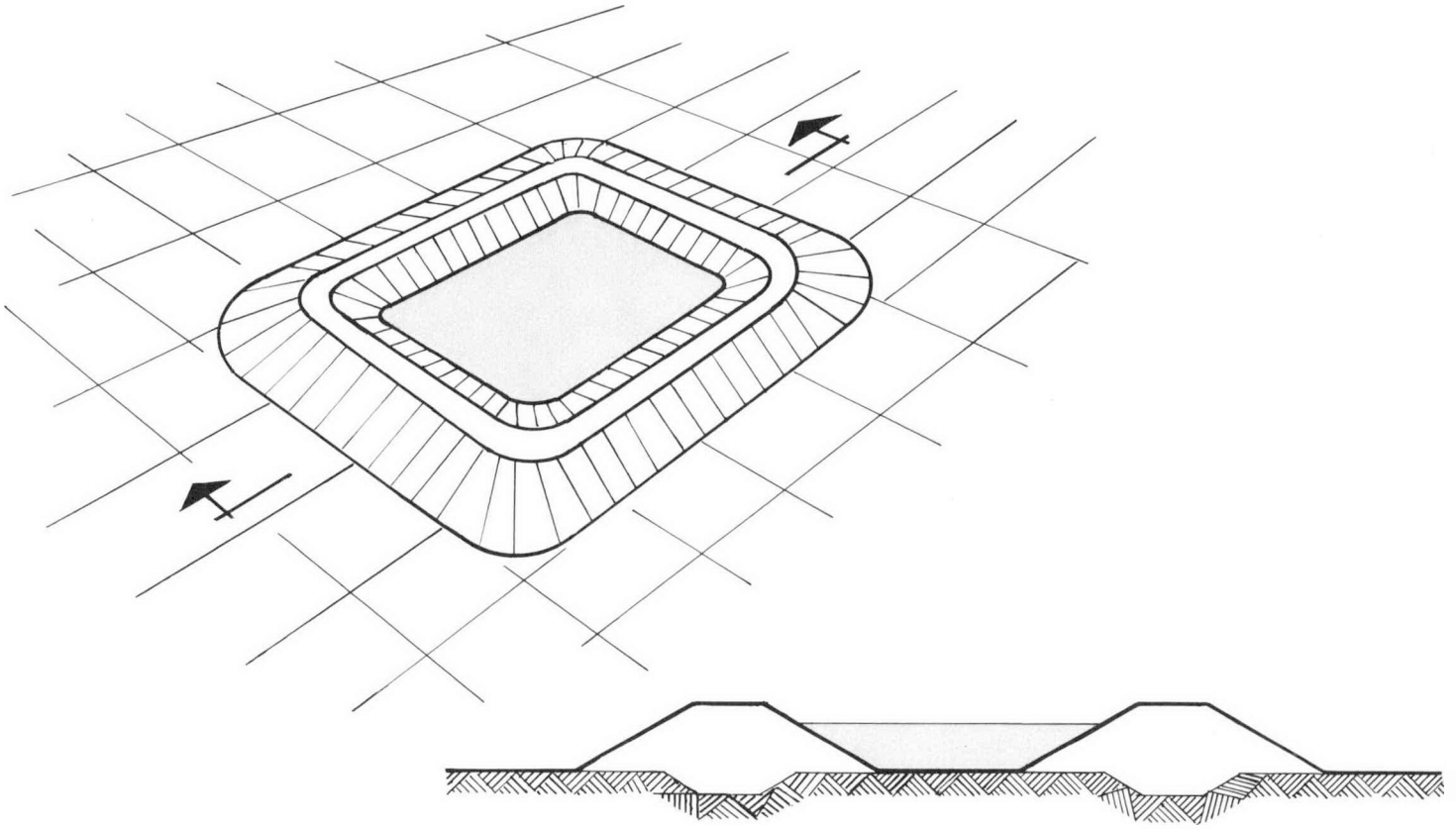


Figure 8-3. Diked Pond Constructed Above-Grade.

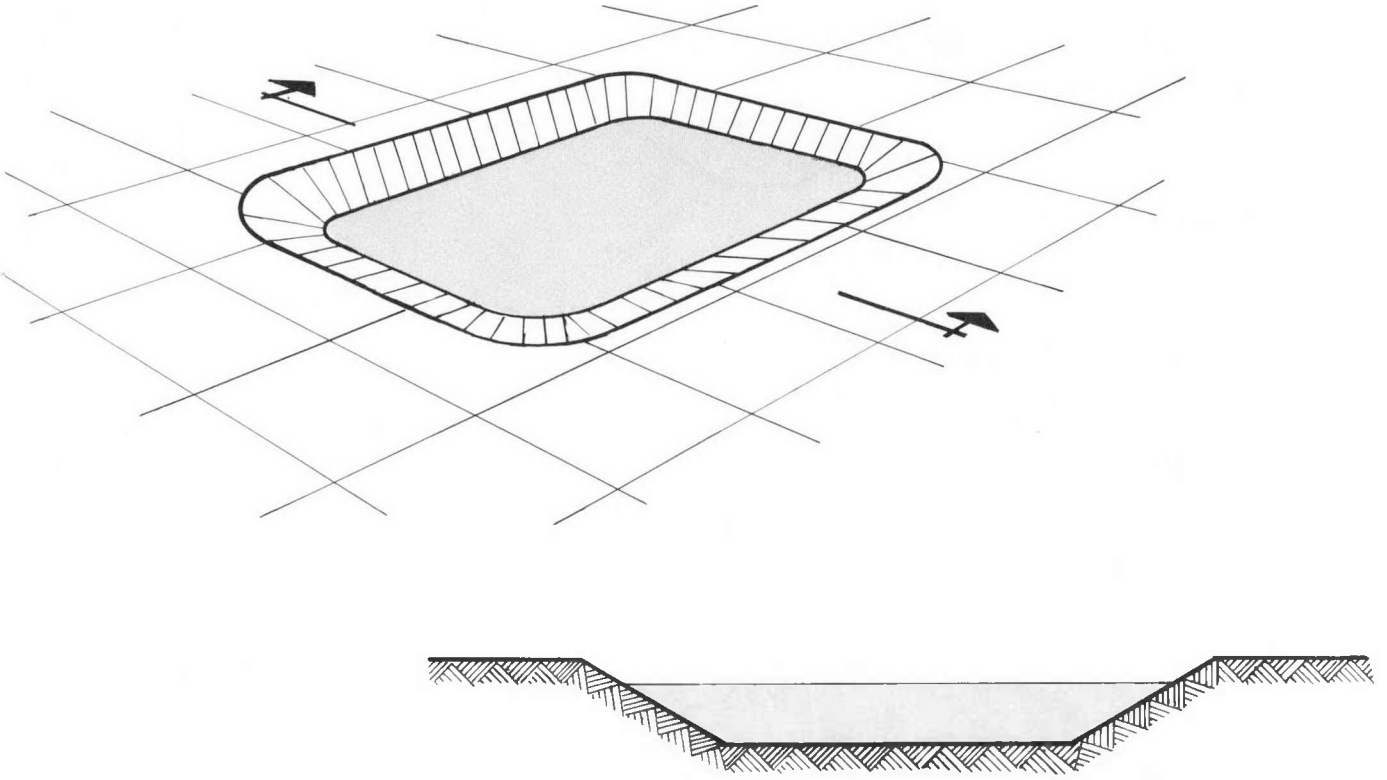


Figure 8-4. An Incised Disposal Pond.

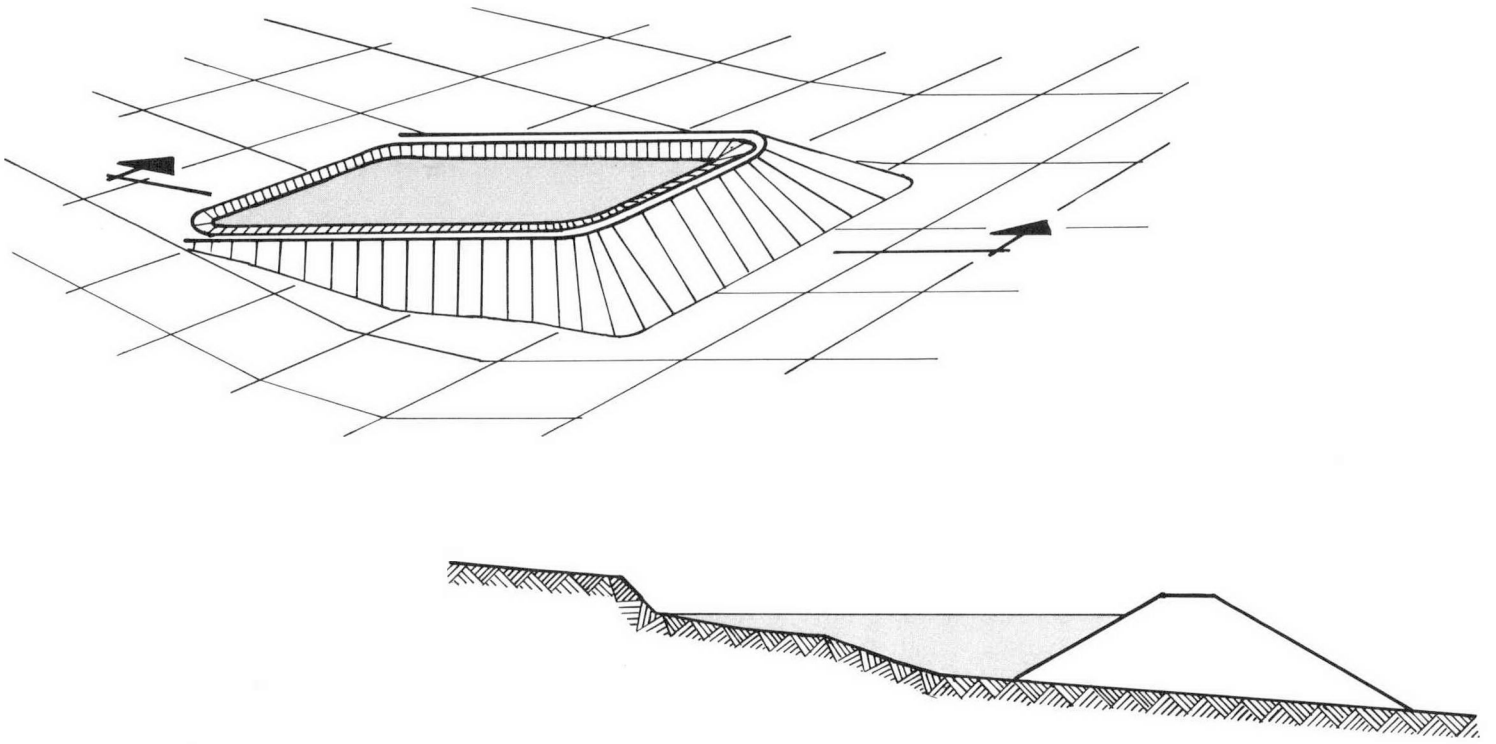


Figure 8-5. A Side-Hill Disposal Pond.

of the valley behind the dam as well as the FGD waste materials. Figure 8-6 shows a typical configuration. The design of this type of impoundment is more critical than the previously discussed pond configurations because it must provide for the controlled storage and discharge of the natural sources of valley water resulting from rainfall, surface runoff and existing springs, as well as adequately handle design flood flows. This type of sludge disposal pond is in use at the Bruce Mansfield Station of Pennsylvania Power Company, shown in Figure 8-7.

Landfill Configurations

Heaped Fill. The simplest configuration for dry disposal of FGD sludge is a heaped fill as shown in Figure 8-8. This type of landfill is typically used in areas where the terrain is level. Groundwater pollution, slope stability and site preparation problems are usually minimal with this configuration. A heaped landfill operation, however, does not blend with the surrounding level terrain and is highly visible. For this reason, this method of disposal may be least preferred by regulatory agencies if other types of fill construction are possible. A heaped landfill operation is shown in Figure 8-9.

Side-Hill Fill. In hilly or gently sloping terrain, side-hill construction as shown in Figure 8-10, is often possible. The fill may be constructed along the side of a hill or valley. Properly constructed, side-hill fills may blend well with the existing terrain and may provide valuable property when reclaimed. Site preparation and slope stability considerations are likely to be more complex than with heaped fills; however, they are not particularly severe problems.

Valley Fill. The most common type of landfill in areas of hilly terrain is a valley fill, shown in Figures 8-9 and 8-11. Since valleys are natural avenues of surface runoff and, in non-arid regions commonly have springs along the side slopes, control of surface water and groundwater is necessary. It is important to direct surface runoff water under or around the fill to avoid impounding water and to help control erosion and surface runoff pollution. Similarly, springs to be covered by the fill must be collected and channelled to reduce leachate generation and slope instability. In general, site preparation is more complex with valley fills than with other landfill configurations.

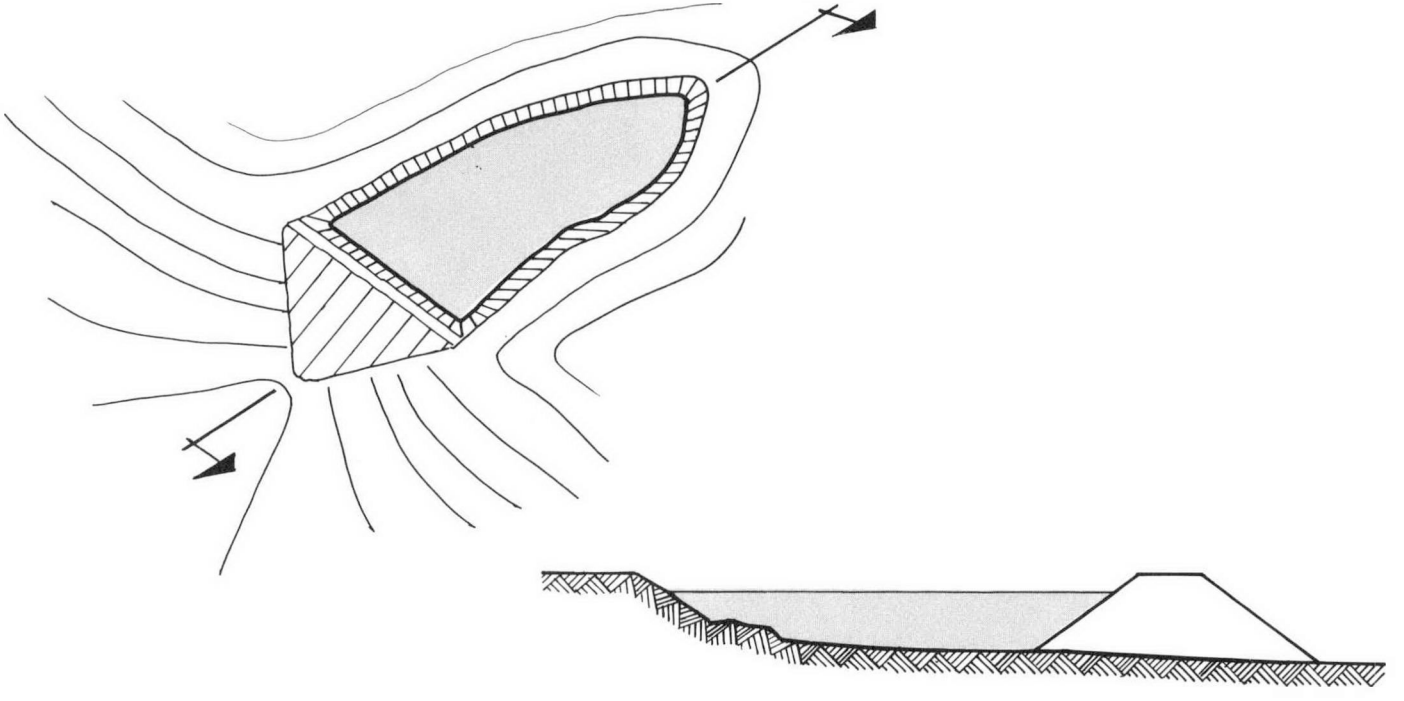


Figure 8-6. A Cross-Valley Pond Configuration.

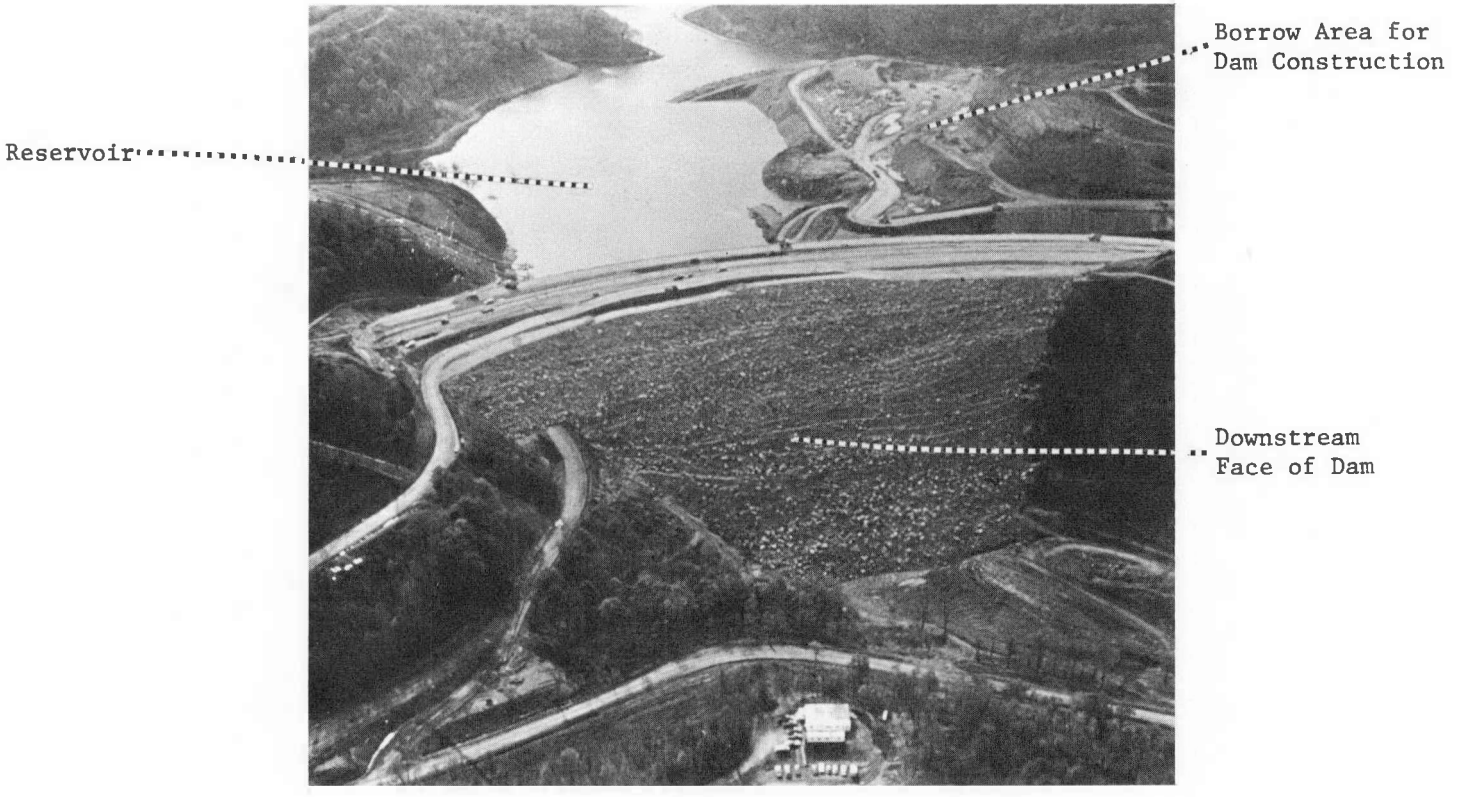


Figure 8-7. Cross-Valley Sludge Disposal Pond
Bruce Mansfield Station, Pennsylvania Power Company.

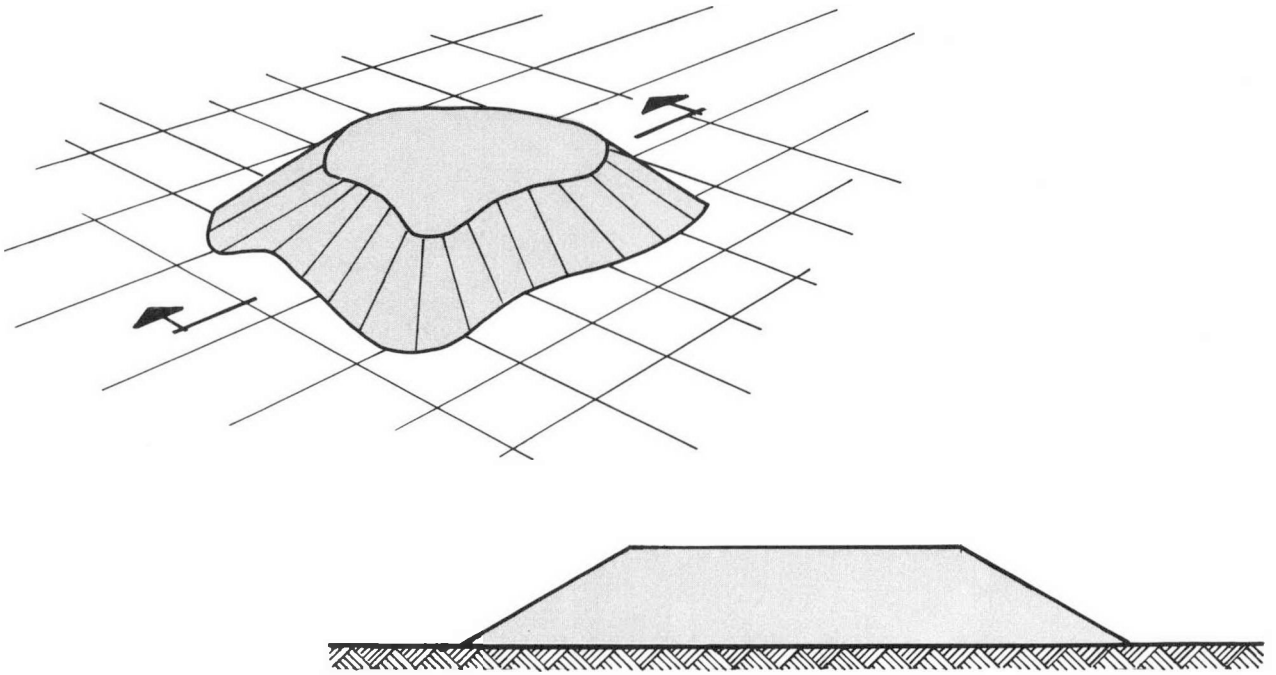


Figure 8-8. A Heaped Landfill Configuration.



Figure 8-9. Examples of Heaped and Valley-Fill Construction

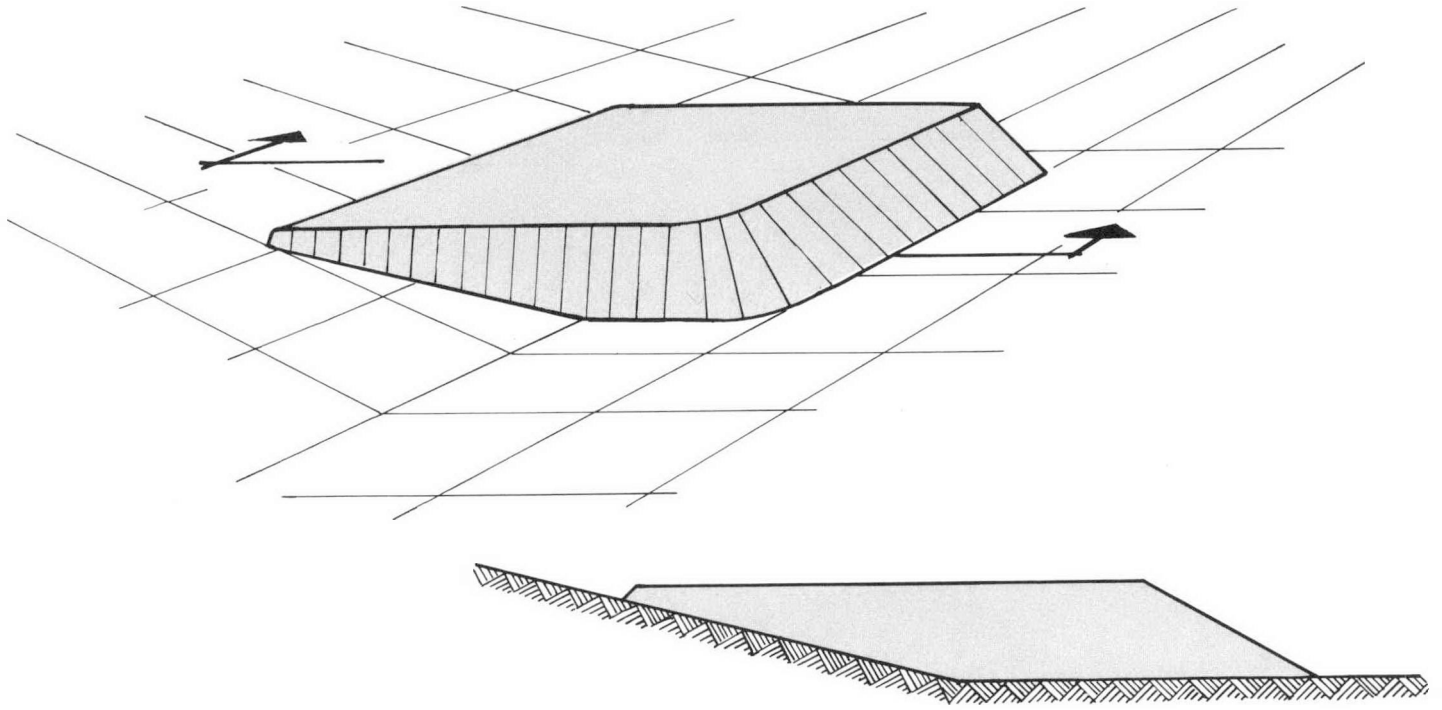


Figure 8-10. A Side-Hill Landfill.

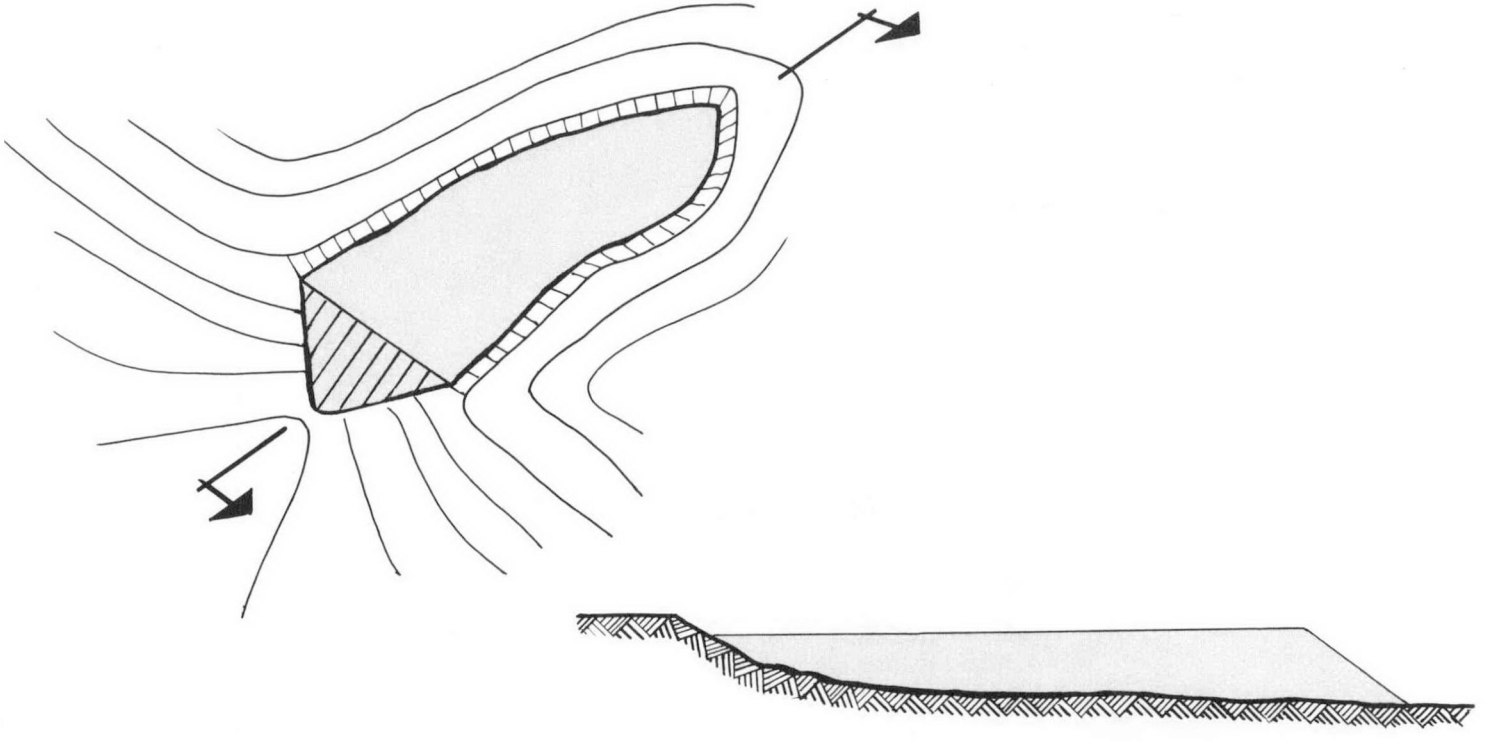


Figure 8-11. A Valley-Fill Disposal Configuration.

GEOTECHNICAL CONSIDERATIONS

The design of disposal areas is primarily a geotechnical engineering function. To accomplish the geotechnical design, it is important to understand the general tasks that will need to be performed, the general considerations that will affect the development of the design, and the general procedures necessary for the successful completion of the design.

Basic Design Tasks

The geotechnical design of a disposal area involves the following basic tasks:

- Evaluate the significance of the surface and subsurface geology of the prospective disposal site.
- Determine the physical and chemical properties of the materials involved in the facility design. These materials are the waste materials that will be placed at the site, and the soil and rock materials that will be used in or will affect the construction of the safety and environmental control features of the disposal facility.
- Specify procedures for the waste material placement and soil and rock construction based on stability, seepage and settlement analyses performed for both the proposed facility embankments and the in situ foundation materials upon which they will bear.
- Monitor the performance of the operational facility to observe the adequacy of the geotechnical design.

General Considerations

Throughout the process of designing the disposal area, there are a number of general considerations that should be kept in mind. Most of these considerations also play an important role in the selection of a disposal site. Attention to these considerations will help the designer to develop a disposal configuration which will efficiently meet the needs of the user and, therefore, will likely be economical to operate. These considerations are:

The Purpose of the Disposal Facility. The purpose of the facility is to provide a means for sludge disposal, not to provide a site for future structures such as buildings or highways, nor to impound water for future power, domestic or recreational purposes. While these future site uses may be feasible and should not be neglected, the primary design of the disposal site should not be directed towards them.

The Characteristics of Sludge Disposal. The operation of FGD sludge disposal areas is similar to the disposal of other waste materials that occur in large quantities such as sanitary wastes, coal refuse, and mill tailings in that:

- The placement of FGD sludge will occur over many years, not during a relatively short construction period. The significance of this on design of the disposal facility would indicate that engineering field control would not be practical during the entire life of disposal operations, and that requirements for controlled construction must be performed during relatively short time periods or be designed to account for the degree of control available that will be at the site.
- The total volume of sludge disposed is greater than that which may be used during the controlled construction phases of the disposal facility. This is particularly relevent in landfill disposals where the soil-like waste may be used in constructing nonimpounding embankment slopes. This disposal characteristic indicates the need for two placement specifications, one for construction purposes and one for general sludge disposal.
- Samples of the FGD waste materials may not be available in the case of disposal design for a new power plant. In addition, the properties of the waste are likely to change from time to time due to variations in coals burned at the plant and variations in the plant operation. This requires the designer of such a disposal facility to estimate the properties of the waste materials based on experience and predictions by the power plant and scrubber plant designers. This may suggest to the designer the need for periodic field sampling and testing of the actual waste to verify these estimates.
- When the capacity of the disposal site is expended, the facility will be abandoned. This characteristic of sludge disposal operations requires the facility to be designed to provide an abandonment configuration that will be environmentally acceptable and relatively maintenance free for an extremely long time.

The Site Conditions. Often the volume capacity and proximity to the power plant are the two principal site characteristics or considerations in the selection of a disposal site. Other site conditions, however, should be considered not only in the site selection process but also in the design of the disposal facility. The following site conditions can significantly affect the number of possible alternative disposal configurations which may be available for use and the cost of constructing the disposal facility.

Topography. The site topography will often dictate the configuration or type of disposal operation that may be designed. Refer to the previous paragraph, ALTERNATIVE DISPOSAL CONFIGURATIONS. Terrain conditions will also have an impact on techniques and costs of material handling, methods and costs of drainage control, and hazard potential of the facility.

Weather. Weather conditions in various regions of the country can have a significant impact on the configuration and design of a disposal area in terms of moisture control of compacted materials used in the construction of embankments and landfills, the design of surface drainage control requirements, the length of the construction season during which critical design features can be constructed, and wind blown waste materials in the case of dry disposal.

Geology and Surficial Soils. The geology and surface soils at the proposed disposal site may indicate the need to consider

- the extent of necessary site preparation in terms of the stability of foundation materials and existing sources of groundwater seepage
- the extent and consequence of past or future mining or drilling in the area
- availability of borrow materials
- the effect of waste disposal on groundwater quality

Scheduling of Construction. It may be impractical and not economical to construct at one time, a disposal facility large enough to accept the entire quantity of wastes anticipated during the life of the site. For this reason, the design of staged construction may be necessary to allow for such work items as increasing heights of impounding embankments, expansion of drainage appurtenances for both pond and landfill operations, and site preparation of unused portions of the site. Along with the likelihood of staged construction, scheduling will play an important role in developing potential borrow sources which may exist within the disposal area, determining the priority of construction for design features requiring careful field control, and the preparation for the abandonment of the site at the end of the anticipated disposal period.

General Design Procedures

With the aforementioned basic design tasks to perform and with the general considerations influencing the design of an FGD disposal system, the following general design procedure is presented to show how the geotechnical design would typically progress for a new disposal facility.

Review Available Site Information.

- Topographic maps
- Geologic maps
- Soil survey maps
- Aerial photographs
- Local experience
- Individual site mapping

Many of these sources may be available to the designer and will provide a means to initiate conceptual design of the disposal area, assist in planning a site

investigation, and provide valuable information for the detailed design of the disposal configuration.

Plan a Field Investigation. A field investigation of the proposed disposal area usually involves a two-step process:

- preliminary investigation
- final investigation

It is impractical to assume that all the field data necessary for the final design can be obtained during the early stages of design development. Planning a field investigation is usually based on:

- Size of the disposal area
- Type and probable configuration of disposal operations
- Method of placement of waste materials
- Anticipated location of major embankments or dikes
- Types of borrow materials that may be required or available
- Complexity of the site geology
- Characteristics of the subsurface materials
- Significance of past or future mining, drilling or surface developments in the area
- Likely drainage or environmental requirements
- Possible changes or alternatives to the conceptualized FGD waste disposal system
- Types of field sampling that will be required.

The investigation should be designed to identify and quantify the surface and foundation material characteristics, and locate possible sources of borrow materials if required for construction.

Following the analysis of the data collected during the preliminary investigation, the disposal design can be advanced to a more detailed stage. At this point, the design of the disposal site, including its ancillary features, will be sufficiently detailed to warrant a final field investigation to collect additional data that may be required at specific areas or locations.

The Field Investigation. The field investigation will typically include a:

- Surficial reconnaissance
- Subsurface exploration

and may involve the following methods of data collection:

- Test borings
- Test pits
- Visual classification of materials
- Field testing and monitoring
- Water flow inventory

A more detailed discussion of the field investigation is presented later in this section.

Testing of Materials. The testing of materials to be deposited as well as those identified and collected during the site investigation is necessary to determine the physical and chemical properties affecting the design of the disposal facility. These materials will consist of the:

FGD waste materials to be deposited at the site

Natural soil and rock materials that will serve as foundation materials and those to be used to construct designed features of the disposal system such as dikes, embankments, and roads

The testing that may be performed may be grouped into two categories:

- Field Testing
- Laboratory Testing

Tests falling into these categories are discussed in more detail later in this section.

Analysis and Design. The geotechnical design of the disposal area requires analysis in terms of the following main subject areas based on the data collected during the site investigation and from the testing performed:

- Foundation preparation
- Seepage control
- Static and dynamic stability of slopes
- Settlement

Discussion of analysis of seepage, stability and settlement are discussed in more detail under the headings dealing with pond design and landfill design.

Construction Requirements. The development of the geotechnical design of a disposal system should consider practical and economical:

- Construction and waste disposal procedures
- Selection of hauling and transport equipment
- Haul road or pipeline locations
- Construction scheduling of the various facility appurtenances
- Field quality control and testing

In addition, the early construction tasks of clearing, foundation subgrade preparation and water control must anticipate both the physical changes in the site as long-term disposal continues and possible future changes.

Some of the above items will be discussed in more detail in subsequent sections dealing with the design of ancillary systems and pond and landfill operation.

Instrumentation and Monitoring. An instrumentation and monitoring program properly tailored to the conditions of the site and the scheme of waste disposal can result in significant savings in terms of the cost of design, operation, and maintenance of a disposal site.

Such an instrumentation and monitoring program may range from simple periodic visual inspections to the installation of an elaborate system of sensing and recording devices for data collection and interpretation. A discussion of monitoring and instrumentation is presented later in this Section.

GEOLOGIC SITE INVESTIGATIONS

The purpose of a geologic site investigation is to collect the geologic data necessary for the design of a disposal facility appropriate for a specific site. The type and extent of the investigation will be dependent upon the factors presented previously for planning a field investigation.

Usually, by means of the site selection process (see Section 6 - SITE SELECTION) and preliminary planning, sufficient general information is available to organize and conduct a preliminary geologic site investigation. As previously discussed, it is impractical to expect that all site data necessary for the final disposal design can be

collected during the early stages of design development. Therefore, as the design advances to more detailed stages, a final field investigation will probably be justified to collect additional field data at specific areas or locations.

The scope of a geologic site investigation will entail:

- Reviewing available site information
- Performing a surficial site reconnaissance
- Performing a subsurface investigation
- Field testing and monitoring

Reviewing Available Site Information

The review of existing sources of information about the proposed disposal site is important to planning and conducting a field investigation. This review, when performed by a trained geotechnical engineer or geologist, will help to maximize the information that will be obtained in the field and provide the geologic framework of the site from which a detailed and economical site investigation can be initiated. These sources of information include the following:

Topographic Maps. Topographic maps are required throughout the design process including the geologic site investigation. Published mapping can be obtained from the United States Geological Survey (USGS). These maps show the ground relief, natural and man-made features, water features and wooded areas. For a geologic site investigation they can indicate watershed boundaries for hydrologic studies, locations where wells and springs may be observed for groundwater conditions, locations of rock outcrops providing geologic information, land forms that relate to various soil types that may be found, and site accessibility which may lead to selection of certain subsurface sampling equipment.

Geologic Maps. These maps are prepared by the USGS or by the State Geological Surveys and generally show surface outcrops of various rock units along with descriptions of the rock units contained in the local geologic section. The maps, when properly interpreted, can provide useful information in terms of understanding the geologic history of the area, and the geologic structural features such as faults, folds and rock dip.

Agricultural Soil Survey Maps. These maps, produced by the Soil Conservation service (SCS) of the U.S. Department of Agriculture (USDA), are especially useful for site

reconnaissances and for planning detailed site investigations. These maps survey surface soils according to color, texture, physical and chemical characteristics and biological nature. Information is also presented about the engineering characteristics of the surficial soils. The best source for these maps is from the local office of the USDA County Extension Agent.

Aerial Photographs. Aerial photography of the proposed disposal site can be extremely helpful, particularly when existing ground surveys may be outdated, incomplete or non-existent. Currently-flown photography will frequently provide more up-to-date and detailed information than the USGS topographic mapping of the area.

The amount and accuracy of information obtained from aerial photographs depends on the skill and experience of the interpreter. Aerial photographs covering most of the United States can often be obtained from either the USGS or the USDA. A variety of photographic scales is available; however, scales smaller than 1:24,000 (1" = 2,000') are not likely to provide the required detail necessary for site planning and design. A scale as large as 1:1,000 may be required.

Previous Investigations and Future Development Plans. In some cases, the site under investigation may have been geologically investigated in the past for other purposes such as mineral resource or surface developments. This geotechnial information may be available and can provide valuable site information at little or no cost.

Since FGD waste producing power generating plants and their associated disposal systems may be in or near coal mining regions, maps of past or future mining activities are important to the design of a new disposal site. Such mining may affect the stability and drainage of the disposal schemes. Likewise, the disposal of wastes may, in some cases, seriously affect the safety and operation of the mining activity. Mine maps are usually available for review in the offices of the mine operator.

Individual Site Mapping. Individual mapping of the site is necessary not only for planning and design purposes, but also for the preparation of construction drawings and submittal drawings for review by the appropriate regulatory agencies. General site plans should typically be prepared to a scale of 1" = 400' or larger. In order to provide sufficient design detail, cross sections and design drawings are usually required at a scale of 1" = 100' or larger with 2 to 5 ft contour intervals. By means of photogrammetric methods, low-altitude, large-scale aerial photography can

provide large-scale topographic mapping appropriate for this use. In cases where additional surface detail may be required, such as at locations of drainage structures, aerial mapping may be supplemented with ground topographic surveys performed by survey parties. Since ground surveys are more expensive per unit area than aerial surveys, the combination of both methods will help to maximize the amount of site information collected and reduce the cost of this information.

Surficial Site Reconnaissance

After reviewing the available site information, a site visit is advisable in order to obtain a "feel" for the conditions shown in the reviewed information and to note additional site detail. The site visit should be conducted as a detailed site reconnaissance and is best performed by an experienced geologist or geotechnical engineer who can recognize the significant site features.

The reconnaissance will involve walking the entire site and observing vegetative cover, soil types, rock outcrops, spring activity, water flow quantities, slope conditions, conditions of cultural features and any other information necessary for a more complete assessment of the site. A site reconnaissance is best performed by two people for the sake of completeness and personal safety. A large-scale topographic site map is useful for recording observations and estimating distances while performing the reconnaissance.

Subsurface Investigation

The purpose of the subsurface investigation is to obtain a reasonably accurate determination of the physical properties of the subsurface soil and rock materials that will influence the design of the landfill or pond disposal method. It is important to recognize that the physical properties determined from testing samples of subsurface materials will, at best, be "reasonably" accurate and representative. This is due to the inherent nature of subsurface exploration and sampling, which only provides information regarding subsurface conditions along often widely spaced vertical lines and provides samples assumed to be representative in terms of lateral extent. Due to this vertical subsurface information and lack of horizontal information, interpolation between points of exploration is necessary and will involve a degree of uncertainty. To reduce this uncertainty and to adapt the exploration program to the requirements of the project and to the subsurface conditions, the engineer in charge of the investigation should be experienced in performing subsurface investigations, familiar with sampling and testing methods, and be capable of interpreting the results of the exploration and testing.

Exploratory Methods. The two most widely used methods of subsurface exploration are test borings and test pits. Due to the expense of drilling test borings, typically $10 to $20/lin ft, and based on the scope of the subsurface investigation, both methods are often used to explore a site. The advantages of using test borings are:

- Variety of drilling and sampling techniques available
- Ability to perform in situ testing as the hole advances
- Opportunity to measure water levels and obtain samples of groundwater
- Opportunity to install devices to monitor groundwater or soil and rock movements at any depth

Test pits are open excavations dug either by hand or power shovels. They are typically dug to the limits of the equipment used, usually 10 to 15 ft, or to refusal on rock. Test pits have the advantages of:

- Being less expensive than test borings
- Providing subsurface information over a larger lateral extent than test borings
- Providing a means of collecting large samples of material from a particular depth

Test pits are usually located in the field to provide supplemental data between test boring locations or to investigate the shallow subsurface soil conditions, such as in areas of potential borrow materials.

Drilling Methods. There are a number of drilling methods used to advance test borings through soil and bedrock strata. These include wash borings, rotary drilling and auger boring through soil, and percussion, rotary, and core drilling in rock strata. Auger boring is probably the most common form of soil drilling because of its ability to penetrate a variety of soil types with relative ease and permits recovery of soil samples. Where rock samples are desired, core drilling is used. Depending on the site terrain, either truck-mounted or skid-mounted drill rigs may be used. Truck-mounted drill rigs will generally drill faster due to their heavy weight and power. Skid rigs, on the other hand, are lighter weight and more maneuverable in rugged or heavily wooded terrain. Reference Sources 8-1,2 and 3 provide detailed descriptions of these drilling methods.

Sampling Methods. There are two primary methods of soil sampling, split-spoon sampling and thin-walled tube sampling. The split-spoon method provides a disturbed soil sample, while thin-walled tube sampling is used to obtain relatively undisturbed samples.

The spilt-spoon method of sampling can be used to sample a wide variety of soil types and at the same time provide information concerning the in situ density or compactness of the soil. This sampling technique uses a standard sampling device consisting of a 30 in. long pipe, 2-1/2 in. I.D., split into two lengthwise halves, thus, the name split-spoon. The two pipe halves are held together by threaded sleeves at the top and bottom. Soil is sampled by extending the split-spoon to the bottom of the boring at any depth and driving the sampler into the soil at the bottom of the boring. Samples are usually taken at three or five ft intervals and at changes in stratum. The manner in which the standard split-spoon sampler is driven has been standarized along with the design of the spoon, and together constitute the Standard Penetration Test (ASTM D1586). (8-4) The sampler is driven by a 140 lb weight dropping 30 in. After the sampler is driven 1-1/2 ft into the soil, the sampler containing the soil sample is removed from the bottom of the boring and the split-spoon halves separated. The soil sample is then visually inspected and described by the driller, recorded in the drillers log, and sealed in a glass jar for inspection and testing by the engineer.

Where relatively undisturbed soil samples are desired, a thin-walled tube is pushed into the undisturbed soil at the bottom of the boring. The tube is then removed and the ends of the tube are capped and sealed with wax. The tube is then ready to be carefully transported to the engineer's laboratory where the sample may be ejected from the tube and used for a variety of tests. Thin-walled tube sampling is usually performed in order to obtain relatively undisturbed samples of significant strata of fine-grained soils such as clays or silts containing few rock fragments. Undisturbed sampling of granular sands and gravels is not typically required and is not possible using this sampling method.

Other methods of soil sampling are available and generally employ variations of equipment and procedures similar to those discussed above. Such sampling methods include the use of special sampler types and require specialized techniques which are described in the literature. (8-1,2)

When rock samples are desired for inspection and testing, core drilling is performed. Rock core drilling utilizes the same drill rig as that used to drill and sample soil. A hollow-diamond bit and core barrel are used to obtain rock core specimens. As the diamond bit rotates, it produces an annular cut in the rock and causes the rock core to extend into the core barrel above the bit. The rock core is recovered by pulling

the bit and core barrel from the bore hole. There are a variety of drill bit sizes to provide different diameter core samples. The bit size used most often is an NX size which provides a rock core 2-1/8 in. in diameter.

Locations and Depths of Test Borings. The selection of test boring locations and depths to be penetrated is difficult to specify because they are dependent on:

- Site and project size
- Type of sludge disposal, either wet or dry
- Complexity and configuration of the project design
- Weight and dimensions of the proposed structures
- Characteristics and complexity of the subsurface stratigraphy
- Groundwater conditions

General rules of thumb have been developed for estimating the number and depths of test borings required for a project; however, these can be misleading and quite dangerous to use due to the number of variables affecting the selection of test boring locations and depths. Test boring locations and depths are best planned by a geotechnical engineer familar with the project requirements and general site conditions.

Usually, for large projects such as long-term disposal facilities, widely spaced preliminary test borings should be performed to identify major subsurface site characteristics first. Then, as the facility design becomes more detailed, additional exploration may be performed in specific areas as required by the design. It is not uncommon for some test borings to be located or relocated and depths changed in the field as information provided by the first borings is obtained.

The type of disposal operation will influence the program of subsurface explorations. Typically, ponding disposal methods involving construction of dikes or dams will require a greater number of test borings than incised pond configurations and dry landfill disposal methods.

As a general guide, test borings for the investigation of a proposed dike or dam should explore the following areas:

> The Longitudal Centerline of the Embankment. Sufficient test borings should be performed along the longitudinal centerline of the embankment to provide a reasonably accurate geologic section across the site of the structure. These borings should be drilled between the two abutments, taking into account the maximum extension of the dam at its final constructed height. The test borings should be

drilled to a depth that will overlap in elevation with adjacent borings. The test borings should normally identify the top of the bedrock surface and the condition of that rock for some depth.

The Section Perpendicular to the Embankment. Several test borings should be located along the section perpendicular to the face of the dam where the highest portion of the embankment will be. This row of borings should include a test boring at the upstream and downstream toe of the proposed dam, and also borings located sufficiently upstream and downstream of the dam to allow a geologic section to be developed. This section will be important to seepage and stability analyses and should penetrate the bedrock surface.

The Area to be Covered by Slurry Waste. The area to be inundated by the impounded waste should be investigated sufficiently to identify the soil types present and groundwater levels. This information will be important to evaluate the potential for groundwater contamination by possible sludge leachate and to identify possible borrow sources of construction materials.

The Location of Appurtenances. Borings should be performed at the location of such appurtenances as decants and spillways when they will be founded in natural soil or rock. The depth of these borings should be at least equal to the width of the structure and preferably be extended into dense soil or competent rock.

Subsurface Voids. In the case of past deep mining within the area of the disposal site, or solution caverns such as are sometimes found in areas of limestone formations, borings should be drilled to investigate the extent and condition of these subsurface voids as well as identify the overlying rock type and condition. Such subsurface voids can be detrimental to the stability of the embankment, accelerate groundwater contamination and, in the case of an active mine, the disposal facility may be hazardous to the mining operations.

Site-Specific Requirements. Additional test borings will probably be necessary to analyze specific details of the disposal design and to explore geologic factors peculiar to the site. These test borings, as well as the entire test boring program, are best planned by an engineer experienced in subsurface investigations and dam design.

For non-impounding landfill disposal embankments, test borings are typically located perpendicular to the embankment face, within the area to be covered by the waste materials, and located in a manner to investigate possible subsurface voids and, where necessary, to investigate site and design specific requirements similar to that described above for dam investigations.

Field Testing and Monitoring

Some amount of field testing and monitoring will be necessary during the subsurface investigation of the site. This testing and monitoring will supplement the laboratory testing of the soil and rock specimens collected and provide ground and surface

water information. The most common field tests are the standard penetration, shear strength, permeability and in-place density tests. The basic monitoring requirements during a disposal site investigation are the periodic measurement of groundwater levels and quality as well as measurement of surface water flows.

Standard Penetration Tests. Standard penetration tests should always be performed during test boring operations in soils. This is the simplest method of obtaining information concerning the degree of compactness or relative density of in situ soil. As described previously, the test involves driving the standard split spoon sampler 1.5 ft into the soil at regular intervals during the drilling of a test boring, using a 140 lb hammer dropping 30 in. The test results are expressed as the number of hammer blows required to drive the sampler the last 12 in. into the soils. Combined with the description of the soil samples obtained and simple classification tests, the standard penetration test can provide a great deal of information meaningful to the geotechnical engineer and to the analysis of the disposal site. In the case of sand strata, the relative density is a significant indicator of the shear strength, bearing capacity, and settlement characteristics of the material. Table 8-1 shows the relation between the number of hammer blows (N) and the relative density.

Table 8-1

RELATIVE DENSITY OF SANDS ACCORDING TO RESULTS OF STANDARD PENETRATION TEST

NO. OF BLOWS N	RELATIVE DENSITY
0 to 4	Very Loose
4 to 10	Loose
10 to 30	Medium
30 to 50	Dense
Over 50	Very Dense

Source: Terzaghi, K., and Peck, R. B., Soil Mechanics in Engineering Practice, 2nd Edition, John Wiley and Sons, Inc., New York, 1967.

When clay is penetrated using the standard penetration test, the shear strength of the clay can be crudely estimated based on N, the number of hammer blows and the following table:

Table 8-2

RELATION OF CONSISTENCY OF CLAY,
NUMBER OF BLOWS (N) ON SAMPLING SPOON, AND
UNCONFINED COMPRESSIVE STRENGTH (qu)

CONSISTENCY	VERY SOFT	SOFT	MEDIUM	STIFF	VERY STIFF	HARD
N	<2	2 to 4	4 to 8	8 to 15	15 to 30	>30
qu, t/ft^2	<0.25	0.25 to 0.50	0.50 to 1.00	1.00 to 2.00	2.00 to 4.00	> 4.00

Source: Terzaghi, K., and Peck, R. B., Soil Mechanics in Engineering Practice, 2nd Edition, John Wiley and Sons, Inc., New York, 1967.

The use of these tables does not eliminate the need for laboratory testing, and the user of the tables should be familiar with their limitations and applications.

In-Place Shear Strength Tests. By means of a vane shear device, in-place shear strength determinations can be made of soft materials free of rock particles, such as soft foundation clays, as well as settled sludge solids. The test involves using a four-bladed vane attached to the end of a vertical rod. The device is pressed into the soil at the bottom of a test boring, and the torque required to rotate the vane and shear the soil is recorded. This torque is a measure of the in situ shear strength of the soil.

Field Permeability Test. To estimate seepage rates and quantities through foundation materials, in situ tests can be performed to determine the permeability of soil or rock strata revealed in the test borings. This type of test can consist of a rather inexpensive variation of a falling head permeability test performed in the test boring holes drilled, or more accurate and more expensive field pumping tests. The selection of the appropriate type of field permeability test will require engineering judgment. To understand more of what these tests entail, the reader is referred to references (8-2 and 3).

In-place Density Tests. In-place density tests are usually performed as a quality control measure to determine the degree of compaction attained during construction of pond embankments and dry landfill disposal of FGD sludge. These are standard tests with procedures described by the American Society for Testing and Materials (ASTM). These tests are described in ASTM specifications D-1556 and D-2167. (8-4)

Measurement of Groundwater Levels. Determining the location of the groundwater level is important in terms of the analysis of embankment stability, the extent and likelihood of groundwater pollution resulting from sludge leachate, and construction and excavation requirements. It is equally important to monitor changes in the groundwater level during and after major phases of construction and FGD waste disposal. Groundwater levels are usually determined by means of observation wells. These wells often consist merely of a perforated plastic pipe inserted the full depth of a drilled test boring. Groundwater measurements will be further discussed later in this section under the title of Monitoring and Instrumentation.

Measurement of Surface Water Flows. From the standpoint of the hydraulic design of either a ponding or landfill disposal facility, the measurement of the quantity and quality of surface water flows from springs and seeps is important. This information is important to the design of subsurface and surface drainage facilities, embankment stability analyses, and assessment of the impact of FGD disposal on ground and surface water quality. Flow measurements and, particularly, water quality tests performed during the initial site investigation will provide baseline data from which such design and evaluation may be based.

Laboratory Testing

Meaningful laboratory soil test results are a necessary basis for the design of any sludge disposal facility, whether it be a ponding or landfill scheme. The magnitude of the testing programs will vary according to the physical characteristics of the proposed disposal plan, and the surface and subsurface conditions of the disposal site. Development of an appropriate testing program should be left to an experienced geotechnical engineer.

A summary of laboratory tests frequently used is presented in Table 8-3. Of these tests, the simplest and often the most important, in terms of the amount of information that can be derived, are the Classification or Index Property Tests. The system of classification most widely used by geotechnical engineers and governmental agencies is the Unified Classification System. This system is shown in Table 8-4 and

Table 8-3

SUMMARY OF TYPICAL LABORATORY SOIL TESTS FOR VARIOUS MATERIALS

TEST	TYPE OF MATERIAL: FINE-GRAINED SOILS	FINE-GRAINED SOILS	CRUSHED ROCK	USE IN DESIGN	ASTM DESIGNATION
1. Classification of Index Property Tests				Evaluation of feasible configurations	
A. Water content	a	a	-	Correlation of materials	D2216
B. Natural density	c	-	-	Selection of samples for other tests	-
C. Specific gravity	b,c	b,c	b	Selection of borrow areas	D854, C127, C128
D. Atterberg limits and and	b,c			Specification of construction procedures	D423, D424, D427
E. Grain-size analysis	b,c	b,c	b	Determination of filter and drainage requirements	D422, D2217
2. Compaction Tests:					
A. Standard Proctor	b	-	-	Evaluation of sample preparation for other tests	D698
B. Modified Proctor, and/or	b	-	-		D1557
C. Relative density	-	b	b	Specification of placement requirements	D2049
3. Permeability:	c,d	d	-	Seepage analyses Determination of pore pressures for stability	D2434
4. Consolidation:	c,d	-	-	Settlement analyses	D2435
5. Shear Strength:					
A. Direct shear	c,d	d	d		D3080
B. Triaxial compression, and	c,d	d	-	Stability analyses	D2850
C. Unconfined compression	c,d	-	-	Structure foundation design	D2166

Legend: The types and numbers of tests conducted will vary, depending on the purpose of the testing program and the conditions being investigated. The use of these guidelines should not be substituted for site-by-site evaluation by a qualified geotechnical engineer.

a - indicates tests normally conducted on all samples
b - indicates tests normally conducted on representative disturbed samples
c - indicates tests normally conducted on representative undisturbed samples
d - indicates tests on specially prepared samples to simulate as constructed-behavior

Source: E. D'Appolonia Consulting Engineers, Inc., Engineering and Design Manual, Coal Refuse Disposal Facilities, U. S. Department of Interior, Mining Enforcement and Safety Administration, 1975.

Table 8-4
UNIFIED SOIL CLASSIFICATION SYSTEM
(Laboratory Classification Criteria Excluded)

Major Divisions			Group Symbols	Typical Names	Field Identification Procedures (Excluding particles larger than 3 inches and basing fractions on estimated weights)			Information Required for Describing Soils
1	2		3	4	5			6
Coarse-Grained Soils: More than half of material is larger than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye	Gravels: More than half of coarse fraction is larger than No. 4 sieve size. (For visual classification, the ¼-in. size may be used as equivalent to the No. 4 sieve size)	Clean Gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines.	Wide range in grain sizes and substantial amounts of all intermediate particle sizes.			For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics. Give typical name; indicate approximate percentages of sand and gravel, max. size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses. Example: Silty sand, gravelly; about 20% hard, angular gravel particles ½-in. max. size; rounded and subangular sand grains coarse to fine; about 15% nonplastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM).
			GP	Poorly-graded gravels, gravel-sand mixtures, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.			
		Gravels with Fines (Appreciable amount of fines)	GM	Silty gravels, gravel-sand-silt mixtures.	Nonplastic fines or fines with low plasticity. (for identification procedures see ML below)			
			GC	Clayey gravels, gravel-sand-clay mixtures.	Plastic fines (for identification procedures see CL below)			
	Sands: More than half of coarse fraction is smaller than No. 4 sieve size.	Clean Sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines.	Wide range in grain sizes and substantial amounts of all intermediate particle sizes.			
			SP	Poorly-graded sands, gravelly sands, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.			
		Sands with Fines (Appreciable amount of fines)	SM	Silty sands, sand-silt mixtures.	Nonplastic fines or fines with low plasticity. (for identification procedures see ML below)			
			SC	Clayey sands, sand-clay mixtures.	Plastic fines (for identification procedures see CL below)			
Fine-Grained Soils: More than half of material is smaller than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye					Identification Procedures on Fraction Smaller than No. 40 Sieve Size			
					Dry Strength (Crushing characteristics)	Dilatancy (Reaction to shaking)	Toughness (Consistency near PL)	
	Silts and Clays: Liquid limit less than 50		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.	None to slight	Quick to slow	None	Give typical name, indicate degree and character of plasticity, amount and maximum size of coarse grains, color in wet condition, odor if any, local or geologic name, and other pertinent descriptive information; and symbol in parentheses. For undisturbed soils and information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions. Example: Clayey silt, Brown, slightly plastic, small percentage of fine sand, numerous vertical root holes, firm and dry in place, loess, (ML).
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.	Medium to high	None to Very slow	Medium	
			OL	Organic silts and organic silty clays of low plasticity.	Slight to medium	Slow	Slight	
	Silts and Clays: Liquid limit greater than 50		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.	Slight to medium	Slow to none	Slight to medium	
			CH	Inorganic clays of high plasticity, fat clays.	High to Very high	None	High	
			OH	Organic clays of medium to high plasticity, organic silts.	Medium to high	None to Very slow	Slight to medium	
Highly Organic Soils			Pt	Peat and other highly organic soils	Readily identified by color, odor, spongy feel and frequently by fibrous texture.			

Source: U. S. Bureau of Reclamation (USBR), Design of Small Dams, 2nd Edition, 1973.

basically divides soils into two classifications: coarse-grained and fine-grained. The Unified Classification System is arranged in such a manner that classification can be performed in the field by visual inspection and simple manual tests, as described in Table 8-4. A numerical version of the classification system is used for laboratory classification of soil samples in order to more accurately classify selected samples and to check the field identifications. Based on the soil classifications determined, correlation of the soil at the site is greatly facilitated and the task of selecting additional, appropriate tests is also made easier. In addition, based on the soil classification, rough approximations of the physical properties of the materials can be empirically determined. This sort of empirically-derived information cannot replace detailed laboratory soil tests; however, it can provide guidance during early planning stages of the disposal facility and help in the selection of additional sample testing.

POND DESIGN

Introduction

The design of a pond for the ultimate wet disposal of FGD wastes must be realistic in terms of the physical conditions of the selected site, the available construction materials, the physical and chemical properties of the particular waste to be impounded, and be realistic in terms of the unique requirements of the utility plant operation.

A majority of the alternative pond configurations previously presented will involve the design and construction of a dam or dike to form the impoundment. These are commonly of earthfill construction. It is likely that most embankments constructed for the disposal of wet FGD wastes, with the possible exception of some cross-valley configurations, may be categorized as small to intermediate in size, based on the U.S. Corps of Engineers dam classification system. This dam size classification is shown in Table 8-5.

Table 8-5

DAM SIZE CLASSIFICATION

CATEGORY	STORAGE (ac-ft)	HEIGHT (ft)
Small	<1000	<40
Intermediate	>1000 and <50,000	>10 and <100
Large	>50,000	>100

Source: Federal Register, Volume 39, No. 168, August 28, 1974.

For the purpose of this text, emphasis will be placed on the design of small and small intermediate size impoundments using simplified design techniques. An excellent reference for this type of design is Design of Small Dams by the U.S. Bureau of Reclamation, although some states have more rigorous dam safety requirements. (8-3) More rigorous and precise design methods are available; however, their use is typically reserved for larger impounding structures where their use is more economically justified.

Design Criteria

The design of an FGD waste disposal pond requiring dike or dam construction is very similar to the design of a water supply impoundment, except that the unit weight of the fluid waste is on the order of 1.5 times the unit weight of water. Because of this, the design criteria for sludge disposal ponds is similar to that of any small dam and must provide for the safe impoundment of waste materials during all phases of construction and disposal operation and, in addition, must provide safe, long-term containment of the waste material after the completion of the disposal operation and abandonment of the site. The following design criteria must be met to accomplish this:

- The impoundment must provide sufficient capacity or outlet structures to prevent embankment overtopping during the combined inflows of the slurry waste and an appropriate design flood.
- The stability of embankment slopes must be maintained during construction phases and during all conditions of the disposal operation.
- The embankment foundation materials must be capable of supporting the loads imposed by the designed structure.
- The flow of seepage through the earth embankments and foundations must be controlled to prevent internal erosion and embankment instability.
- The exposed surfaces of the embankments must be protected against erosion due to wave, wind and rain action.

It is obvious the above design criteria will prove satisfactory only if proper construction methods and field supervision and control are used to implement the design.

It should also be noted that the control of seepage flow through foundation and embankment materials, noted in the fourth criterion, is referenced in terms of the stability of these materials. Seepage control for reducing potential leachate contamination of groundwater should be treated separately as an environmental protection measure and is discussed in Section 7 - LEACHATE. Usually control of leachate may be accomplished through the use of impermeable pond liners. These kinds of liners should not be considered as a long-term seepage control device for dike or dam stabilization because of their unproven performance and life expectancy when in contact with FGD sludge. Finally, it should be recognized that sludge impoundment also differs from common water impoundments in that the settlement of sludge solids is desirable while siltation in a water storage reservoir is not, and that the buildup of settled sludge solids should progressively reduce some of the seepage problems that must be considered in water impounding structures.

General Design Considerations

It is evident from the above design criteria that the general considerations for design can be grouped into the broad categories of geotechnical design considerations for all but the first criterion, and hydrologic and hydraulic design considerations for the first design criterion.

The geotechnical design considerations must include:

- Selection of the type of earth embankment
- The design of the embankment foundation in terms of stability, settlement and seepage
- The design of the embankment in terms of stability, seepage, surface erosion and, if necessary, staged construction

The hydrologic and hydraulic design considerations, to meet the first design criteria, should include:

- Determination of pond inflow quantities resulting from surface water runoff, direct precipitation, and FGD waste disposal
- Effect of the proposed pond configuration on hydraulic design requirements
- Design storm criteria
- Available storage capacity of the proposed pond
- Requirements for outflow structures

Selection of the Type of Earth Embankment

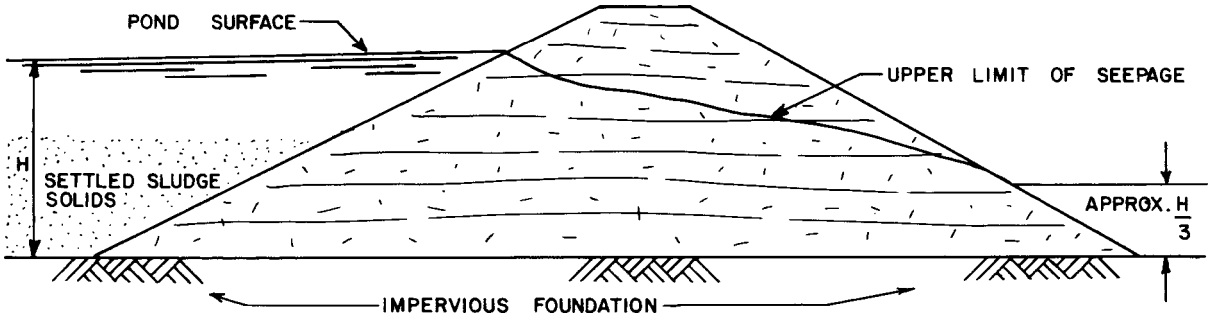
The selection of the type of embankment or dam that may be constructed is primarily determined by the variety of readily available materials at or near the construction site. There are two types of embankments commonly used for construction of small and small intermediate size dams that are appropriate for discussion within the scope of this text. These are the homogeneous type and zoned embankment type.

Homogeneous Type. A homogeneous embankment is constructed of one type of soil material. The material used must be sufficiently impervious to retard the flow of sludge supernatant through the embankment. The term "retard" is important to understand because seepage through and under impounding structures, regardless of the type of construction, cannot be prevented because no material is completely impermeable. In the case of a purely homogeneous embankment under steady state conditions, seepage will emerge on the downstream slope at a height equal to approximately one-third the depth of the impounded pool. Due to this seepage condition and possible rapid draw-down of water levels during flood regulation or for recovery of plant makeup water, both the upstream and downstream slopes of an homogeneous embankment must be relatively flat to prevent slope instability. Figure 8-12(A) shows a typical cross section of such an homogeneous embankment.

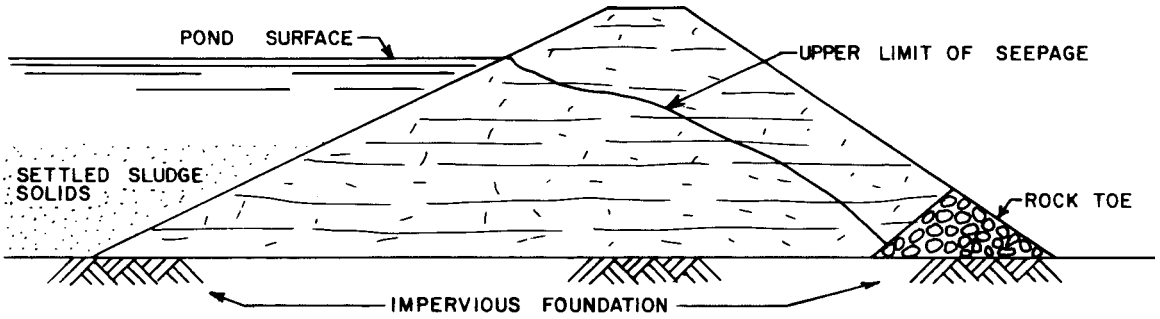
To permit steeper slope construction in order to reduce material quantities and, construction costs, rock toes or filter blankets are usually incorporated into the homogeneous embankment design to redirect and control the seepage through the embankment. These two forms of seepage control are shown in Figure 8-12(B and C).

The necessity of incorporating the above drainage provisions make the use of completely homogeneous construction uncommon and undesirable for the long-term storage of sludge. The modified type of homogeneous embankment that includes rock toe or filter blanket provisions is commonly used where readily available soil types of different permeabilities are absent or limited.

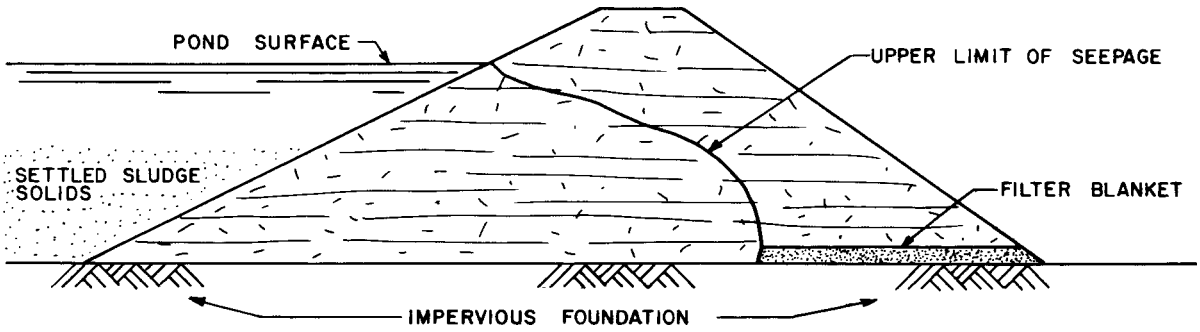
Zoned Embankment Type. A zoned type of embankment is one in which an impervious core is built within a shell of more permeable soil. The pervious shell, typically constructed of sand, gravel, rock, or mixtures of these materials, serves to support and protect the less permeable core materials. The pervious outer zones provide stability to the upstream embankment slope during periods of rapid draw-down of the supernatant, and performs as a drain to control the line of seepage on the downstream embankment slope. Figure 8-13 shows a typical cross-section of a zoned embankment.



(A) Completely Homogeneous



(B) With Rock Toe



(C) With Filter Underdrain

Figure 8-12. Homogeneous Pond Embankments.

Source: U. S. Bureau of Reclamation, (USBR), Design of Small Dams, 2nd Edition 1973.

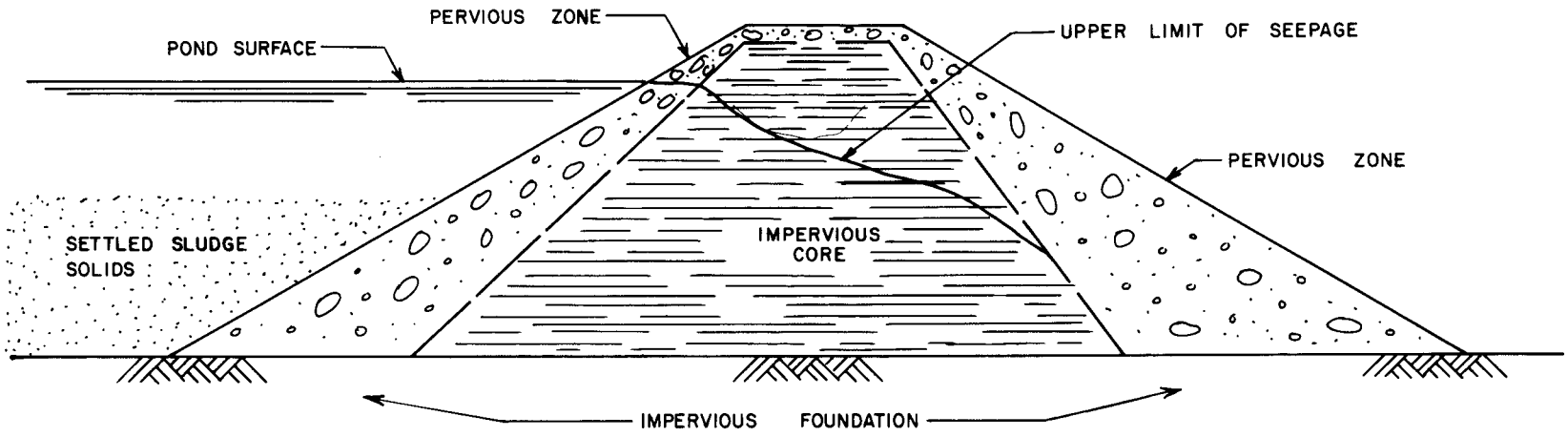


Figure 8-13. Typical Zoned Embankment Section.

The impervious core of the embankment typically has a minimum thickness of 10 ft and, at any elevation, the thickness should be greater than or equal to the height of the dam above that elevation. The maximum width of the embankment core is determined by stability and seepage conditions and on the availability of suitable fine-grained material.

It may be evident from this discussion that if a variety of soils with contrasting permeabilities is readily available at or near the construction site, the zoned embankment type should be chosen over the homogeneous type of embankment because of reduced construction costs brought about by the need for reduced material volumes.

The Embankment Foundation Design

The design criteria presented previously require that the embankment foundation materials be capable of supporting the imposed loads of the impounding structure and provide sufficient seepage control to prevent internal erosion. While the foundation of an embankment is not actually designed, there are methods of treating the foundation to meet this criterion. These treatments may involve stabilization of weak foundation materials, reducing seepage in permeable foundations, or collection of under seepage.

Ordinarily, complex analyses of the foundations for small impounding embankments, which comprise the majority of the situations being dealt with in this text, is not warranted. In these cases, it is appropriate to base the foundation design on judgment and the use of substantial factors of safety. The construction costs saved through the use of more precise design methods is seldom justified due to the cost of the additional field exploration, testing and engineering required. However, in the case of unusual site conditions and the sometimes large cross-valley impoundment configurations that may be developed, the services of a geotechnical consultant should be obtained.

In order to determine the appropriate foundation treatment for a particular impoundment site, the embankment foundation must be classified according to its general character. There are three main classifications:

- Rock foundations
- Coarse-grained foundations (sand and gravel)
- Fine-grained foundations (silt and clay)

Often, pervious coarse-grained foundation materials present few problems in terms of settlement and stability. The opposite is true for fine-grained foundations where seepage is normally not a problem, and settlement and stability become significant considerations. In the case where the foundation soils are similar in permeability and shear strength to that of the proposed embankment, little foundation design or treatment will be necessary. The minimum foundation treatment required for any embankment construction is the removal of topsoil, organic matter or other unsuitable material.

The foundation conditions at a particular impoundment site may consist of more than one of the above classes of foundations, and may involve a variety of design problems. Such a case may exist where sands and gravels or fine-grained soils exist in a valley floor, or at the base of a hillside while rock may be exposed along the hillside.

The following discussions will deal with the various foundation treatments required by each of the foundation classifications listed above.

Rock Foundations. The principal concern with ponds constructed on bedrock is leakage and loss of impounded water through joints, crevices, fault planes and permeable strata located beneath the embankments. Design of a storage impoundment, such as a disposal pond, should consider sealing these sources of leaks to a depth equal to the depth of the proposed impoundment above the rock. Unless subsurface exploration shows rock with little or no openings, grout is often used to seal the rock.

When constructing the impounding embankment on bedrock, it is important to obtain a good seal or contact between the impervious section of the dike and the bedrock surface. When the bedrock surface is smooth, a concrete cutoff wall may be constructed to restrict the flow of seepage. If the rock surface is soft and prone to rapid weathering, such as some shales and claystones, it may be necessary to excavate any weathered rock exposed or produced during construction, immediately prior to placement of the embankment materials.

In most cases where embankments are to be constructed on bedrock or where bedrock is reached through trenching of the overburden, substantial rock excavation is seldom required.

Coarse-Grained Foundations. Coarse-grained foundation materials will consist of soil particles ranging from sand size to gravel size, and will often consist of stratified mixtures of sand and gravel. The primary design consideration for these pervious foundation materials is the amount of seepage that will occur through them and the uplift or seepage forces that will result. The analysis of seepage through pervious foundation materials beneath an embankment is important in terms of stability against internal erosion of the soil. The loss of water from an FGD waste disposal pond may also be important where the sludge supernatant is to be recycled for makeup water at the power plant, or where groundwater contamination may result.

To determine the amount of seepage that will occur under a pond embankment, a reasonably accurate estimate of the coefficient of permeability of the foundation soils is required. Field methods for determining the coefficient of permeability have been previously discussed. Once the foundation permeability has been determined, the amount of seepage can be estimated using the Darcy formula:

$$Q = KiA$$

where:

Q = seepage discharge per unit of time

K = coefficient of permeability

i = hydraulic gradient

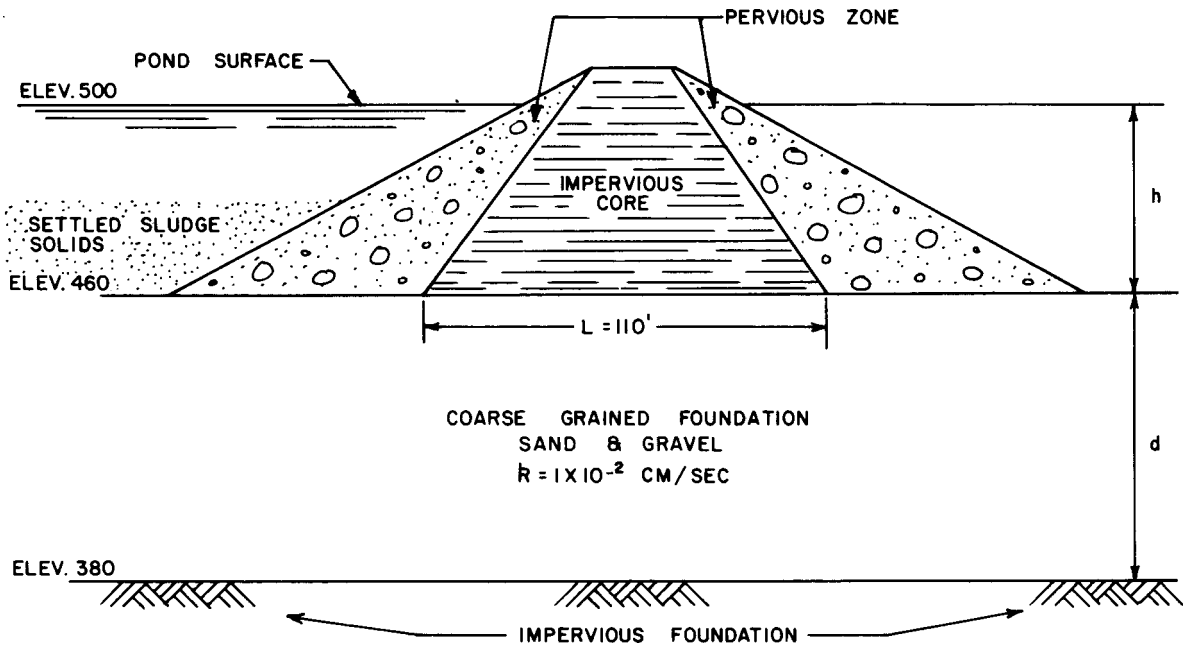
i = h/L = difference in head ÷ the length of the drainage path

A = cross sectional area of foundation material through which seepage flows

The accuracy of this calculation should be considered an estimate of an order of magnitude, and will depend on the accuracy of the permeability coefficient and the homogeneity of the foundation material. For the more common stratified foundations, where the vertical permeability is less than the permeability in the horizontal direction, an average coefficient of permeability should be used in the formula based on the permeability of each stratum which is weighted by the thickness of the respective layers. This weighted average permeability will provide a conservative estimate of the seepage quantity.

An example calculation of the quantity of seepage under an embankment using the Darcy formula is shown in Figure 8-14.

The seepage forces associated with this flow through the foundation and at the downstream toe of the embankment, result from the friction between the percolating water



$$Q = kiA$$

$k = 1 \times 10^{-2}$ cm/sec = 0.02 ft/min

$$i = \frac{h}{L} = \frac{500 - 460}{110} = 0.364$$

A = (d) (unit width of 1 ft) = (80')(1') = 80 ft^2

Q = (0.02 ft/min)(0.364)(80 ft^2)

= 0.581 ft^3/min per ft of embankment length

or

= 4.35 gpm/ft of embankment length

Figure 8-14. Example Calculation of Seepage Underflow.

and the surfaces of the soil pores through which it flows. The seepage forces that develop are proportional to the friction loss over the length of the drainage path and act in the direction of flow. If the seepage forces at the downstream toe of the dam exceed the weight of the soil, "piping" occurs and soil is washed from beneath the toe of the slope. This internal erosion then would progress backwards under the dam creating a continuous subsurface channel or pipe that would lead to loss of the impounded sludge supernatant, possibly a portion of the sludge solids, and would severely weaken or cause the embankment to fail.

The magnitude of the seepage forces depends on the rate of head loss experienced in the foundation soils. Coarse-grained soils, due to their open and pervious structure, offer less frictional head loss than do fine-grained soils of low permeability. The magnitude of these forces and their distribution in the foundation soils can be determined by the graphical construction of a flow net. The method of sketching a flow net and its application to the solution of subsurface seepage problems is presented in references 8-2,6,7, and 8. The graphical construction of an accurate flow net requires considerable time and experience, especially where the foundation profile is strongly stratified or where drains or cutoffs are to be installed as part of the embankment. The use of flow nets for seepage analysis is also limited where minor geological features exist that may alter the seepage flow from that theoretically assumed. Due to the need for detailed subsurface exploration and analysis to produce an accurate flow net and, in light of the above limitations, the construction of flow nets for the design of small size impounding embankments is not necessary.

There are various methods for controlling the flow of seepage through pervious embankment foundations in order to meet the third design criterion, previously presented for the successful design of an impoundment. The method of control will depend on the requirements for preventing the loss of the sludge supernatant from the pond surface, the stability of the foundation materials with respect to the seepage forces, and the influence of foundation stratification with layers of less permeable soils.

Commonly used methods for restricting the flow of seepage beneath an embankment are:

- Cutoff trenches
- Sheet piling cutoffs
- Upstream impervious blankets
- Filters

These methods should be adequate for a majority of pervious foundation conditions. Other foundation seepage control methods exist and are commonly used in a case where the pervious foundation is overlain by a stratum of relatively impervious soil ranging in thickness from three ft to a thickness equal to the depth of the impoundment. These additional methods and those listed above are discussed by the U.S. Bureau of Reclamation and, when necessary, reference to this source is recommended. (8-3)

Cutoff Trenches. Whenever the pervious embankment foundation is relatively shallow, 20 to 30 ft thick, seepage should be cut off by a trench excavated to the underlying bedrock or impervious soil stratum. This is the most effective means of controlling the quantity of seepage and preventing excessive seepage forces at the downstream toe of the embankment.

The minimum bottom width of a cutoff trench, usually 20 ft, should be sufficient to allow operation of excavating and compaction equipment and proper contact with the underlaying impermeable stratum. An adequate bottom width for a cutoff trench will be a function of the height of the impounded sludge and the depth of the trench, and may be determined by the following formula:

$$w = h-d$$

where:

w = the bottom width of the cutoff trench

h = the maximum head of sludge slurry to be impounded

d = depth of the trench below the ground surface

In cases where groundwater is encountered during excavation, dewatering may be required using well points or sumps.

A variation of the cutoff trench method is the partial cutoff trench. Where generally pervious foundation materials extend to depths greater than about 30 ft, a partial cutoff trench may effectively reduce seepage forces by increasing the vertical path of the underseepage. The partial cutoff trench is only effective where it will intercept shallow, more pervious strata than that located at deeper elevations. Where possible, the partial cutoff trench should terminate in a less pervious stratum located within the generally coarse-grained foundation. Figure 8-15 shows typical cutoff and partial cutoff trench configurations.

Sheet Piling Cutoffs. Steel sheet piling can be used to increase the depth of a cutoff. The use of sheet piling is typically limited to pervious foundation materials free of cobbles and boulders which are relatively easy to penetrate. It is difficult to obtain a watertight seal between the interlocking sheeting sections and, therefore, a sheet piling cutoff should be considered 80 to 90% effective when it is terminated in an impervious layer. Figure 8-16 shows such a sheet piling cutoff.

Upstream Impervious Blankets. The upstream impervious blanket method for reducing the flow of seepage is commonly used where the pervious foundation materials are too deep to allow effective cutoffs to be constructed. The upstream blanket method of seepage control

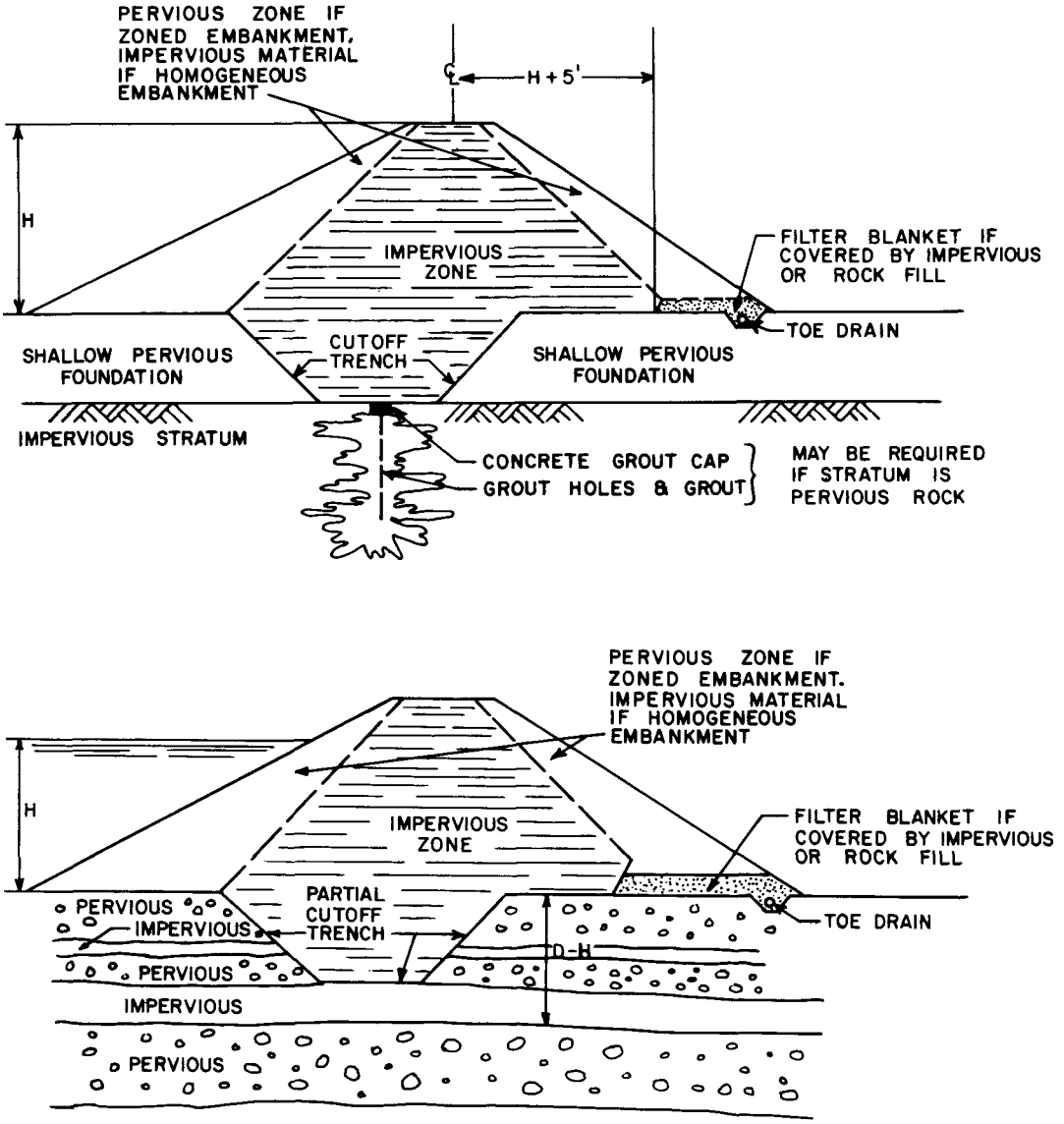


Figure 8-15. Cutoff and Partial Cutoff Trenches.

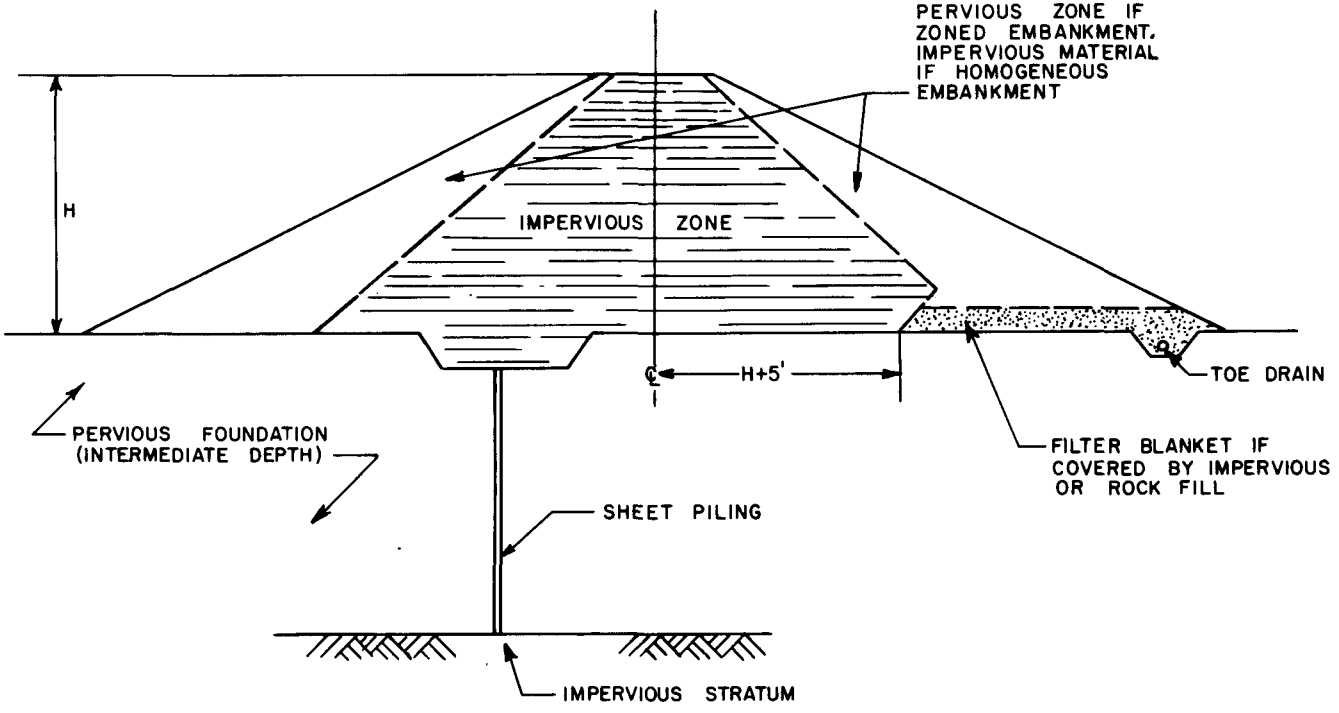


Figure 8-16. Typical Sheet Piling Cutoff.

is particularly attractive and applicable to the design of FGD waste ponds because of the relatively impermeable deposits of settled sludge solids that will form in the pond as disposal progresses. Once such a blanket of sludge solids forms, the flow of seepage and resulting seepage forced beneath the embankment is greatly reduced due to the increased length of the seepage flow path and the increased frictional head loss offered by the sedimented sludge. The requirements for an effective upstream impermeable blanket are that the blanket must be a minimum of three ft thick and be in contact with the impermeable portion of the embankment. For a zoned type of embankment, this would require the banket to be constructed beneath the upstream pervious shell of the embankment before the impoundment becomes operational. Also, prior to the sedimentation of a sufficiently thick layer of sludge solids, foundation seepage must be controlled. This seepage control may be accomplished by one of the previously-mentioned seepage control methods, by a pond liner that may be required anyway to reduce leachate contamination of groundwaters, or by a downstream filter blanket and filters that will be subsequently discussed. When naturally-occuring impermeable materials exist at or near the ground surface within the impoundment area, an effort should be made to leave them in place and undisturbed.

Downstream Filter Blankets and Toe Drains. Regardless of the effectiveness of the impervious blanket and settled sludge solids to reduce seepage quantities and forces, filter blankets and toe drains should be included in the pond design to control and collect seepage that will result downstream of the embankments. This will help to insure not only long-term embankment stability, but will also serve to collect and allow monitoring of the quality of seepage or leachate that will occur with time beneath and through the pond embankments.

Horizontal filter blankets should be designed for any dam bearing on a relatively homogeneous and deep pervious foundation where positive seepage cutoffs are not provided beneath the embankment. Downstream filter blankets permit the collection of seepage discharges below the embankment, reduce the risk of piping failures and subsurface erosion by providing weight to the downstream area and, when properly designed, the movement of foundation soil particles by the flow of seepage. Also, when constructed in conjunction with a homogeneous type of embankment, as will be subsequently described, the filter blanket will serve to lower the water surface within the embankment and, thus, increase the stability of the embankment. Where an embankment without seepage cutoff provisions is founded on a stratified pervious foundation, a filter blanket located at the downstream toe will not be effective in collecting foundation seepage because upward seepage flow into the blanket is reduced due to the greater horizontal permeabilities of the stratifications.

In order to simplify the design of the required length of filter blanket for the purpose of designing small to small intermediate size dikes for pond disposal facilities, the recommended blanket length is three times the height of the embankment. The general configuration of the filter blanket is shown in Figure 8-17 for both zoned and homogeneous types of embankments without seepage cutoff provisions.

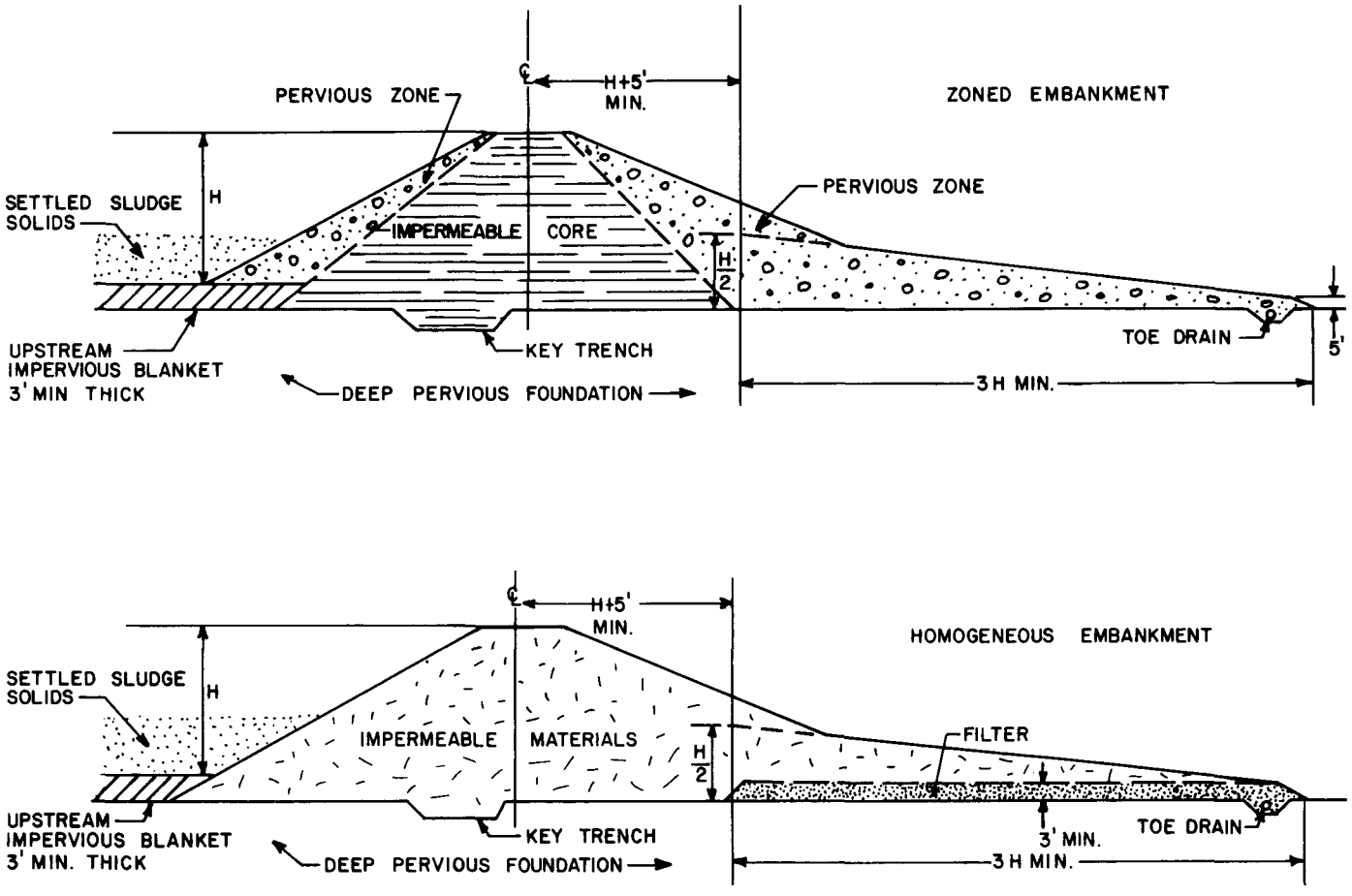


Figure 8-17. Upstream Impervious Blankets and Downstream Filter Blankets.

Toe drains are usually constructed in conjunction with downstream filter blankets as shown in Figure 8-17. They serve to collect the seepage from the blanket drain and conduct it to a desirable discharge point such as a stilling basin or natural stream channel. Such seepage collection also facilitates monitoring the quality of seepage generated by the impounded sludge, and will help to limit uncontrolled discharges into the groundwater.

Typically, toe drains include perforated pipe which may need to vary in diameter, depending on the length of the pipe, the quantity of flow, and number of discharge points provided. Pipe diameters normally range from six to eight in. Toe drains are laid in trenches that, for small impoundments, are commonly a minimum of four ft deep and two to three ft wide at the bottom. The toe drain design must conform to the design criteria for filter construction and will be similar to the example illustrating a filter design which follows.

The filters shown in Figure 8-17, as well as any filter that may be designed, must be constructed of materials meeting certain gradation requirements, in order to prevent the filter from becoming clogged with either foundation or embankment soil particles. In some cases, this may require multilayered filters to be constructed. Whenever possible, however, multilayered filters should be avoided because of the added expense of construction and quality control necessary. If filter materials are readily available, filter layers thicker than those shown in Figure 8-17 can be used and will allow greater deviations from the following specific filter gradation requirements.

The criteria for any filter is that it must (1) be sufficiently permeable to pass the anticipated seepage quantities and (2) protect the adjacent embankment and foundation soils from washing into the filter. To satisfy these criteria, the following filter gradation requirements are necessary:

- To provide sufficient permeability

  $$\frac{D_{15} \text{ of the filter}}{D_{15} \text{ of the adjacent soil}} \geq 5 \leq 40$$

  (the filter material must not contain more than 5% silt or clay size particles)

- To protect adjacent soils from erosion

  $$\frac{D_{15} \text{ of the filter}}{D_{85} \text{ of the protected soil}} \leq 5$$

- The grain-size gradation curve of the filter material should be approximately parallel to that of the adjacent foundation and/or embankment soils, and the maximum filter particle size should be no greater than three in.

In the above requirements for filter design, D_{15} refer to the diameter of soil particles for which 15% of all the soil particles are smaller than this. Similarly, D_{85}

is the diameter of soil particles for which 85% of all soil particles for a particular material are finer. A grain size distribution curve, Figure 8-18, should be developed in the soil testing laboratory for each type of material being considered for filter construction in order to determine these parameters.

When a perforated pipe is deemed necessary to increase the permeability of a filter and to reduce quantities of filter materials, the filter material must meet the following additional requirement in order to prevent soil washing into the pipe:

- $\frac{D_{85} \text{ of the filter}}{\text{size of pipe perforations}} \geq 2$

To illustrate the filter design procedure, an example from USBR is shown in Figure 8-18 which will require the use of two layers of filter material and includes a drain pipe. (8-3)

As stated earlier, the design or method of treating coarse-grained embankment foundations is aimed primarily at controlling seepage and the effects of seepage beneath the embankments of an impoundment. The aforementioned methods of pervious foundations design are commonly used; however, treatment methods are not limited to these alone and may involve a combination of those discussed. To summarize the foundation treatment methods discussed thus far, their application and possible combinations that may be required, Table 8-6 is presented. It should also be remembered that the methods discussed here pertain to generally pervious foundation materials that are exposed or within three ft of the ground surface. Similar principles, however, different seepage control methods, are used where the pervious materials are overlain by a thickness of relatively impervious soil. These additional methods are discussed by the U.S. Bureau of Reclamation and should be consulted when this kind of site condition is encountered. (8-3)

While stability and settlement are not usually significant problems associated with coarse-grained foundation materials for earth embankments, they should not be totally neglected. Typically, instability and significant settlement may result from densification of loose, cohesionless soils brought about by either man-made or natural vibrations or shocks such as blasting or earthquakes. Of these materials, saturated, loose, fine, uniform sand is particularly prone to instability through the vibration-induced phenomenon of liquefaction. Generally, coarse-grained foundation materials should be futher investigated in terms of stability and settlement when their rela-

Example of Filter Design

Given: Average gradation curve of foundation soil shown on Figure 8-18, with D_{15} = 0.006 mm and D_{85} = 0.10 mm. Openings in drainpipe, ½ in.

Find: Gradation limits of filter materials.

Procedure:

1. Lower limit of D_{15} of filter = 5 x 0.006 = 0.03 mm.

2. Upper limit of D_{15} of filter = smaller of the values: 40 x 0.006 = 0.24 mm, and 5 x 1.10 = 0.50 mm; use 0.24 mm.

   To meet conditions (1) and (2) and the criterion of parallelism, a sand shown as F_1 in Figure 8-18 was selected. For F_1, D_{15} = 0.14 mm and D_{85} = 2.4 mm. This material is too fine to place adjacent to a pipe with ½-in. openings, since the requirement is for D_{85} of the filter to be at least 2 x ½ = 1 in.; hence, a second filter layer of gravel or crushed rock is required.

3. Lower limit of D_{15} of gravel is 5 x 0.14 = 0.70 mm.

4. Upper limit of D_{15} of gravel = the smaller of the values: 40 x 0.14 = 5.6 mm, and 5 x 2.4 = 12.0 mm; use 5.6 mm.

5. Least D_{85} of gravel = 2 x ½ = 1 in. = 25.4 mm.

   To meet conditions (3), (4) and (5) and the criterion of parallelism, the gravel shown as F_2 in Figure 8-18 was selected. The lower and upper limits of the D_{15} for F_1 and for F_2 as well as the lower limit for D_{85} for F_2 are shown below.

Figure 8-18. Example of Typical Filter Design.

Source: U. S. Bureau of Reclamation (USBR), Design of Small Dams, 2nd Edition, 1977.

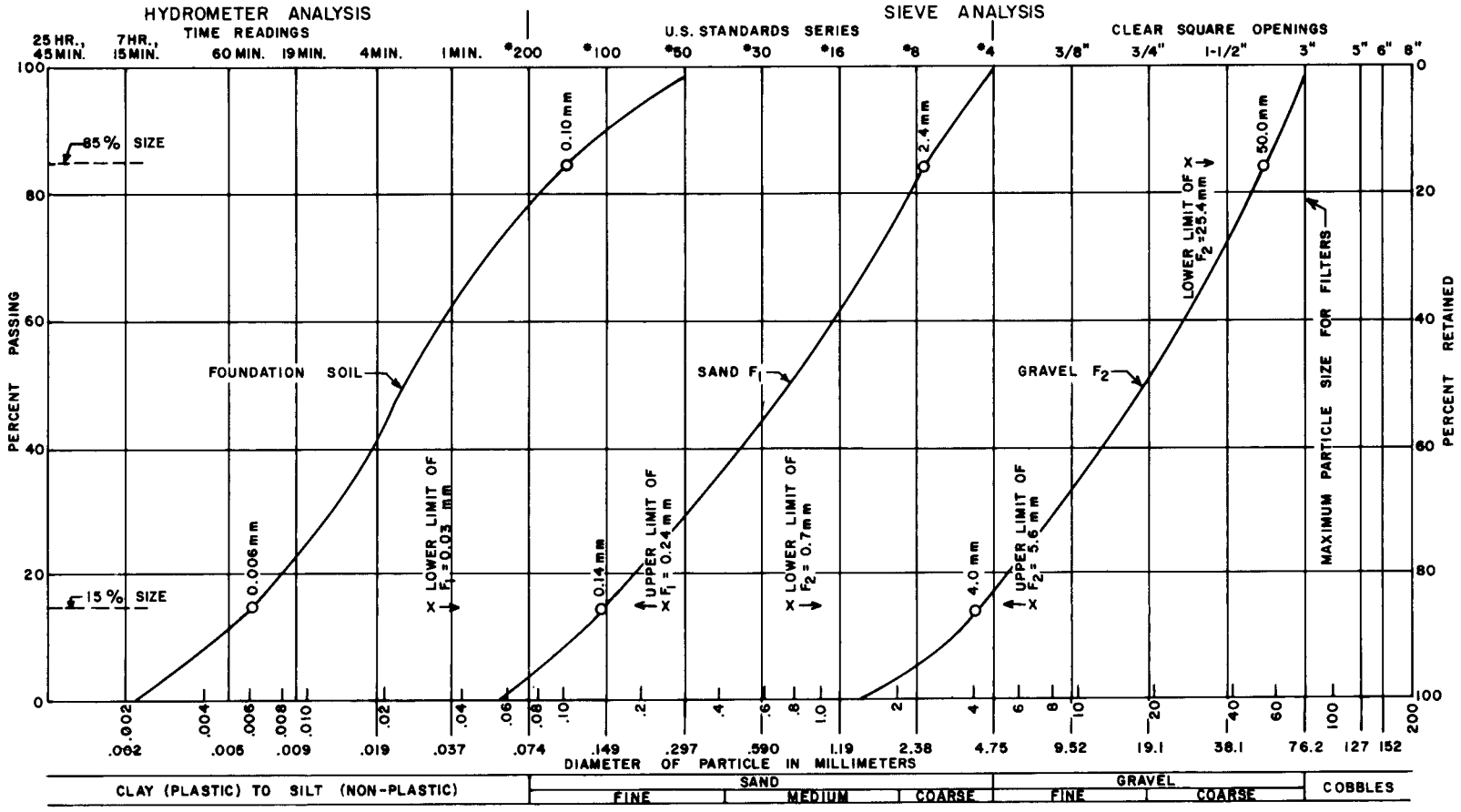


Figure 8-18. Example of Typical Filter Design. (Cont.)

Table 8-6

TREATMENT OF COARSE-GRAINED FOUNDATIONS

FIGURE NO.	DEPTH OF PERVIOUS FOUNDATION	STRATIFIED OR HOMOGENEOUS	FOUNDATION TREATMENT METHOD	ADDITIONAL REQUIREMENTS (OTHER THAN STRIPPING)
8-15	Shallow	Either	Cutoff Trench	Downstream filter blanket may be required Toe drain Rock grouting may be required
8-16	Intermediate	Either	Sheet Piling Cutoff	Downstream filter blanket may be required Toe drain Large core required for[1] zoned embankments Key trench
8-15	Intermediate to Deep	Stratified	Partial Cutoff Trench	Large impervious core[1] required for zoned embankments Toe drain Downstream filter blankets may be required
8-17	Deep	Homogeneous	Downstream Filter Blanket	Large impervious core[1] required for zoned embankments Upstream impervious blanket may be required to reduce seepage quantities Toe drain Key trench

[1]See impervious core sizes under EMBANKMENT DESIGN subsection.

Source: U. S. Bureau of Reclamation, (USBR), Design of Small Dams, 2nd Edition, 1973.

tive density is found to be less than 50%. In areas of known seismic activity, stability analyses are especially critical and should be performed by experienced geotechnical engineers.

The relative density of cohesionless soils may be estimated from the results of the standard penetration tests performed during the test boring subsurface site investigation.

Fine-grained Foundations. Embankment foundations are considered fine-grained if they are composed of relatively impermeable silts and clays, and extend to depths exceeding the anticipated height of the pond embankment. The primary considerations for design or treatment of this kind of foundation are stability and settlement. In addition, the treatment of fine-grained foundations must account for the eventual saturation of the materials brought about by the impoundment of the FGD slurry.

The method of foundation design will depend on the (1) soil type, (2) location of the groundwater table, and (3) the consistency or stiffness of the fine-grained soils. For most fine-grained soils, the standard penetration test will provide a reasonable estimate of the soil consistency, see Table 8-2.

The consistency of most fine grained soils is a function of the history of geologic loads the soil has experienced. Soils that have not experienced loads greater than those presently being applied by the overburden are termed normally consolidated. Normally consolidated soils are typically weaker than soils that have been preconsolidated or pre-loaded in the past by glacial ice, or soil which has since been removed through geologic processes. Preconsolidated soils provide stable foundations for structures and embankments imposing loads less than the geologic preconsolidation loads experienced in the past. One means of recognizing preconsolidated soils, other than by laboratory consolidation tests, is by their high resistance to the standard penetration test which is typically greater than 20 blows per ft. Normally, consolidated silts and clays generally have penetration results of between 4 and 20 blows per ft. Construction on foundations of soft, unconsolidated deposits of fine-grained soil with standard penetration blow counts of less than four should be avoided whenever possible, since additional testing and more detailed analysis would be required. Based on the above generalized information and the determination of the soil type, the standard penetration test can be used to identify foundation conditions which may be treated by the simplified design methods presented in this text.

The following are four methods of stabilizing or increasing the shear strength of fine-grained foundation soils for the construction of pond embankments:

- Excavation of Soft Materials. Where soft, unconsolidated soil deposits are not excessively thick, removal of these materials may be practical, provided that the cost of excavation and backfilling with compacted material does not exceed the cost of special investigations and construction methods. Where relatively small areas of unconsolidated material exist within a generally suitable foundation, excavation should be performed as part of the foundation preparation work.
- Flattening Embankment Slopes. Flattened embankment slopes reduce shear stresses in the foundation by increasing the length of the most critical potential failure surface and, thereby, decreasing the average shear stresses along this surface. This treatment method requires additional volumes of material to flatten the slopes through the construction of stabilizing fills at the upstream and downstream embankment toes. Since the only purpose of the additional fill is to provide weight, any type of material and construction method can be used.
- Installation of Foundation Drains. To hasten the consolidation of relatively impervious fine-grained foundations soils and, thereby, increase foundation shear strength, systems of vertical and horizontal granular drains may be constructed within the foundation strata to dissipate the excess pore water pressures created by embankment construction. This type of foundation treatment is not commonly used in conjunction with impoundment construction, rather, it is more widely used to stabilize foundations for landfills which will be discussed later. In addition, foundation drains are not recommended based on the scope of this text because rather specialized design procedures must be used in their design for impoundment applications.
- Staged Embankment Construction. Construction of the pond embankments in stages can help to allow the underlying foundation soils to consolidate and gain shear strength during construction. This may not only be a technical advantage, but it may be more economical, in some situations, to heighten the embankments as additional storage capacity is needed and as funds are available. Methods of staged construction will be presented when the design of the embankment is subsequently discussed.

Of the above methods for stabilizing saturated, fine-grained foundations for relatively low disposal pond embankments, probably the most practical method is that of flattening the embankment slopes with stabilizing fills. Figure 8-19 shows a simplified embankment section using this method of foundation stabilization. Table 8-7 gives slopes for the construction of the stabilizing fills as recommended by the USBR for the various foundation soil types and consistencies shown. (8-3)

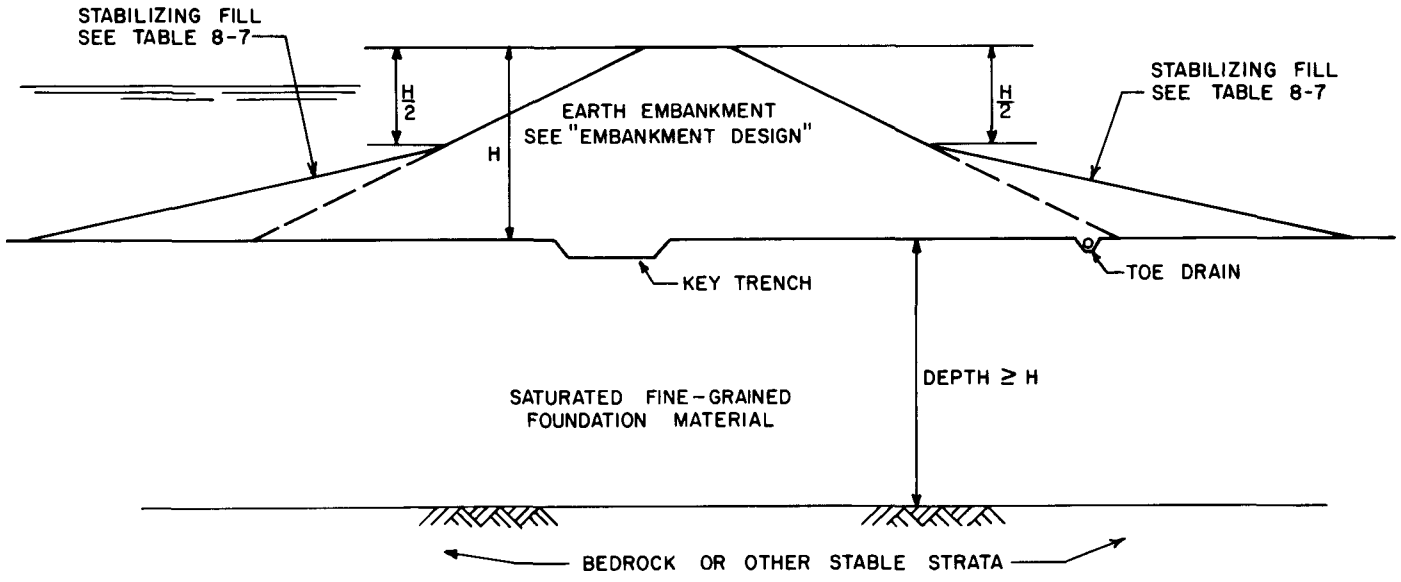


Figure 8-19. Flattened Embankment Slopes for Stabilization of Fine-Grained Foundations.
Source: U. S. Bureau of Reclamation (USBR), Design of Small Dams, 2nd Edition, 1973.

Table 8-7

RECOMMENDED SLOPES OF STABILIZING FILLS FOR
DAMS ON SATURATED SILT AND CLAY FOUNDATIONS

CONSISTENCY	AVG. NO. OF BLOWS/FT[a] WITHIN FOUNDATION DEPTH EQUAL TO HEIGHT OF DAM	FOUNDATION SOIL[b] CLASSIFICATION	SLOPES FOR VARIOUS HEIGHTS OF DAM[c] 50 ft	40 ft	30 ft	20 ft	10 ft
Soft	Less than 4	Special soil tests and analyses required.					
Medium	4 to 10	SM	4½:1	4:1	3:1	3:1	3:1
		SC	6:1	5:1	4:1	3:1	3:1
		ML	6:1	5:1	4:1	3:1	3:1
		CL	6½:1	5:1	4:1	3:1	3:1
		MH	7:1	5½:1	4½:1	3½:1	3:1
		CH	13:1	10:1	7:1	4:1	3:1
Stiff	11 to 20	SM	4:1	3½:1	3:1	3:1	3:1
		SC	5½:1	4½:1	3½:1	3:1	3:1
		ML	5½:1	4½:1	3½:1	3:1	3:1
		CL	6:1	4½:1	3½:1	3:1	3:1
		MH	6½:1	5:1	4:1	3:1	3:1
		CH	11:1	9:1	6:1	3:1	3:1
Hard	More than 20	SM	3½:1	3:1	3:1	3:1	3:1
		SC	5:1	4:1	3:1	3:1	3:1
		ML	5:1	4:1	3½:1	3:1	3:1
		CL	5:1	4:1	3:1	3:1	3:1
		MH	5½:1	4:1	3:1	3:1	3:1
		CH	10:1	8:1	5½:1	3:1	3:1

[a]Standard penetration tests.

[b]Unified Soil Classification System. See Table 8-4 for classification definitions.

[c]Slopes of the upstream and downstream stabilizing fills to be made the same.

NOTE: Stabilizing fills are not needed when embankment slopes required by Tables 8-8 and 8-9 are equal to or flatter than the slope listed above.

Source: U. S. Bureau of Reclamation (USBR), Design of Small Dams, 2nd Edition, 1973.

When pond embankments are constructed on partially saturated, fine-grained soils the effects of eventual saturation of the soil should be considered.

An important group of unsaturated soils which are significantly affected upon saturation are wind-blown deposits and slope wash deposits. These deposits are commonly found in arid or semi-arid regions of the country, and are characterized by their relatively high dry strength and low density in their natural state. When these kinds of deposits become saturated from pond seepage, they usually become soft and rapidly produce large settlements under the weight of the pond embankments. This is a significant problem with relatively dry fine-grain deposits such as these because an earth pond embankment can normally withstand considerable differential settlements over a long period of time. However, rapid settlements of even lesser magnitudes can result in embankment failures through cracking of the embankment materials or by overtopping through reduction of freeboard.

In order to determine the potential for settlement upon saturation and the method of treating partially saturated, fine-grained foundation soils, laboratory consolidation tests must be performed on relatively undisturbed samples of the material. The test consists of loading the soil specimen in increments to a maximum pressure equal to the approximate weight of the proposed embankment. After consolidation is achieved under this pressure, the specimen is saturated by inundation and any additional settlement recorded. This additional settlement represents post-construction settlement brought about by saturation of the foundation soil.

Based on the consolidation characteristics recorded, a method of foundation treatment may be considered. If little post-construction settlement is indicated, a minimum of foundation preparation will be required. Preparation will consist of stripping the embankment site of organic topsoil, excavating a key trench for the embankment, and installation of a toe drain to prevent saturation of the downstream foundation materials. If significant post-construction settlement is indicated upon saturation, then the method of foundation treatment should be designed to reduce the settlement or cause it to occur during construction rather than after construction. For a relatively shallow depth of unsaturated material, excavation and recompaction of the material will probably be the most practical solution. Where the deposit is too thick for excavation and recompaction, other methods should be considered and designed by an experienced geotechnical engineer. One such solution is prewetting the soil by irrigation before construction to induce most of the settlement to occur during construction.

Regardless of whether a fine-grained soil is saturated or partially saturated, significant settlement may be experienced during the consolidation of the loaded foundation. Settlement is an important design consideration because it may result in: cracking and ultimate failure of the embankment, overtopping of the embankment through loss of freeboard, reduction in pond storage capacity, and damage to buried pipes and filters as well as surface structures. In some cases, these problems may not become evident for some time due to the time required for consolidation to occur.

The magnitude of foundation settlement is a function of the embankment weight, the depth and thickness of the compressible material and the compression characteristics of the soil. Relatively accurate predictions of settlement can be calculated from laboratory consolidation tests. If it is determined that settlement will be an important consideration in the design of the disposal pond, estimates of the rate of consolidation as well as locations of various magnitudes of settlement should be obtained. This will allow the designer to plan construction phases and locate buried pipes and structures in areas less prone to settlement. Finally, in order to provide a basis for revising the settlement predictions and to allow for possible modification to the design or construction sequence, field settlement data should be collected during and after construction of the disposal facility.

The Design of the Embankment

The primary task of designing an impounding embankment is determining a cross-section that will satisfy the design criteria which have been previously presented and require that the embankment:

- Be stable under all conditions during construction and pond operation
- Not induce excessive stresses in the foundation materials
- Control seepage through the embankment
- Be safe from overtopping
- Protect slopes against erosion

Presently, the design of an embankment cross-section is based on past experience with existing successful embankments supplemented by additional investigations and analyses of unusual or site-specific conditions and by controlling material selection and placement.

General Design Considerations. Based on the above design criteria for earth embankments, the general design is concerned with establishing and maintaining stability

and seepage control. Various methods exist for analyzing the stability of slopes and are of varying degrees of complexity. In general, they employ the shear strength of the soil and certain assumptions regarding the shape of the failure surface along which a slide would occur.

The development and application of these various methods of stability analyses are discussed in references 8-2,9,10,11 and 12. For the purposes of this text, however, their presentation is not warranted. The designer should be aware, however, that these calculations may need to be performed even for small impounding structures to investigate specific site conditions or to satisfy requirements of various regulatory agencies. The analysis of seepage conditions within an embankment and its foundation are often visualized through the use of flow nets, as previously described, and can be used to estimate seepage quantities and the magnitude and distribution of seepage forces. Their construction and use, however, are generally not required nor economical for the design of small sized embankments. For this reason, the simplified design methods presented here for small size embankments do not require flow net construction.

Primary to a successful disposal pond design is the selection of stable embankment slopes. Slope design will depend upon the embankment soil types, the foundation conditions of the embankment, and the height of the embankment. The various slopes that will subsequently be sited are for construction of the embankment, and do not include or replace the additional embankment features and slopes needed to stabilize or treat the pervious or weak embankment foundations as previously discussed.

Upstream embankment slopes can range from 2:1 to 4:1 (horizontal:vertical). More typically, they will be 2-1/2:1 or 3:1. The use of the flatter slopes can eliminate the need for sometimes expensive slope erosion protection and will reduce instability that may result from rapid draw-down of ponded water. The condition of rapid draw-down is not anticipated to occur, however, in most cases of sludge pond disposal operation. A rapid draw-down condition constitutes a lowering of the water level in a pond at a rate of six in. or more per day following prolonged storage at high levels. This rapid draw-down results in pore pressures and uncontrolled seepage leaving the upstream slope and is inducive to slope failure. Failure of upstream embankment slopes is rare, except during construction or where rapid draw-down occurs, because the weight and seepage forces created by the impounded sludge act to stabilize the slope.

Downstream slopes of relatively small impoundments are typically 2:1 or 2-1/2:1 when drainage is provided to prevent saturation of the slope. The slopes are also determined by the type of embankment to be constructed, in this case homogeneous, modified homogeneous or zoned.

Homogeneous Embankments. As stated earlier, homogeneous embankments should only be constructed when sufficient quantities of pervious materials are not readily available for construction of a zoned type of embankment, or for construction of internal drainage facilities to modify the homogeneous design. The drainage facilities desired for an homogeneous embankment design have been shown in Figure 8-12 (B) and (C) and previously discussed. The drains shown in Figure 8-12 should be designed in accordance with the guidance previously given for the design of filters. In order for the blanket drain shown in Figure 8-12 (C) to effectively lower the water level within the embankment and stabilize the downstream embankment slope, it should be of uniform thickness and extend under the embankment from the downstream toe to within a distance equal to the height of the embankment plus five ft from the embankment centerline. This upstream extent of the drain has been selected to approximate the upstream limit of a pervious zone associated with a zoned type of embankment. Laterally, the blanket drain should extend the entire length of the embankment and, where applicable, up the abutments to an elevation equal to the maximum height at which the pool level will exist.

It is likely during the construction of a homogeneous embankment there will be variations in the nature of materials used. Whenever practical, the more pervious materials should be placed near the outer slopes of the embankment in order to strive for the increased stability and improved seepage control provided by a zoned type of construction.

Table 8-8 lists slopes that may be used to design small, homogeneous earth pond embankments bearing on foundations designed or treated as previously discussed. The sets of slopes indicated are for embankments constructed of any one or combinations of the soil groups listed for that set of slopes.

Table 8-8

RECOMMENDED SLOPES FOR
SMALL HOMOGENEOUS EARTHFILL DAMS ON STABLE FOUNDATIONS

TYPE	SUBJECT TO RAPID DRAWDOWN[1]	SOIL CLASSIFICATION[2]	UPSTREAM SLOPE	DOWNSTREAM SLOPE
Homogeneous or Modified-Homogeneous	No	GW, GP, SW, SP	Pervious,	Not Suitable
		GC, GM, SC, SM	2½:1	2:1
		CL, ML	3:1	2½:1
		CH, MH	3½:1	2½:1
Modified-Homogeneous	Yes	GW, GP, SW, SP	Pervious,	Not Suitable
		GC, GM, SC, SM	3:1	2:1
		CL, ML	3½:1	2½:1
		CH, MH	4:1	2½:1

[1]Drawdown rates of six in. or more per day following prolonged storage at high reservoir levels.

[2]Unified Soil Classification System; OL and OH soils are not recommended for major portions of homogeneous earthfill dams. Pt soils are unsuitable. See Table 8-4 for classification definitions.

Source: U. S. Bureau of Reclamation (USBR), Design of Small Dams, 2nd Edition, 1973.

Zoned Embankments. Whenever there is a variety of natural material of significantly different permeability at or near the proposed disposal site, a zoned type of pond embankment should be constructed. A zoned embankment is preferred over an homogeneous dam or dike because it is typically more economical to construct. Due to the internal configuration of a zoned embankment, there is better use of the wide variety of materials that may be available, and steeper slopes may be designed which reduce the volume of the embankment to be constructed.

A zoned embankment consists of three or more zones or sections, depending on the number of types of construction material available. The central zone is composed of the least permeable materials available and serves as an impermeable core. The outer zones, adjacent to the impermeable core, are constructed of coarser, more permeable materials which, typically, are more stable than the inner core because of their superior drainage characteristics which results in greater frictional shear strength. The number of pervious zones constructed will depend on the variety of coarse-grained materials available. Each zone placed should be progressively coarser as the outer embankment slopes are approached. Consideration must be given to the gradation of

immediately adjacent zones so that the finer grained zones will not erode into the coarser outer zones. In a case where rock fragments must be placed against the impermeable core, a transition zone composed of sand and gravel or rock fines should be placed between the two zones. If this transition zone must be thin (a few feet), it should be designed as a filter.

The design of stable slopes for zoned embankments is a function of the size of the impervious core and the size of the adjacent pervious zones. Figure 8-20, shows various recommended core sizes for small, earthfilled embankments (approximately 50 ft or less in height). The various core sizes shown are dependent on the type of embankment foundation, the presence of complete foundation cutoff provisions, and the slopes of the outer embankment surfaces. The core sizes shown are based on practical and theoretical considerations. The 10-ft core crest width is recommended in order to accommodate the operation of hauling and compaction equipment. The smallest core size shown, that for a dam on an impervious foundation or pervious foundation with positive cutoff provisions, is sized in accordance with the criterion stated earlier that requires the minimum core thickness at any elevation to be not less than the height of the embankment above that elevation. This criterion limits the average hydraulic gradient through the core to less than one and, thereby, eliminates excessive seepage forces that would require high quality filter zones to be constructed between adjacent embankment zones. Such a necessity for high quality filter zones is neither economical nor practical, based on the scope of this text. Embankment cores smaller than those shown in Figure 8-20 would be more susceptible to damage from possible foundation differential settlement. The central location of the recommended core sizes within the embankment reduces the significance of the core materials on the overall stability of the embankment. The stability of the outer embankment slopes is primarily governed by the strength characteristics of the materials comprising the outer pervious zones. Materials suitable for pervious zone construction are rock, well-graded gravel (GW), poorly-graded gravel (GP), and well and poorly-graded sands (SW, SP), provided they also contain gravel.

Table 8-9 shows slopes recommended by the USBR for small zoned earth embankments based on the core sizes and soil composition of the core, and on the size and composition of the pervious zones. (8-3) Slopes for embankments containing an intermediate size core, which will include the minimum core for a pervious foundation with no positive cutoff provisions, will be between those given for the minimum core size for impervious foundations or pervious foundations with positive cutoff provision, and the slopes

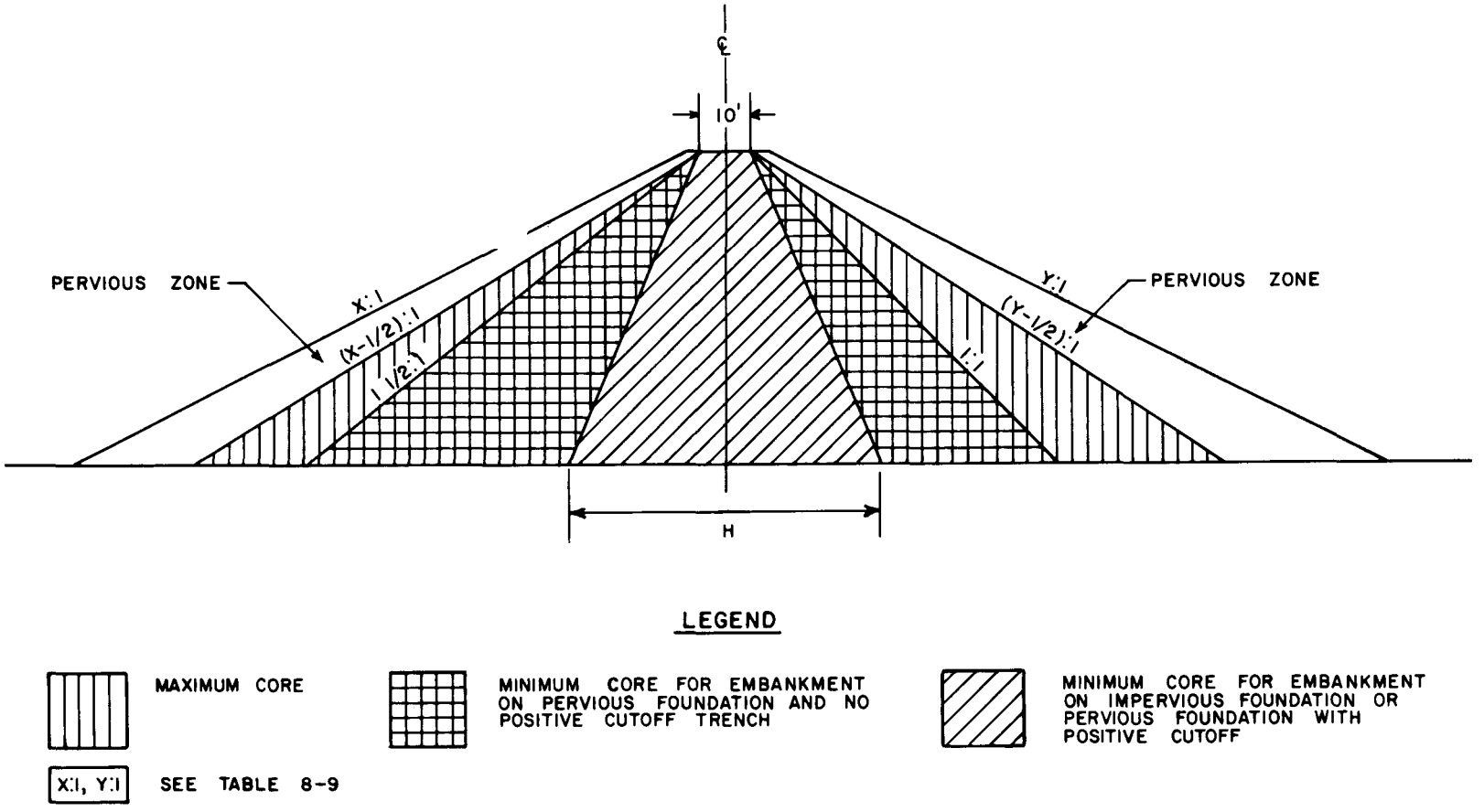


Figure 8-20. Range of Impervious Core Sizes for Zoned Embankments.

Source: U. S. Bureau of Reclamation (USBR), Design of Small Dams, 2nd Edition, 1973.

given for the maximum core size, either subject to or not subject to rapid draw-down conditions. The groups of soils listed for each set of slopes given in Table 8-9 indicate the embankment may be constructed to these slopes using any one of the soils listed or a combination of them.

Table 8-9

RECOMMENDED SLOPES FOR
SMALL-ZONED EMBANKMENTS ON STABLE FOUNDATIONS

TYPE	SUBJECT TO RAPID DRAWDOWN[2]	PERVIOUS SHELL MATERIAL CLASSIFICATION[3]	CORE MATERIAL CLASSIFICATION[3,4]	UPSTREAM SLOPE	DOWNSTREAM SLOPE
Zoned with Minimum Core[1]	Not critical[5]	Not critical; Rockfill, GW, GW, GP, SW, (gravelly), or SP (gravelly)	Not critical, GC, GM, SC, SM, CL, ML, CH, or MH	2:1	2:1
Zoned with Maximum Core[1]	No	Not critical; Rockfill, GW, GP, SW (gravelly) or SP (gravelly)	GC, GM SC, SM CL, ML CH, MH	2:1 2¼:1 2½:1 3:1	2:1 2¼:1 2½:1 3:1
Zoned with Maximum Core[1]	Yes	Not critical; Rockfill, GW, GP, SW, (gravelly) or SP	GC, GM SC, SM CL, ML CH, MH	2½:1 2½:1 3:1 3½:1	2:1 2¼:1 2½:1 3:1

[1]See core sizes shown in Figure 8-20.

[2]Rapid drawdown is a drawdown rate of six in. or more per day following prolonged water storage at high levels.

[3]Classifications are according to the Unified Soil Classification System. See Table 8-4 for classification definitions.

[4]OL and Oh soils are not recommended for major portions of the cores of earthfill dams. Pt soils are unsuitable.

[5]Rapid drawdown will not affect the upstream slope of a zoned embankment which has a large upstream pervious shell.

Source: U. S. Bureau of Reclamation (USBR), Design of Small Dams, 2nd Edition, 1973.

The Embankment Crest Design. The crest width of an earth dam is usually determined empirically because of the difficulty of determining a width that will provide a safe hydraulic gradient through the embankment when the pond surface is at its maximum height. The following empirical formula is normally used to determine the required crest width for small pond embankments:

$$W = (H/5) + 10$$

where:

W = width of the crest in ft

H = the maximum height of the embankment in ft

The minimum width of the crest should not be less than 10 ft in order to accommodate construction equipment and provide pond access for maintenance equipment.

For dams exceeding 100 ft in height, maintenance, operational uses and overtopping potential will determine crest width. Where significant foundation and/or embankment settlement is anticipated, the crest may be constructed with a camber or arch. The camber will help to maintain the desired freeboard as settlement occurs. The amount of camber to provide is variable depending on the amount of settlement and consolidation that is expected. Normally, the primary source of long-term settlement will be from foundation consolidation. Where a foundation is relatively incompressible, a typical camber would be about 1% of the embankment height. Several feet of camber may be required where dams are founded on compressible materials.

Embankment Freeboard. The freeboard of a dam is the vertical distance between the pond surface and the crest of the dam without camber. Two types of freeboard are normally considered in the design of any impoundment:

- Normal freeboard
- Minimum freeboard

Normal freeboard is the freeboard necessary to meet the requirements of long-term storage. Minimum freeboard is the vertical distance between the dam crest and the maximum pond elevation that would result from the inflow of the design flood, and is based on the full capacity of functioning outlet works. In addition to prevent overtopping of the embankment during the design flood, the minimum freeboard can also be designed to provide a margin of safety against the following:

- Foundation and embankment settlements in excess of that anticipated during the selection of crest camber

- Water inflow quantities larger than that from the design flood
- Increased pond levels resulting from malfunction of the spillway or outlet controls due to human or mechanical failure

Freeboard requirements may be designated by federal and/or state regulatory agencies. Typically, minimum freeboard requirements will be on the order of three to five ft. To determine the embankment height necessary to provide a particular freeboard, consideration must be given to the hydrology of the local drainage conditions (both natural and man-made), and the potential of the pond configuration to collect surface runoff water. Based on these considerations, calculation of design inflow quantities must be made and the capacity of the pond determined. If discharge from sludge disposal ponds is permitted, then outlet works may be designed to reduce the capacity of the pond to store the design flood.

Slope Protection. Some form of erosion protection should be provided to the slopes of constructed embankments or excavated ponds. The type selected should protect against erosion due to surface water runoff, wave action, and the erosive action of sludge pipeline discharges. Often, a well-established grass cover is effective and most practical for downstream embankment slope erosion protection. For upstream slopes where impermeable pond liners are not used, riprap is often the most effective and maintenance-free form of erosion protection. In the case of zoned embankments, adequate erosion control is usually already present in the form of the pervious outer zone.

Staged Pond Construction. Wet disposal systems are relatively inflexible to future changes in methods of operation. Initial construction of pipelines, pumping facilities and impounding structures often involve a considerable capital investment directed to a specific disposal site and method of operation. Therefore, if some future change, such as extension of the useful life of the power plant or addition of presently unplanned units exhausts the disposal site capacity before the power plant is retired, an entirely new disposal system must be developed. Alternately, if some future change in plant operations or government regulations prevents complete utilization of the disposal site, capital costs already expended will be wasted. To reduce the impact of these occurrences, it may be advantageous to provide staged ponding. Staged ponding refers to the construction of several smaller ponds or to increasing the height of the existing pond embankments periodically, rather than constructing one large pond initially.

The selection of the method of staged construction will be largely dependent on the availability of a number of small suitable pond sites within the proximity of the power plant. If such is the case, a number of small disposal ponds may be economically feasible and can be designed as described in the text. If it appears that the only means of staged construction available is to enlarge the existing pond embankments, there are two methods that may be employed, the upstream method and the downstream method.

The Upstream Method. A typical section showing the upstream method of enlarging a pond embankment is shown in Figure 8-21. The major advantage of the upstream method of embankment construction is the reduced volume of materials required for each embankment stage as compared to the downstream method. There are numerous technical considerations, however, and relatively complex analytical procedures are required for the successful use of this method of construction. For this reason, an experienced geotechnical consultant should be responsible for the design. Among the considerations for the use of the upstream method of construction are:

The construction of the initial or starter embankment. If the starter embankment is to eventually be the toe portion of the overall embankment, it should be constructed primarily of compacted, coarse-grained materials in order for it to function similarly to a toe drain.

The discharge of sludge into the first stage pond should be located along the starter embankment. This will allow the larger sludge particles to settle adjacent to the embankment and will provide a coarser sludge with slightly better shear strength upon which the next embankment stage will be constructed.

Extremely conservative estimates of differential settlement should be made for the embankment stages partially supported by settled sludge solids.

The stability and behavior of the embankment materials (the settled sludge solids and the natural soil and rock), must be carefully analyzed under both static and dynamic conditions.

Effective and conservatively designed seepage control provisions should be designed.

It is likely that the use of chemically-stabilized sludge may facilitate the design and feasibility of the upstream method of embankment construction. Nevertheless, careful engineering analysis and design should be exercised.

The Downstream Method. The downstream method of embankment construction is illustrated in Figure 8-22. This method of construction can be used for both impounding and non-impounding embankments. The downstream method requires substantial volumes of construction materials; however, when they are available, the result is an embankment that is easier to design and construct than an upstream embankment. The design of the internal drainage and impervious zones of an embankment built by the downstream method will be similar to that for homogeneous embankments.

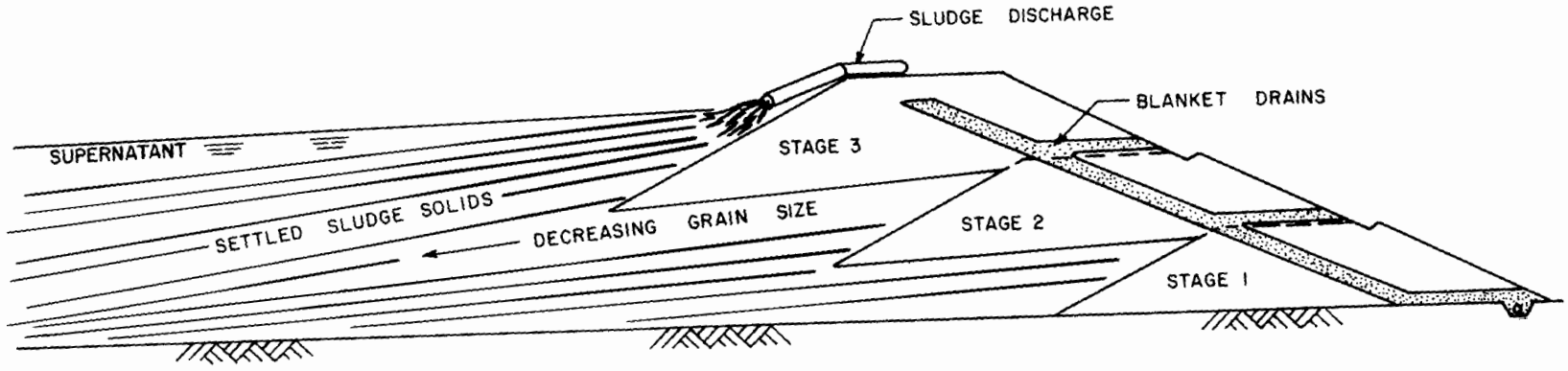


Figure 8-21. Staged Ponding, Upstream Method.

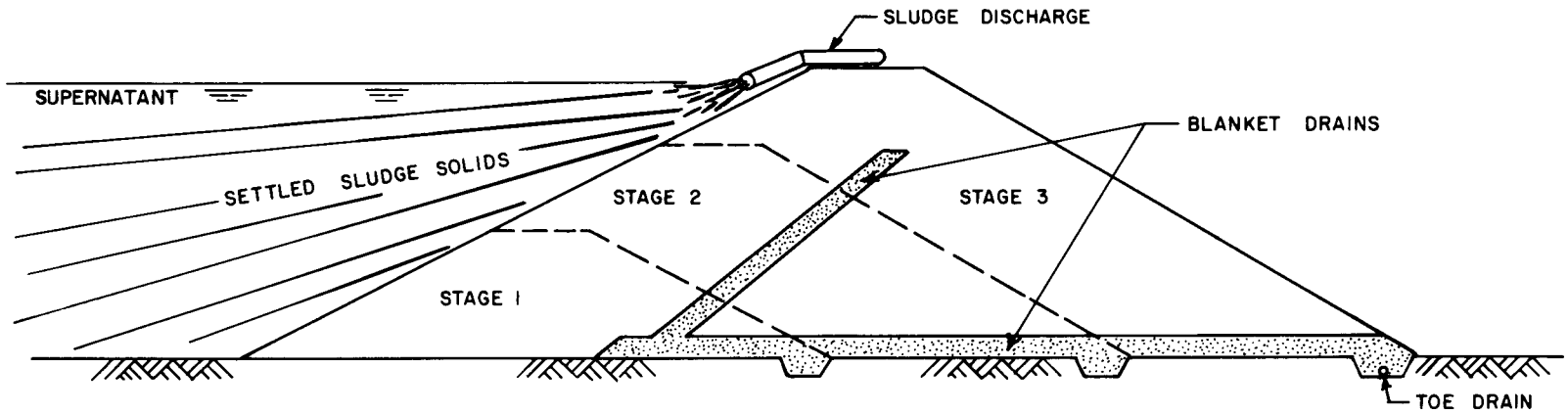


Figure 8-22. Staged Ponding, Downstream Method.

Hydrologic and Hydraulic Design Considerations

In addition to impounding wet FGD wastes, disposal ponds will collect water resulting from direct rainfall and rainfall-induced surface runoff. The hydrologic and hydraulic design of the ponding facility is necessary to determine the quantity and rate of flow of this water, and to design the methods that will be used to control the water in a safe, economical and environmentally acceptable manner.

The basic principle underlying any hydrologic-hydraulic design of an impoundment states that the flow into the impoundment must be either stored in the impoundment and/or discharge from the impoundment. Simply stated:

$$\text{INFLOW} = \text{STORAGE} + \text{OUTFLOW}$$

The inflow is determined through a study of the hydrology of the disposal site; that is, the climatic and physical conditions governing the natural occurrence of water flows. The elements of storage and outflow are determined from the geometry and hydraulic characteristics of the proposed ponding facility.

The key hydrologic design parameter for the design of a ponding disposal system is the design storm. The design storm is a rainfall of particular frequency and duration appropriate to the area of the country in which the pond is to be constructed. Of concern to the hydraulic design of the ponding disposal facility are both the inflow rate and total inflow volume of the design flood flows resulting from the design storm. By knowing both the rate and volume of water inflow, the elements of storage and outflow can be analyzed and balanced to obtain a desired hydraulic condition within the pond.

The significance or impact of the design storm rainfall on the hydraulic design of the disposal pond will depend primarily on the watershed characteristics and on the type and size of the pond configuration selected.

The Watershed. The watershed is the catchment area or drainage basin that slopes toward and drains into the impoundment area of the pond. The size of the watershed is the primary factor determining the amount of inflow that a disposal area will be required to handle. Based on hydrologic and hydraulic considerations, the best site or pond configuration is the one with the smallest watershed draining into or around the disposal facility. In some cases, this consideration must be secondary to those regarding proximity to the power plant and the requirements for sludge handling and

transport. The boundaries and the area of the watershed influencing the design of the disposal pond are normally determined from topographic mapping available through the U.S. Geological Survey (USGS).

The surface runoff potential of the watershed also affects the rate and volume of water inflow to the disposal pond. Surface runoff is that portion of the precipitation not retained in the watershed soils or by vegetation. The difference between the amount of rainfall and the amount of surface runoff indicates the runoff potential of the watershed and is dependent on:

- The types and extent of surface soils and their ability to absorb water
- The condition of the ground surface immediately prior to the rainfall, whether it be dry, wet, frozen or snow covered
- The type and density of vegetative cover
- The presence and extent of man-built features such as paved surfaces, storm sewers, channels and bodies of water

The Pond Configuration. The type of pond configuration to be used will affect the relative importance of various hydrologic and hydraulic design factors that must be considered in the development of a wet disposal system. The following is a general discussion of some of the more common concerns relevant to the types of pond configurations that may be used:

> Cross-Valley Ponds. The cross valley pond configuration is the most critical type of pond in terms of a hydrologic and hydraulic design. Due to its location within a natural drainage path, a valley, it is subject to the greatest water inflow of the pond configurations presented earlier in the text. As a result, the design of the storage and outflow elements is also extremely important and sometimes complex.
>
> The combination of outflow and storage designed for a cross-valley type of pond serves to optimize the design of the disposal facility. The primary concern is how to remove the natural water inflow from the pond and, at the same time, maintain sufficient capacity for a long disposal operation period. Spillway construction for this purpose is usually impractical because a spillway that will remove surface inflow water to the pond will not allow a sufficient storage capacity for long periods of waste disposal. Typically, a spillway may be used to control the inflow water to an abandoned pond that requires further waste storage capacity, or to prevent overtopping a completed embankment during active disposal operations.
>
> Regardless of the amount of storm runoff that will be handled by storage, the outflow structures must account for the continual rise in the normal pool level caused by the settling of the sludge particles and control the resulting discharge of stored water. For

this purpose, a decant system is often used to remove the supernatant. The amount of water required to be discharged as a result of the settling of the sludge solids will also depend on the amount of pond water returned to the plant for make up purposes and the anticipated evaporation rate at the pond.

In addition to the combination of storage and outflow selected for a pond, hydrologic and hydraulic consideration must be given to the pond conditions at the time of abandonment. If, at the time of abandonment, the pond has a significant capacity to store water, it will be necessary to either limit or eliminate the capacity to store water. This may be done by (1) backfilling the pond either totally or partially, (2) providing a spillway around the embankment to limit the amount of impounded water or to conduct all water through the abandoned pond, or (3) a combination of backfilling and spillway construction. These considerations may be dealt with during the final stages of active disposal, since preliminary or conceptualized abandonment schemes may be subject to change during the period of active disposal due to possible unforeseen operational or regulatory requirements.

The interception and diversion of surface runoff waters around a disposal pond is sometimes a sound method for reducing pond inflow quantities and reducing the storage and outlet requirements. Unfortunately, due to the typically large pond size created by most cross-valley pond configurations, diversion ditches for this purpose are usually impractical. Diversion ditches which may be economical for this type of pond are usually limited to accommodating light to moderate runoff volumes. Such ditching cannot be expected to divert much of the runoff resulting from severe storms. For this reason, the hydrologic and hydraulic design of cross valley disposal ponds should not rely on the use of diversion ditches to reduce pond inflows.

Side-Hill Ponds. Side-hill pond configurations usually have small watersheds which greatly reduce potential runoff inflow quantities. Uphill runoff can be directed into the pond for eventual discharge, or one or more diversion ditches may be used to conduct all or part of the runoff around the disposal pond. If diversion ditching is to be used to reduce the storage and outflow requirements of the pond, the ditching must be designed as a channel to accommodate runoff from the appropriate design storm. As such, the channel design should consider:

Hydraulics of open channel flow

The stability of uphill and channel materials

The potential and consequences of overtopping

If it is not feasible to divert the runoff away from the side-hill pond and there is insufficient pond storage for the design flood, a spillway must be constructed in the natural hillside material at one end of the pond. As in the case of the cross-valley pond, a decant system is usually necessary to regulate the amount of water below the spillway elevation and above the level of settled sludge solids.

Diked Ponds. The hydrologic and hydraulic design of diked ponds is relatively simple compared to that of cross-valley and side-hill ponds. Because they are generally constructed on flat terrain, which may include wide valley bottoms, the extent of the watershed contributing natural water inflows to a diked pond is limited to the perimeter of the pond. Therefore, the primary source of natural inflow is rainfall directly on the pond. This water is temporarily stored and drawn off, if necessary, through the decant system.

Where a diked pond is located adjacent to a stream, such as on a flood plain, consideration must be given to the flooding potential of the stream and its effect on the pond embankments.

Incised Ponds and Existing Basins. The hydrologic and hydraulic design of incised ponds and wet sludge disposal facilities utilizing existing below-grade basins, such as abandoned quarries and strip mines, typically have little impact on the overall facility design. This is because the watershed contributing inflow to these kinds of ponds is usually small, and because there is little risk of a pond failure that could release the impounded sludge. There are three principal hydrologic and hydraulic considerations for the design of incised ponds and for disposal ponds formed in existing basins:

The area surrounding the pond may be graded to either drain into the pond, discharging the resulting flow through a decant system, or graded to divert runoff around and away from the ponds, causing natural inflows to be limited to precipitation falling directly on the pond surface.

If discharges are anticipated and permitted after accounting for evaporation rates and plant make-up water requirements, a decant or overflow weir will probably be necessary to control the amount and location of the discharge from the pond.

The flooding potential of nearby streams and bodies of water should be determined to evaluate the risk of the disposal pond being inundated. If flooded by adjacent streams or lakes, sludge solids may be washed from the pond and/or the capacity of the pond reduced by the deposit of stream sediments.

Design Storm Criteria

The size and cost of the hydraulic appurtenances for a ponding disposal facility are primarily determined by the quantity and rate of inflow resulting from an appropriate design storm. The primary criteria for the selection of an appropriate design storm are based on:

- The size and volume of the disposal pond
- The downstream hazard potential should pond failure occur

Other less common criteria may exist for various parts of the country. For this reason, local, state, and federal regulations governing the construction of water or waste disposal impoundments should be consulted so that the pond design is acceptable.

If a significant hazard exists in terms of potential loss of human life or property if the proposed impoundment were to fail, the hydraulic design of the disposal facility is based on the "Probable Maximum Precipitation" (PMP). The PMP, according to USBR, is the amount of rainfall that represents "an envelopment of maximized intensity-duration values obtained from all type of storms" as determined by meteorologists. (8-3)

For disposal ponds presenting a low hazard potential, the general design storm criteria is the 100 yr storm. This storm is one that would occur or be exceeded on an average of once every 100 yr. This storm is determined by the National Weather Service and is the storm with a One Percent Probability (OPP) of occurring each year.

The PMP and OPP design storms are based on a six hr duration of precipitation with an exception in the western United States west of the 105th meridian. The 105th meridian is a line of longitude that passes through western Texas, central New Mexico and Colorado and eastern Wyoming and Montana. In these western states, the six hr PMP and a one hr Probable Maximum Thunderstorm (PMTS) are used as design storm criteria. The PMTS is a very intense, short duration storm. When pond disposal facilities are designed in this western region, the more severe of these two design storms is used.

Regardless of the degree to which pond storage is used to control the design storm flood flows, the hydraulic design of the pond must be capable of removing 90% of the volume of water stored during the design storm within a 10 day period. (8-5) This design feature allows for continued adequate storage capacity in the event two or more high intensity storms were to occur within a relatively short period of time.

Selection of an Appropriate Design Storm. The selection of a design storm criteria for the design of a disposal pond is presented in Table 8-10. As stated above, the selection is based on the size and hazard potential classification of the disposal facility. No storm more severe than the PMP need be considered, provided 90% of the flood water volume stored by the pond can be evacuated within a 10-day period. This water evacuation requirement can be met through one or a combination of the following factors:

- The discharge capacity of the spillway
- The discharge capacity of the decant system
- Anticipated pond evaporation rates
- The return of stored water to the power plant as make-up water

Table 8-10

MINIMUM DESIGN STORM CRITERIA FOR LONG-TERM DISPOSAL IMPOUNDMENTS[a]

1. Impoundment Size Classification

CATEGORY	IMPOUNDMENT SIZE		
	MAXIMUM VOLUME OF STORED WATER DURING DESIGN STORM (ac-ft)		MAXIMUM DEPTH OF WATER DURING DESIGN STORM (ft)
Small	50	and	20
Intermediate	50 and 1,000	or	20 and 40
Large	1,000	or	40

2. Hazard Potential Classification[b]

CATEGORY	DESCRIPTION
a. Low Hazard Potential	Facilities located in rural or agricultural areas where failure would cause only slight damage, such as to farm buildings, forest or agricultural land, or minor roads.
b. Moderate Hazard Potential	Facilities located in predominantly rural areas where failure may damage isolated homes, main highways or minor railroads disrupting service or relatively important facilities.
c. High Hazard Potential	Facilities located where a failure could be reasonably expected to cause loss of life, serious damage to house, industrial and commercial buildings, important utilities, highways and railroads.

3. Recommended Design Storm for Long-Term Conditions

IMPOUNDMENT SIZE	HAZARD POTENTIAL	MINIMUM DESIGN STORM BASED ON PRECIPITATION[c]	ADDITIONAL CRITERION
Small	a. Low	OPP	The indicated storm is appropriate only if the combination of spillways and decants for the facility can evacuate 90% of the maximum volume of stored storm water within 10 days.
	b. Moderate	1/2 PMP	
	c. High	PMP	
Intermediate	a. Low	OPP	
	b. Moderate	1/2 PMP	
	c. High	PMP	
Large	a. Low	1/2 PMP	
	b. Moderate	PMP	
	c. High	PMP	

[a]See Table 8-11 for recommended minimum design storm criteria for short-term disposal impoundments.

[b]See Source for discussions justifying classification criteria.

[c]In areas of the U. S. west of the 105th meridian, both the six-hr duration PMP and one-hr PMTS duration storms shall be evaluated and the more critical of the two shall be used for design purposes.

Source: E. D'Appolonia Consulting Engineers, Inc., Engineering and Design Manual Coal Refuse Disposal Facilities, U. S. Department of Interior, Mining Enforcement and Safety Administration, 1975.

The Design Storm Precipitation (PMP, PMTS, OPP). The inches of rainfall associated with the six hr duration PMP and the six hr OPP precipitation has been determined by the U.S. Weather Service. (8-13,14) Methods of applying these data to a specific watershed are discussed in these references and example problems are presented by the Soil Conservation Service (SCS). (8-14)

For areas west of the 105th meridian, both the six hr PMP and the one hr PMTS should be considered. The most severe storm is then used for design purposes. The rainfall associated with the one hr PMTS can be determined from the literature. (8-3,13)

Design Storm Criteria for Minor Hydraulic Structures. Major hydraulic structures critical to the overall performance and safety of a ponding dispoal facility should be designed for the appropriate design storm discussed above. Many hydraulics of a ponding facility, however, are not of a critical nature and function to limit erosion or other types of localized instabilities. Such non-critical hydraulic features could include minor diversion ditches not designed to reduce the amount of pond inflow from the design storm, channels or drainage structures installed for environmental purposes, or culverts beneath haul roads or non-critical access roads. For minor hydraulic features such as these, a lesser design storm criteria is appropriate and necessary. The following design storm criteria, based on the potential hazard classifications previously presented in Table 8-10, are recommended for these minor hydraulic structures:

Table 8-11

MINIMUM DESIGN STORM CRITERIA FOR
SHORT-TERM HYDRAULIC STRUCTURES

HAZARD POTENTIAL CLASSIFICATION	RECOMMENDED DESIGN STORM
Low	½ OPP
Moderate	OPP
High	OPP

Source: E. D'Appolonia Consulting Engineers, Inc., Engineering and Design Manual Coal Refuse Disposal Facilities, U. S. Department of Interior, Mining Enforcement and Safety Administration, 1975.

Design criteria for minor drainage installations are also available through many highway departments at both the federal and state levels, and may provide more specific design guidance for the installation of minor hydraulic appurtenances.

Hydrologic Inflow Determination

To underscore the importance of the basic principle governing any hydrologic-hydraulic design of an impoundment, it should be clear that the inflow to a pond must be either stored within the pond, discharged below the pond, or handled by a combination of storage and discharge:

$$\text{INFLOW} = \text{STORAGE} + \text{DISCHARGE}$$

The inflow is determined through a study of the hydrology of the disposal site. Specifically, the peak rate and total volume of inflow must be determined in order to design the necessary hydraulic features of a ponding disposal facility. There are three methods available to make these determinations. Each method has certain characteristics and applicability to the design of an impoundment. These three methods are:

- The Hydrograph Method
- The Key Parameter Method
- The Rational Method

Each method will be briefly explained subsequent to the following general discussion of basic hydrologic inflow considerations.

Basic Hydrologic Inflow Considerations. In order to predict pond inflow volumes and rates, the following three factors must be considered:

- Precipitation - Intensity and Duration. The total volume and rate of inflow to a disposal pond is related to the interaction of intensity and duration of rainfall resulting from an appropriate design storm or any precipitation occurrence. Precipitation intensity is the rate of rainfall expressed in inches per hour. Precipitation duration refers to the increments of time associated with a storm or increments of time of constant rainfall intensity.
- Storms can be identified by their intensity-duration relationships such as a high-intensity, short-duration thunderstorm or a low-intensity, long-duration rainfall. For hydraulic design purposes, the intensity-duration relationship used should be the one that results in the maximum peak inflow rate. The intensity-duration relationship recommended for the six hr OPP or PMP design storm is presented by the SCS. (8-14)

For the one hr PMTS criteria west of the 105th meridian, the rainfall intensity-duration relationship recommended by the USBR is used. (8-3) Where a hydrograph is to be constructed to determine the peak inflow rate (see subsequent paragraph, Hydrograph Method of Determining Inflow), the USBR recommends and discusses an adjustment to this relationship.

- Watershed - Size and Time of Concentration. The size of the watershed uphill of the proposed disposal pond is the primary determinant of the volume of precipitation collected during the design storm. A secondary characteristic of the watershed is the time of concentration, Tc. The time of concentration is the time required for water to flow from the most remote point in the watershed to the proposed disposal site. The time of concentration is important to the construction of an inflow hydrograph for the purpose of hydraulic design. To estimate the time of concentration, (Tc), the following equation is often used:

$$Tc = \left(\frac{11.9\ L^3}{H}\right)^{0.385}$$

where:

L = the length of the longest watershed course in miles

H = the height or difference in elevation along L expressed in ft

- Runoff - A Portion of the Total Precipitation. The amount of rainfall that becomes surface runoff depends on the:

  Types of surficial soils

  Condition of the surficial soils, i.e., wet, dry, frozen or snow-covered. This condition is called the Antecedent Moisture Condition (AMC)

  Type and density of vegetation

  Type and extent of cultural developments, e.g., paved surfaces, storm sewers, channels

  Presence of dams, lakes, ponds or swamps within the watershed which could retain water either permanently, release water slowly, or release sudden, large volumes of water

Through a graphical procedure utilizing various numbered runoff curves, the SCS has developed a means of estimating the amount of runoff that may be expected from a given storm based on a wide range of watershed conditions. (8-14) Each of the various runoff Curve Numbers (CN) that may be used in this procedure represent a particular combination of watershed characteristics affecting the amount of runoff that will be derived from a precipitation occurrence.

To determine the proper CN for use in this graphical runoff determination, the following watershed conditions must be estimated for the watershed in question:

The hydrologic classification of surface soils

The land use and condition

The hydrologic effect of the land use and condition

The Antecedent Moisture Condition (AMC)

There are four hydrologic soil classifications defined by the SCS, A, B, C and D.

To assist in categorizing surficial soils, the SCS and USBR list the hydrologic soil classification, either A, B, C, or D, for soils mapped on the local SCS agricultural soil survey maps. (8-3,14) These soil survey maps have been discussed previously in this text in the subsection titled GEOLOGIC SITE INVESTIGATIONS.

The hydrologic effect of the watershed land use and condition is rated according to one of three classifications: poor, fair or good. A classification of poor represents a condition of highest runoff potential while a rating of good indicates a lesser potential for surface runoff. A description of the various land uses and conditions along with their hydrologic rating is presented by the SCS. (8-14)

The antecedent moisture condition (AMC) of the watershed is estimated from one of the following three conditions:

AMC-I - Lowest runoff potential. The watershed soils are dry enough for satisfactory plowing or cultivation. This condition is not considered applicable for the design storm INFLOW computations.

AMC-II - The average conditions.

AMC-III - Highest runoff potential. The watershed is practically saturated from antecedent rains.

Having estimated the four watershed conditions listed previously the appropriate CN describing the watershed may be selected as described by the SCS and used to graphically estimate the amount of runoff that will result from the design storm. (8-14)

The above SCS procedure for determining the amount of runoff applies to non-thunderstorm design criteria east of the 105th meridian. For western thunderstorm criteria, either the OPP or PMTS, the prediction of runoff is more difficult due to limited runoff data. (8-3, Appendix A). Based on available data, the vegetation type and density and the time sequence of rainfall appear to be more important to runoff calculation than the antecedent moisture condition or hydrologic soils classification.

The USBR presents tables that may be used to select an appropriate runoff CN and describes its use in the above SCS graphical solution to estimating watershed runoff.

Hydrograph Method of Determining Inflow. The hydrograph method of determining inflow is applicable to all hydrologic and hydraulic design analyses. It is typically used where balancing of the inflow with the elements of storage and outflow, known as reservoir routing, is required, or when less exact methods of estimating inflow will not provide for an economical drainage design. A hydrograph is a plot of the flow rate resulting from a rainfall at the point of interest, the disposal pond location, versus the time after the storm initiation. Obtained from the hydrograph are both the profile of the varying inflow rate as well as the total volume of inflow resulting from the storm of interest. The construction of the design inflow hydrograph for the appropriate design storm, selected as previously discussed, requires analysis of the watershed characteristics as discussed above. An appropriate and often used method of constructing the design hydrograph is presented in Chapter 21 of reference 8-14. Through the discussions and examples presented in this reference, a design inflow hydrograph can be developed with relative ease. The large cross-valley disposal pond constructed for the Bruce Mansfield Plant, Shippingport, Pennsylvania, was hydraulically designed using an inflow hydrograph computed by this SCS procedure.

Key Parameters Method of Determining Inflow. The key parameters method is extremely useful because, with little calculation, the peak inflow rate and the total volume of inflow can be determined. This is a graphical method and is used, typically, when a time history of inflow, a hydrograph, or a reservoir routing analysis is not required. This situation arises when the disposal pond is designed to (1) temporarily store the total volume of surface runoff, or (2) where the water storage capacity is so small that the outflow equals the inflow. This second condition is typical of the hydraulic conditions for a non-impounding landfill disposal facility. The key parameters method is also useful during the early planning stages of the disposal site design, due to its ease and rapid use for preliminarily sizing various hydraulic structures prior to performing the more detailed and accurate construction of inflow hydrographs.

Through the use of figures presented in reference 8-5, the total inflow volume of surface runoff can be determined as a function of the total rainfall associated with the selected design storm, the watershed size, and the appropriate runoff CN describing the watershed.

To determine the peak inflow rate using the Key Parameter Method a separate set of graphs is used. Their use requires the total rainfall associated with the six hr design storm, calculation of the Tc, discussed above under the sub-heading of Basic Hydrologic Inflow Considerations, and the watershed runoff CN.

The Rational Method of Determining Inflow. This method was developed by the U.S. Bureau of Public Roads and is found in many engineering texts. (8-15) The rational method is commonly used for the design of small drainage structures, such as diversion ditches and road culverts, for watersheds less than 200 ac and for storms less severe than the OPP. The peak inflow rate is calculated from the formula:

$$Q = CiA$$

where:

Q = the peak rate of runoff in ft^3/sec

C = a runoff coefficient

i = the average precipitation intensity for a duration equal to the Tc for the watershed and the selected design storm. It is expressed in in./hr

A = the area of the watershed draining to the disposal site expressed in acres

The runoff coefficient (C) is defined as the ratio of the rate of surface runoff to the rate of precipitation.

Values of the runoff coefficient vary according to the characteristics of the watershed. A weighted coefficient is used where a watershed is composed of a number of different conditions each having a specific coefficient.

The average intensity of precipitation (i) is derived from a study of available rainfall data, or from precipitation frequency charts published by the U.S. Weather Bureau. (8-13)

Hydrologic Pond Storage

The storage capacity of a disposal pond is not only for the containment of FGD waste generated at the plant, but also serves to reduce the amount of storm water inflow that must be discharged during the storm. For a disposal pond, the storage capacity available to temporarily contain storm water is continually decreasing as sludge disposal proceeds. This characteristic of disposal ponds must be considered in the hydraulic design of the facility. Near the time of site abandonment, the ability of the pond to store storm water inflows will be practically zero and the hydraulic design of the pond must function as that for a landfill disposal system where inflow must equal outflow.

Preliminary determination of pond storage capacity is commonly done using USGS topographic mapping of the site. Determination of storage capacity for final design purposes, however, is best done from large scale topographic mapping with contour intervals of two to five ft. The calculation of storage capacity should be shown as a graph of elevation versus storage.

Pond Outflow Systems

This section presents a brief, general discussion of pond hydraulic systems and, in particular, outflow structures. It is intended to acquaint the reader with general design procedures and types of commonly used hydraulic outflow structures. For detailed hydraulic design, the reader is referred to Table 8-12 of References for Hydraulic Design.

Basic Design Considerations. Each disposal pond location has a unique hydrologic setting that must be considered in the design of hydraulic systems. There are, however, the following common disposal pond characteristics that will help the designer to select and plan an appropriate hydraulic system for the impoundment facility:

- Throughout the period of wet FGD sludge disposal, the pond storage capacity continually decreases. Hydrologically, this results in changes in the balance of storage and outflow resulting from naturally occurring water inflows.
- Where staged construction of pond embankments is used to increase the storage capacity of a pond, a number of intermediate drainage systems may be required.
- Upon abandonment of the pond, the storage capacity of the pond will be eliminated or limited. This will affect the design of the hydraulic system for the final stages of disposal operation in that the outflow capacity of the hydraulic structures must equal the inflow in excess of the fixed storage capacity.
- Due to changes in storage capacity during the sludge disposal operation, and possible changes to the pond embankments through staged construction, complex hydraulic structures are not necessary or desirable. Normally, excavated channels in natural soil and rock and/or decant systems are used.

Components of Outflow Systems. The hydraulic systems designed to convey water through or around a disposal pond, usually open channels and/or decants, have three basic components. Any one or a combination of these components or sections can be designed to control the volume and rate of outflow by varying their size, location, elevation, slope and shape. For example, the size of the inlet section can control the volume of flow, while the slope of the transport section can limit the rate of

Table 8-12

REFERENCES FOR HYDRAULIC DESIGN

ITEM	8-16	8-17	8-18	8-19	8-20	8-21	8-22	8-23	8-24	8-25	8-26	8-27	8-28	8-29	8-30	8-31	8-32	8-33	8-34	8-35	8-36	8-37	8-38	8-15	8-39	8-40	8-41	8-3
I. Hydraulic System Components																												
Inlets	X	X		X	X		X		X	X				X		X		X	X		X		X		X			X
Transport Sections					X					X				X				X						X				X
Open-Channel Flow	X	X	X	X	X		X		X	X				X				X						X				X
Conduit Flow	X		X	X		X	X		X	X				X				X					X		X			X
Outlets	X	X			X		X		X				X	X			X	X			X							X
II. Design Consideration																												
Erosion Protection	X	X							X			X	X				X	X		X	X			X				X
Cavitation							X		X					X		X					X							X
Bends in Open-Channel Flow		X			X		X		X	X				X														
Bends in Conduit Flow						X	X		X	X				X														X
Waterhammer in Conduits							X		X	X	X			X														
Trash Racks, Debris Control									X						X			X										X
Vortex Control															X	X												
Seepage Cutoff Collars															X													X
Pipe Bedding	X							X														X				X		
Ice Pressure									X																			X
Impact													X	X														
Energy Dissipators		X			X				X				X	X							X							X
Materials Selection	X					X																						X
III. Hydraulic Systems																												
Decants				X			X			X				X	X	X		X	X		X							X
Spillways		X			X		X		X	X				X	X			X			X							X
Diversion and Collection Ditches		X	X		X		X		X					X				X						X				
Siphon and Pump Facilities							X		X	X				X														X
Culverts	X	X	X	X	X	X	X		X	X				X				X					X		X			
Natural Streams		X			X				X	X				X														X

Source: E. D'Appolonia Consulting Engineers, Inc., Engineering and Design Manual Coal Refuse Disposal Facilities, U. S. Department of Interior, Mining Enforcement and Safety Administration, 1975.

flow and the location and configuration of the outlet section can be designed to reduce downstream erosion.

- Inlet Sections. The purpose of an inlet is to direct flow into the transport section of the system and/or control the volume or rate of flow into the transport section. If its function is to simply direct flow, it should be designed with a capacity greater than that of the transport section. If the inlet is to regulate flow, it is designed as a weir, either a broad crested weir or a sharp crested weir. Where an inlet is to control the volume and rate of flow, the head or height of water above the inlet elevation and the size of the opening is important.

  It should be remembered that the combination of the inlet, transport and outlet sections of the pond outflow structure establish the overall discharge capacity of the structure. It is also important to limit the maximum head of water in the pond to that required to produce the desired rate of flow through the designed outlet structure, and not to allow the head to exceed the physical limits of the outflow structure nor reduce the pond freeboard to less than the minimum allowable pond freeboard. These conditions may be checked when the elements of storage and outflow are balanced through the design process of reservoir routing which will be discussed later in the text.

- Transport Sections. The transport section of an outflow structure conveys water from the inlet to the outlet. There are three types of transport flow sections:

  Open channel flow as in the case of spillway structures and diversion ditches

  Closed conduit flow which is common to decant systems

  Free-fall flow where water simply flows over a weir and falls. There is little hydraulic design to this type of transport section.

Open channel flow is gravity flow where the depth of flow and velocity is a function of the channel configuration and slope, surface materials and sometimes the inlet and outflow conditions. Open channel flow also applies to less than full conduit flow. The design of open channels employs Manning's formula, which applies to steady flow conditions in a uniform channel section and the equation of continuity. (8-5)

A repetitive design procedure is required to determine an acceptable depth of flow and velocity which satisfies the Manning equation for a trial channel section and for the rate of flow resulting from the design storm. To facilitate this design procedure, nomographs or charts may be used for the solution of Manning's equation and determination of the depth of flow. (8-18,33)

The determination of an "acceptable" flow velocity, mentioned above, is a flow velocity that will not erode the materials lining the channel. Comparison of the computed velocity from Manning's equation with the appropriate permissible velocity for the material through

which the channel is excavated will indicate whether the computed velocity should be reduced or if the channel should be protected by a lining.

Also to be considered in the design of open channels is the erosive effects of cavitation and the significance of directional changes in the flow of pond discharges. References discussing these topics are presented in Table 8-12.

The other form of transport section is a closed conduit. When flowing full, the behavior of conduit flow is similar to the analysis of pressure pipe flow. The conduit may be prefabricated or cast in place using either square, round, oval or rectangular cross-sections. Factors affecting the flow in such closed conduits are the slope, size, shape, length, roughness and the effects of inlet and outflow configurations. The interaction of these factors determines the discharge capability of the conduit.

Additional consideration should be given to the following features and characteristics of closed conduit flow using the design references listed in Table 8-12.

-- External embankment pressure
-- Internal water pressure
-- Impact considerations for decants
-- Trash racks
-- Vortex control
-- Flow at conduit bends
-- Cavitation
-- Water hammer
-- Material selection

- Outlets. The size, location and configuration of the outlet section of a hydraulic structure will partially depend on the purpose of the outlet. An outlet may be designed to control the discharge through the entire structure in which case, it is designed for weir or orifice control. Or, the outlet may be designed in a more general case to limit the erosive effect of the downstream pond discharges.

  The general design criteria for constructing an outlet section to a hydraulic structure such as a spillway or decant system are that:

  -- The manner of discharge must not endanger pond embankment stability, lives or significant downstream property.
  -- For unusually large storms, such as the PMP, the outlet need not be designed to totally prevent downstream damage, provided the first criterion above is met.

The design requirements for outlet features such as stilling basins, riprap protection, energy dissipators, and drop structures are discussed in literature. (8-3,28,33 and 36)

Types of Discharge Systems

The following general discussions concern the types discharge hydraulic systems commonly used in conjunction with the hydraulic design of disposal ponds.

Decant Systems. Decant systems serve one or more of the following purposes:

- Removal of supernatant during normal sludge disposal operations
- Provide outflow for minor storm inflow quantities
- Provide removal of stored water resulting from major storms, such as the appropriate design storm, within a reasonable amount of time (see the Design Storm Criteria section of this text). This discharge capacity may be supplemented by spillway discharge as well.

The primary design considerations of a decant system are the location, configuration and type of inlet with regard to the total disposal facility configuration, the location of pipeline sludge discharges, the rate at which the pond level will rise during normal disposal operations, and the eventual requirements for site abandonment. More specifically, the following questions, should be addressed during the design of a decant system: (8-5)

- What is the limiting height of the decant above the surface of settled sludge solids to assure an adequate retention time to clarify the slurry water?
- Where should the inlet be located relative to the slurry inflow point, considering that the level of the settled slurry normally is highest at the point of inflow and decreases gradually from that point? (From a geotechnical viewpoint, it is desirable to have the slurry inflow pipe located adjacent to the crest of the embankment forming the impoundment.)
- How can the inlet height be increased to serve the rising level of the water surface as additional sludge is settled, and will access to the inlet be possible for height extension?
- Should the inlet be a sloping pipe along the natural hillside forming the impoundment, or along the upstream face of the embankment, so that access for extension is simplified?
- How will the method of embankment construction (see upstream and downstream staging methods) affect subsequent extensions of the inlet?
- Will the inlet tend to become clogged with debris if not protected with a specially designed trash rack?
- Will the eventual total height of the inlet be such that forces (due to flowing water) at its junction with the transport section must be considered during the intial installation to avoid future problems due to movements or breakage?

- Would it be practical to avoid using a decant system at all? This would require the use of overflow weirs constructed at increasing levels as the facility rises, with discharge directly into a channel designed to protect the overall safety of the facility.

Additional considerations relevant to the design of a decant system are presented by the Mining Enforcement and Safety Administration (MESA) and include: (8-5)

- The possible inclusion of a trash rack to prevent the inlet from becoming clogged. (8-3)
- The possible inclusion of an anti-vortex device at the top of a vertical inlet, particularly when the head above the inlet will be great. (8-31)
- The possibility of external forces being applied to the protruding portions of the inlet, such as that due to the buildup of ice in the winter. (8-3)
- Joints in the transport section should be sufficiently flexible to move longitudinally and to change curvature if lateral expansion or settlement of the foundation is anticipated. Coordination with the geotechnical engineer is required to determine the importance of this. (8-30)
- Cutoff collars should be provided along the length of the conduit to avoid the possibility of seepage adjacent to the conduit from the upstream impoundment. (8-3)
- The conduit must be designed to withstand the external pressure of the embankment above it, which can be very large for high embankments. (8-23)

Spillway Systems. Spillway systems are the most important hydraulic structures for the safe disposition of pond inflow and storage resulting from major storms. The requirement for a spillway to transport large flows from a high elevation to a lower elevation over a relatively short distance makes spillway design one of the most difficult hydraulic tasks in the design of a wet sludge disposal facility.

As described earlier, a spillway is usually located at a significant height above the initial pond elevation in order to provide adequate sludge storage capacity for long periods of disposal. This eliminates the need to construct intermediate spillways as the pond level rises due to sludge disposal. This type of design is initially similar to a total storage concept with no requirement for a spillway. However, as the pond level rises during disposal operations, the spillway becomes increasingly active or potentially active until, at the time of abandonment, the spillway must discharge all inflow quantities due to the small or nonexistent water storage capability of the disposal pond. To control and limit storm water stored in the pond

below the spillway elevation and above the normal pond level, a decant system is often included.

The most commonly used and most economical spillway structure for disposal ponds is an open channel excavated into natural soil and/or rock at the abutment of the pond embankments. The required flow capacity of the spillway is determined through reservoir routing procedures, which are subsequently discussed.

The following general criteria and considerations are presented for spillway design guidance: (8-5)

- If the spillway will only be activated during very large storms (such as those exceeding the 1% probability precipitation, see Design Storm Criteria section), special provisions are seldom required at the outflow point since the resulting erosion damage most often will not be significantly greater than general erosion damage in the area, and since the probability of the spillway functioning many times during the operational period of the facility is low.
- If the spillway is expected to be activated as often as every 25 years, or more frequently, special provisions should be made to transport the flow without excessive erosion, or the flow should be discharged through a parallel decant system.
- Initial planning and design should account for the manner in which the spillway system could be modified as the disposal facility increases in size.
- The channel materials must resist erosion.
- The stability of the excavated slopes forming the channel must be considered.

Reservoir Routing

Reservoir routing is a method of balancing the elements of inflow, storage and outflow for an impoundment, and serves to assist in the design of a hydraulically and economically effective impounding system. Reservoir routing is important to the final sizing of discharge structures, such as spillways and decants, necessary to handle design flood inflows, while at the same time maintaining a practical and economical pond and embankment size in addition to a sufficient embankment freeboard. The procedure is one of determining outflow from the pond and storage in the pond as it varies with time based on the known inflow to the pond.

There are several techniques of flood routing that may be used and range from a totally mathematical method to a total graphical method. A simple method often used and

appropriate to the scope of this text is an arithmetical trial and error tabular method. This method is outlined and an example presented in the USBR. (8-3)

Regardless of the routing method used, the following input data are necessary:

- Inflow hydrograph (curve of inflow versus time)
- Pond storage capacity (curve of pond storage versus pond surface elevation)
- Discharge curve (rate of outflow versus pond elevation). More than one discharge curve may be needed if there is more than one discharge structure in the pond, for example a spillway and decant system.

Resulting from the flood routing methods is an outflow versus time curve. The area under this curve is equal to the volume of outflow from the pond. As discussed earlier in the text, the capacity of the spillway and/or the decant system must be capable of removing 90% of the water stored during the design storm within a period of 10 days.

POND OPERATION

Where ponds are installed, correct operation is an important factor in overall scrubber plant management. The reasons for this include:

- Water balance. The ideal situation, considering restrictions on liquid discharges, is that no water makeup to the scrubber system is required except to replace that lost by evaporation or with the discarded sludge. The latter should be restricted to that which is inextricably combined or held with the sludge. The ideal is seldom, if ever, attained because of unavoidable water addition or loss due to meteorological conditions or emergency situations. However, good operation can minimize the effects.
- Clean return liquor. Adequate retention time is required to permit separation of sludge from the liquor. The returns are not required to be crystal clear, but suspended solids should be minimized for uses such as reagent dilution or pulverizing and slurrying limestone.
- Regulatory requirements. Some states require close control of freeboard, dike/dam integrity and discharges. These can only be controlled by good pond management.
- Public safety. Failure of retaining structures in built-up areas can result in conditions varying from vexatious to catastrophic. In either extreme, monetary loss can result, and good pond operation is cheap insurance.

Ponds can be classified according to use as either interim or long-term. The former is used for the purpose of solids separation prior to removal of the solids to another location for either wet or dry ultimate disposal. Long-term ponds are those generally used for ultimate disposal and will eventually be closed as ponds or drained, covered and vegetated as landfills. Good management is required for both types.

Ponds can also be classified as on-site or remote. The former is more easily kept under surveillance and control than those located in remote areas. However, good operation is still an important part of overall scrubber performance.

Operating Instructions

Operation and monitoring are closely allied, and cooperation between the responsible personnel is necessary. In fact, operating instructions should require a knowledge of and familiarity with the monitoring requirements and check lists. Explicit, written instructions should be provided for the operating personnel responsible for the ponds. Instructions should require/include:

- Maintenance of a complete log of events, including instrument readings, notation of alarms and actions taken, record of maintenance required, and conditions relative to monitoring.
- Description and purpose of pumping facilities with list of normal and abnormal conditions that may be observed and actions that should be taken.
- Description and purpose of instrumentation and alarms with normal inspection and corrective actions required.
- Duties to be followed in respect to routine pond inspection and condition of facilities, including lighting, communication and safety equipment.
- Actions to be taken in case of emergencies, including a list of personnel to be notified. The latter may include regulatory agencies, as required in some states.

Pumping Facilities

Redundant pumps should be provided for transporting sludge to the ponds(s) and for supernatant return. Back-up pump operation should be automatic in case of primary pump failure or excessive pumping requirements. Supervisory lamps should indicate pump operation, and back-up pump operation should be alarmed. As previously noted, alarms should be logged and investigated. Back-up pump operation should be checked on a routine schedule. Emergency, gasoline-driven pumps should be available on site.

Closely allied to pump operation is the condition of the suction tanks or sumps. Sludge tanks or sumps require continuous agitation to prevent sludge settling, with subsequent clogging of pump suctions. Agitator operation should be observed routinely, and cessation of operation should be alarmed. Level activation of pumps is subject to failure by clogging with sludge, and routine inspection, trial operation and cleaning are required. Similarly, sump return pumps and controls require routine inspection and cleaning.

Instrumentation

Flow and pressure of both sludge and return pumps should be continuously recorded and periodically logged. Normal readings should be established, and deviation from these values should be reason for investigation and, in some cases, should be alarmed.

Deviation in pressure could indicate pipe leakage, pipe plugging, suction plugging or pump wear. Changes in flow not associated with day-to-day scrubber operation could indicate leaks from the piping or pond(s), pump wear, heavy rain or pluggage in the thickener(s), sludge tanks or return sumps.

Inspection

At least once-per-shift inspection of the pond area is recommended. Items to be covered include:

- Pond freeboard. Changes from a set reference point should be logged and investigated if the trend continues.
- Exclusion facilities. The condition of fences and gates of offsite ponds should be noted.
- Sludge deposition. Uniform distribution is necessary in order to fully utilize the disposal area and avoid short-circuiting the flow from inlet to outlet. The latter shortens residence time and prevents adequate settling. Repositioning or extension of inlet piping may be necessary.
- Outlet sump, weir and rakes. Signs of clogging or abnormal conditions should be noted and corrected. Ice accumulations should be removed.
- Weather conditions. Abnormal winds or precipitation should be observed and immediate effects corrected, if possible. Wind action may be such as to cause bank erosion or spillage over the berms, either of which could affect dike or dam integrity. Abnormal precipitation could have similar effects or could result in decreased freeboard. Supervisory personnel should be alerted to long-term effects.
- Oily and foreign matter. Oil slicks on the pond surface could indicate accidental or intentional discharge from equipment in the

area. Oil changes have been made by draining the oil on berms or on hillsides around ponds, the oil then washing into the pond with subsequent rains. Debris has been washed or been thrown and animals have drowned or been thrown into ponds. Immediate removal should be made, if possible. Otherwise, the condition should be logged for action later.

Equipment

The following should be provided:

- Transportation for off-site inspection
- Adequate permanent lighting for on-site ponds, portable for off-site
- Telephone or radio communication facilities
- Ice removal equipment
- Safety equipment including life vests, preservers and lines
- Boat
- Rope and grappling hook

Off-site equipment that is left at the site should be protected against the weather, vandalism and theft, and should be subjected to periodic inspection.

LANDFILL DESIGN

Introduction

Differing from the ponding method of disposal, landfill disposal requires some degree of processing of the wet scrubber sludge to obtain a soil-like material that may be loaded, transported and placed as a fill. In addition, the properties of the processed sludge must be known during and after placement in order to design, construct and operate a structurally stable and environmentally acceptable landfill.

Design Considerations

The primary considerations for the design of a landfill disposal operation are the stability and environmental impact of the fill embankment. The major design criteria for these considerations are the development of methods to:

- Reduce or eliminate contamination of surface and ground waters caused by landfill leachates and surface runoff
- Prevent landfill instability in such forms as landslides, slumping and erosion
- Abandon the completed landfill in a manner that will satisfy the above two criteria on a long-term basis

The design of the landfill will be based in part on the chemical and physical properties of the FGD waste, and on the topography, geology, and hydrology of the disposal site. In its untreated state, FGD sludge is a fine-grained, low-shear strength, thixotropic material with a high water-retentive capability. The fixation/stabilization of scrubber sludge, as discussed in Section 12 - FIXATION/STABILIZATION, or utilization of forced oxidation is necessary not only to obtain a soil-like material suitable for handling and placement in a landfill, but also to improve the shear strength and reduce the permeability and leachability of the sludge. The geology and hydrology of the disposal site also play an important part in the design of a stable and environmentally acceptable landfill operation. Here, the major concern is the ground and surface water within and adjacent to the area to be covered with the FGD wastes. The proper management of this water is important because water is the only means of transporting pollutants and generating leachate. The degree of ground and surface water contamination depends on the amount of water that passes through or is in contact with the waste material. Secondly, the properties of the landfill foundation materials and the influence of possible deep mining or cavities below the disposal site are important to the stability of the fill.

The stability of the fill is especially important in relation to safety aspects of the disposal operation. The landfill designer should be aware of the following three potential hazards and design accordingly:

- A landfill will have a high hazard potential if it is located where a slope failure (landslide slumping or sloughing) would have a high possibility of causing injury, death or extensive property damage.
- A landfill may have a high hazard potential if it is located adjacent to a stream where significant sloughing or shifting of the fill would block or restrict the stream flow creating a temporary impoundment which could release a hazardous floodwave after breaking through the sloughed material.
- A landfill may have a high hazard potential if water is unexpectedly impounded during some stage of development, despite the existence of underlying drainage systems. This unanticipated accumulated water could structurally weaken the fill to the point where slumping or sloughing results.

To prevent these potential hazards from developing and to minimize the environmental impact, some or all of the design criteria listed below must be met: (8-44)

- Landfill slope areas must be designed so that high pore pressure cannot be developed by ground water or rainfall infiltration.

- If necessary, a granular underdrain system should be incorporated in critical portions of the fill to insure that pore pressure will not adversely affect stability. Unless there is strong evidence to counterindicate its use, such a drainage system is advisable.
- The fill must be designed so that water which is temporarily impounded will not remain long enough to create pore pressure conditions hazardous to the fill's stability.
- If necessary, surface runoff control should be provided to limit leachate generation and minimize erosion.
- If necessary, a dike should be constructed around the landfill to prevent inundation by neighboring streams or rivers.
- If necessary to prevent leachate infiltration of the ground water, an impervious layer or liner should be provided under the fill.
- If necessary to prevent ground water contamination, an underdrain system should be placed under all or portions of the landfill to collect leachate.

Which of these measures are necessary must be decided on the basis of the conditions found at each individual site.

Preliminary Steps

Prior to initiating the detailed design of the fill it is necessary to develop background information which will be used in the design and to make some preliminary decisions. These preliminary steps are:

- Determine the rate of sludge production (weight and volume) over the operating profile of the plant. Section 4 - WASTE QUANTITIES shows how to make these calculations. It is necessary to know in advance of any change in annual production in order to plan the sequence of filling.
- Select and investigate an appropriate site. It is assumed for this discussion that a site has been selected which is sufficient to accomodate the waste for the design period and meets appropriate regulatory standards. Information on site selection is provided in Section 6 - SITE SELECTION. Information on general geotechnical considerations and detailed site investigation are provided in the GEOTECHNICAL CONSIDERATIONS subsection of this Section of the Manual.
- Determine or estimate the sludge characteristics. Of particular importance are the density and strength properties of the sludge. The density will assist in determining the disposal area and filling sequence. The strength characteristics are important in determining acceptable slopes to provide fill stability. It should be noted here that literature values of strength will be suitable only for planning purposes. FGD sludges are sufficiently variable that tests must be conducted on the actual sludge generated from an individual utility after the scrubber is in operation. Design values for degree of compaction and fill slopes must then be adjusted to reflect

the properties of the sludge generated. Typical values for the engineering properties of FGD sludges are provided in Section 3 - WASTE COMPOSITION.

- Determine the general configuration to be utilized. The local topography will often dictate the configuration for the fill. The previous subsection, ALTERNATIVE DISPOSAL CONFIGURATIONS, shows the three primary alternatives: heaped or mounded fill, side-hill fill, and valley fill.
- Develop the base map. If not already done for the site selection and site investigation, a base map should be prepared, showing the disposal area and nearby land which may be affected by site operations. Much of the design of the fill is defined using illustrations on the base map. The base map should be a topographic map showing existing site topography prepared to a convenient scale (typically, 1" = 100' to 1" = 400'), depending on the size of the site. As a minimum, five ft contour intervals should be delineated. More detailed mapping, typically at two ft contour intervals, will be necessary in areas where permanent structures such as buildings and drainage devices will be located. If available maps are inadequate or out-dated, new mapping should be obtained. The property line, buildings, buffer areas, vegetation, wells, rock outcroppings, roads, utilities and other pertinent details should be shown. (8-48)

Site Development Plan

A landfill operation is, in effect, a long-term construction project. As a result, the operation should be carefully planned and all phases of the construction, including site preparation and start-up, interim stages, and final abandonment should be considered. As with any other construction project, development of the site should be shown in a series of phase development drawings which illustrate the method of development.

The drawings should include:

- The base map showing existing topography and initial site improvements
- Interim maps and/or cross-sections showing site topography, excavation, and other improvements at various stages of site completion
- Detailed drawings of lifts, roads, drainage facilities, and other aspects
- A final map showing the planned contours and the facilities to be located on the fill

The number of interim drawings will be determined by the complexity of the site and the rate of filling. The drawings should be sufficiently detailed to effectively guide the site operators.

In general, the method of site development is determined in large measure by the local topography and the general fill configuration to be used. The following subsections describe alternative methods of site development which are available. All or a combination of methods may be used, depending upon the land available.

One of the most important factors entering into the development plan is what to do with the surface runoff. Methods for controlling surface runoff are discussed in the subsection entitled "Drainage Facilities" which follows below. However, because of its importance to site development, it is discussed as part of the overall development plan.

General Description. Regardless of the site characteristics, the general method of filling is the same. Sludge is delivered to the working area on the site, spread in thin, horizontal layers in a confined area on the ground or on previously filled sludge, and compacted with heavy equipment. These thin layers are continued until a group of successive layers are built up in one area to a reasonable working height of from about 10 to 20 ft. This set of successive layers, termed a lift, is repeated until the available area is filled. Figure 8-23 shows a typical section through the centerline of a valley or side hill fill.

Contrary to landfills of municipal-type wastes, no daily soil covering of FGD waste is normally required because the sludge is not attractive to animals and is noncombustible. However, an attempt is usually made to reduce the working area to minimize dust and erosion problems.

Heaped Fill. Figure 8-24 shows an example of a heaped fill on flat terrain in a valley bottom. This type of fill is built from the bottom up, usually starting in one corner and working progressively to establish the fill. Two different sequences are shown in Figure 8-25. The primary consideration is for conveying precipitation, which falls directly onto the facility, to the base of the fill without deleterious erosion. This type of fill has no water storage capacity so all precipitation must be directed off the facility as it occurs.

Collection ditches on the gently graded top should have very shallow depths which will not erode excessively. However, the drains conveying water down the face of the slope will be subject to high velocity flows and must be protected from erosion.

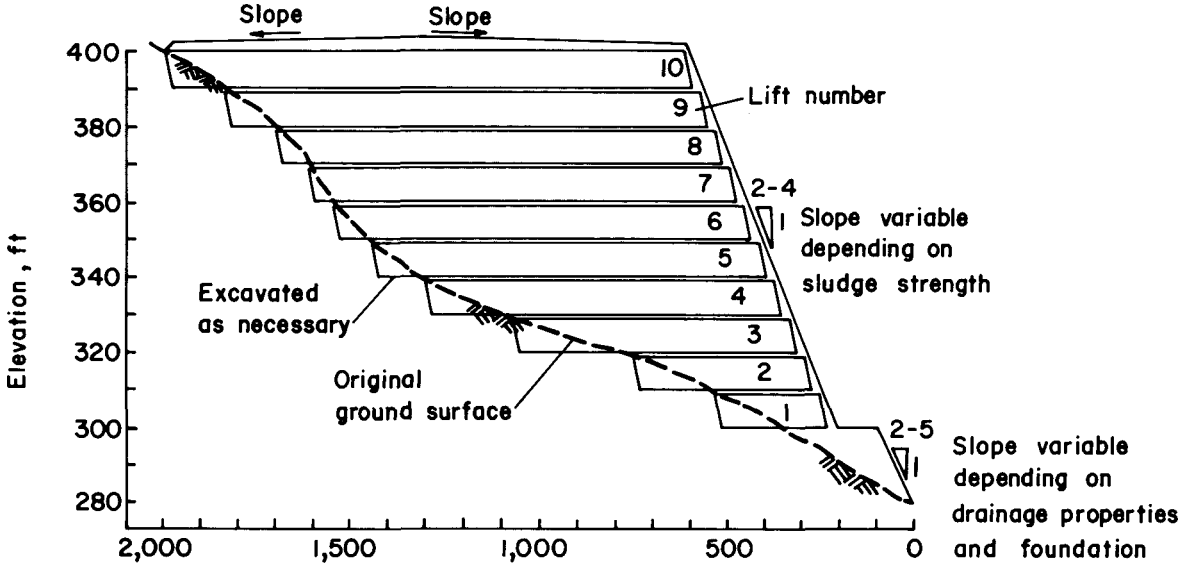
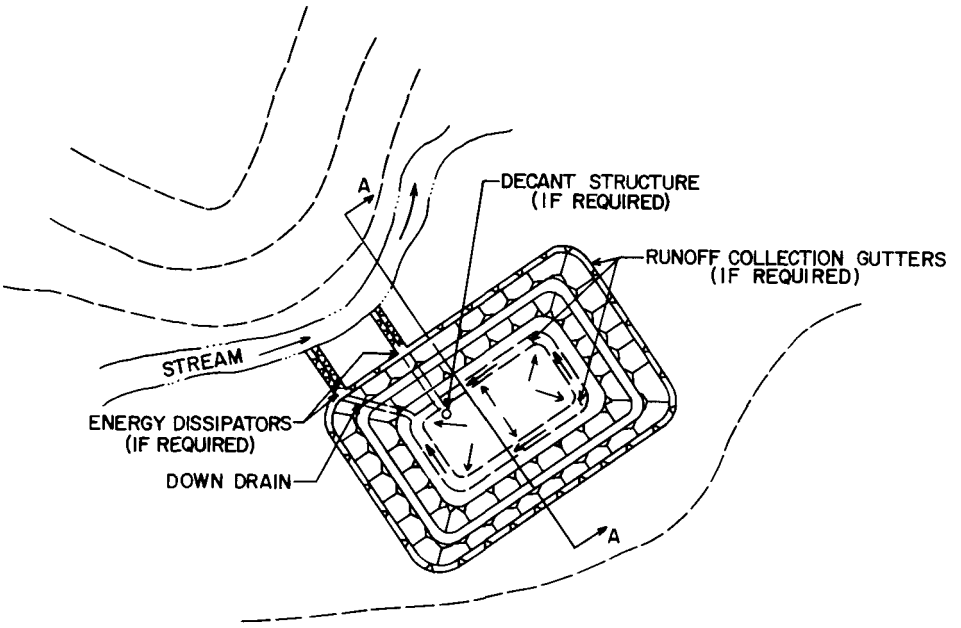
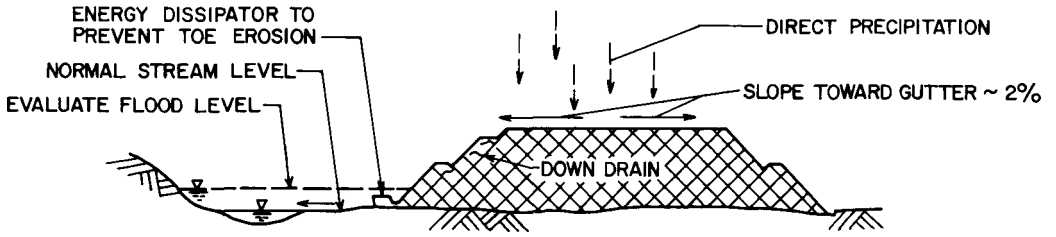


Figure 8-23. Typical Section through Approximate Centerline of Valley-Fill or Side-Hill Fill Showing Lift Details.

Source: Tchobanoglous, et al., Solid Wastes, McGraw Hill Book Company, New York, NY (1977).



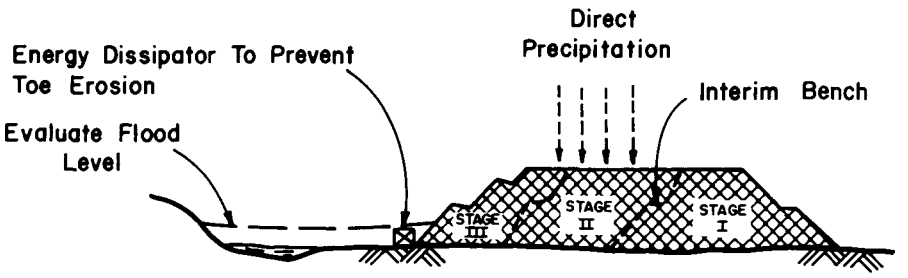
(a) Plan View



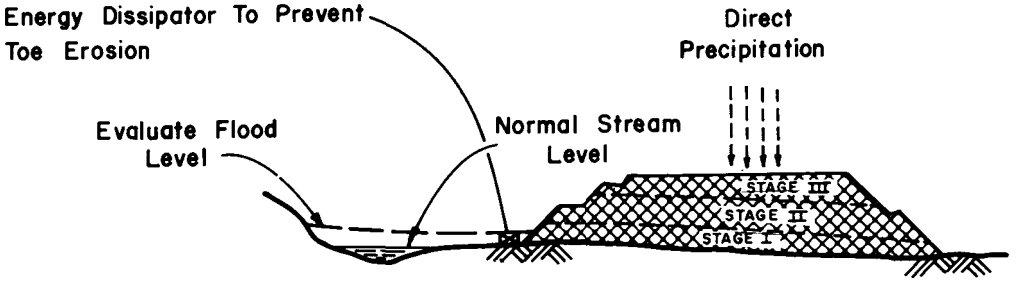
(b) Section A-A

Figure 8-24. Schematic Example of Heaped Landfill.

Source: E. D'Appolonia Consulting Engineers, Inc., Engineering and Design Manual, Coal Refuse Disposal Facilities, U. S. Department of Interior, Mining Enforcement and Safety Administration, 1975.



(a) Horizontal Development



(b) Vertical Development

Figure 8-25. Examples of Methods of Development of Heaped Fills.

Side-Hill Fill. Figure 8-26 shows schematic examples of side-hill landfills. The figure shows construction from the lower elevation to the upper elevation. Although the watershed above these types of landfills is smaller than in a valley fill operation, the amount of runoff must be calculated and diversion or decant structures provided to handle the design flow. Ordinarily, it is not advantageous to construct the fill as an impounding device (as shown in Figure 8-26c) because of increasing seepage into the fill.

All diversion and collection ditches must be sized and constructed to convey water in a controlled manner and to reduce erosion.

Valley Fill. Valley fill landfills, as illustrated in Figure 8-27, can be constructed by starting at the top and working down the valley in a manner which never creates an impoundment (downstream method) or, alternatively, by starting at the bottom with a non-impounding, cross-valley fill and progressing uphill (upstream method). Both methods result in the same final configuration.

The principal design considerations for the downstream method are:

- Collection of runoff from the watershed above the landfill
- Collection of runoff from the surface of the landfill
- Control, conveyance, and discharge of the collected runoff
- Erosion protection of the face of the embankment

Figure 8-27 (d) and (e) show different ways to handle these runoff flows. Use of the upstream catchment shown in Figure 8-27 (e) is generally not recommended for several reasons:

- The catchment outlet may be too small to contain runoff resulting from unusual storms, creating temporary storage and increasing seepage in the fill.
- The outlet pipe is subject to clogging with debris and, because it can lie at substantial depth, may not be easily cleaned.
- The outlet pipe must remain open and operational upon abandonment and its practical life must be considered to be limited.

These problems can be overcome by using the method while construction is occurring, but then changing the slope conditions upon abandonment to eliminate the need for the catchment device and drain pipe.

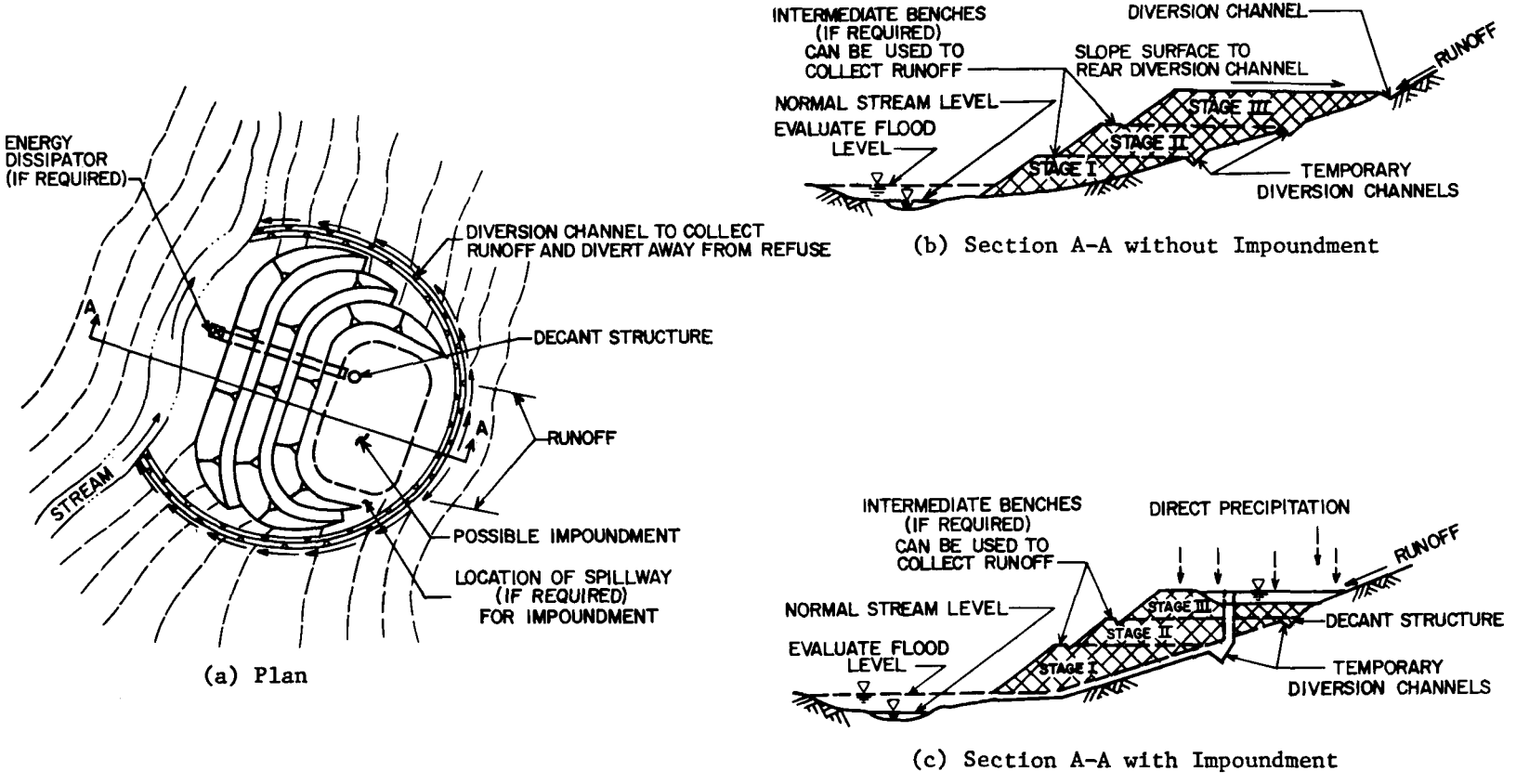
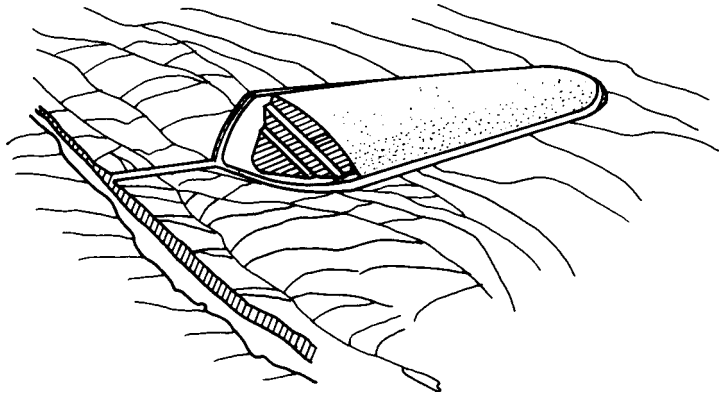
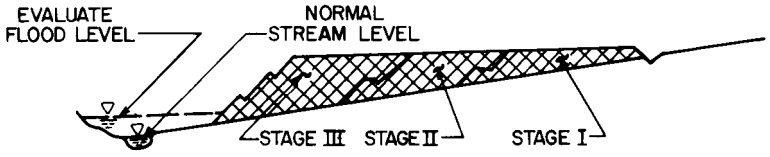


Figure 8-26. Schematic Examples of Side-Hill Landfills.

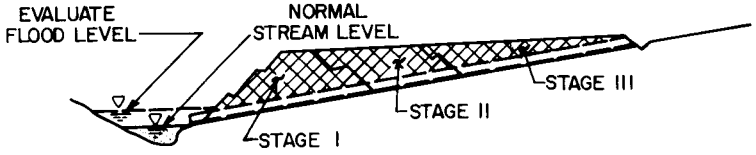
Source: E. D'Appolonia Consulting Engineers, Inc., Engineering and Design Manual, Coal Refuse Disposal Facilities, U. S. Department of Interior, Mining Enforcement and Safety Administration, 1975.



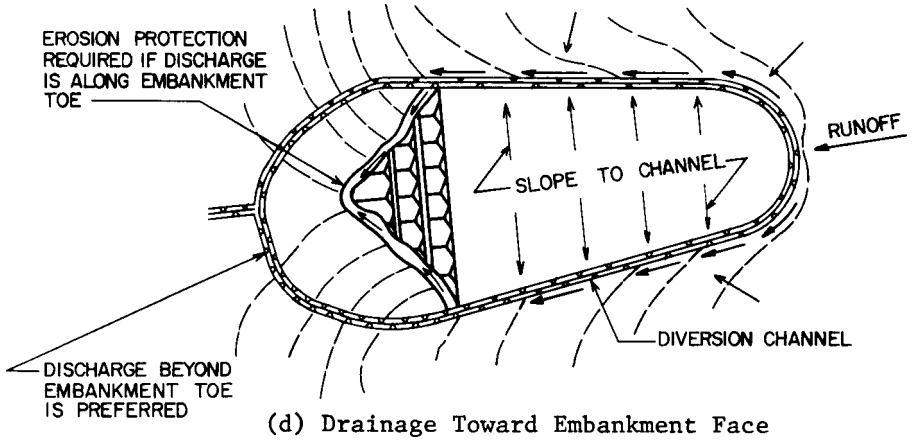
(a) Illustration of Valley-Fill or Cross-Valley Landfill



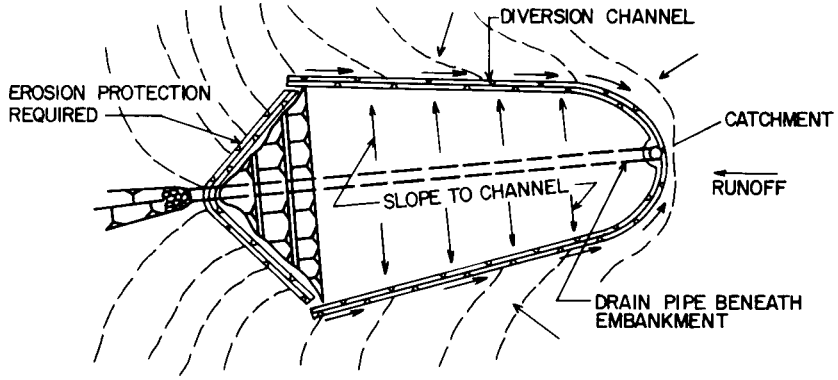
(b) Cross-Section of Placement by Downstream Method



(c) Cross-Section of Placement by Upstream Method



(d) Drainage Toward Embankment Face



(e) Drainage Toward Upstream End with Discharge Pipe

Figure 8-27. Schematic Examples of Valley-Fill Landfills.

Source: E. D'Appolonia Consulting Engineers, Inc., Engineering and Design Manual, Coal Refuse Disposal Facilities, U. S. Department of Interior, Mining Enforcement and Safety Administration, 1975.

The principal design criterion for the upstream method is that drainage through the site not be impounded. Impoundments are possible but generally not advantageous. Drainage onto and from the site should be conveyed through the fill by a pipe or culvert beneath the fill. The pipe or culvert is usually sized to pass the runoff from the design storm, but with provision for temporary impoundment during flows which exceed the design storm.

The engineer must make provision for this temporary storage in designing the stability of the fill. If necessary, a spillway must be provided. When closing the site, it is preferable to regrade the upper surface so that the pipe or culvert will no longer be needed.

Other general design considerations for valley fill configurations are:

- If a natural stream channel passes near the site, protection must be provided to protect the toe of the slope from eroding during flood periods. Proposed regulations issued under the Resource Conservation and Recovery Act of 1976 require the construction of dikes around any landfill disposal facility located within the 100-year floodplain to prevent flooding of the fill.
- Sedimentation ponds will ordinarily be required at the ends of collection ditches. Adequate room must be provided for these facilities.
- Pipes and culverts must be designed to withstand maximum load under the full height of the fill.

Foundation Characteristics

The shear strength and settlement characteristics of the foundation materials upon which the landfill will be constructed are important to the design of stable fill slopes, and to the integrity and effectiveness of subfill drains and impermeable liners.

The shear strength of the soil and rock foundation materials is primarily a concern only in the vicinity of proposed fill slopes. Here the foundation soils may play an important part in the design and stability analysis of the proposed landfill slopes. Where these materials are found to be weaker than the sludge and ash fill when placed, the methods cited earlier in the text for stabilizing fine-grained foundation soils for pond embankments may be used. Of these methods, the most commonly used and practical are removal of the weak soils from the vicinity of the slope or flattening of the fill slopes. The design of the slopes will require the calculation of the factor of safety for stability using the shear strength parameters of the specific fill and foundation materials involved and various fill slopes and configurations.

The settlement of the foundation materials under the weight of the filled sludge is normally not an important design consideration unless the settlement will be detrimental to the operation of underdrains or liners constructed beneath the fill. Where settlement is considered to be a problem, underdrains and impermeable liners should be designed sufficiently thick and drain pipe sufficiently flexible to undergo differential movement without failure to perform as designed.

Drainage Facilities

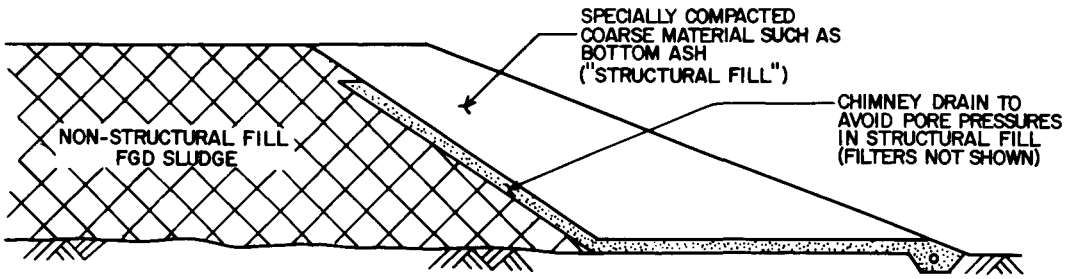
Drainage facilities must be provided for two different types of surface water:

- Existing sources and flows such as springs and marsh areas that will be covered during the landfill operations
- Rainfall runoff which originates from precipitation falling directly on the fill or flows in the direction of the fill area

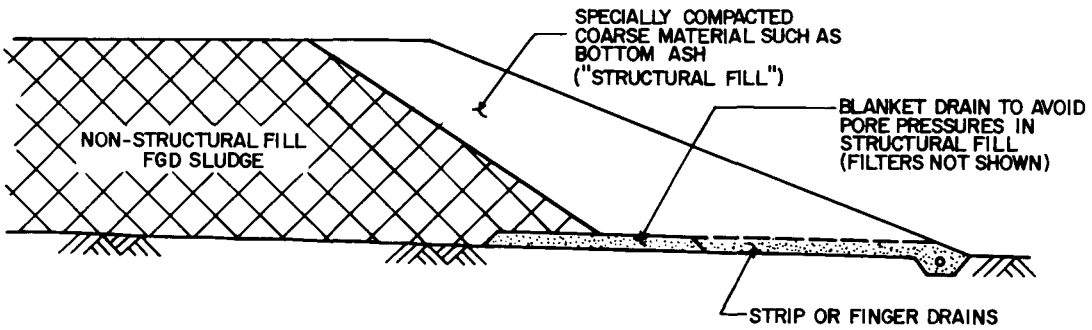
Existing Sources. Drainage must be provided for existing sources and flows of surface water such as springs and marsh areas that will be covered during the landfill operation. Collecting and conveying this water through the site beneath the constructed landfill is important to the structural stability of the landfill by preventing the buildup of pore water pressures beneath the fill, and helping to reduce contamination of the water and generation of leachate by preventing direct contact between the water and landfill materials. Depending on the quantity of water to be collected and conveyed, pipe and/or granular drains may be required. Figure 8-28 shows typical underdrain schemes for landfills. The design of these drains should be in accordance with the criteria for filter design, previously presented during the discussion of The Embankment Foundation Design for POND DESIGN.

If there are seeps and springs located on the site and these will be covered, it is usually desirable to collect these without permitting water to enter the fill. Figure 8-29 shows a typical granular material collection facility at a spring.

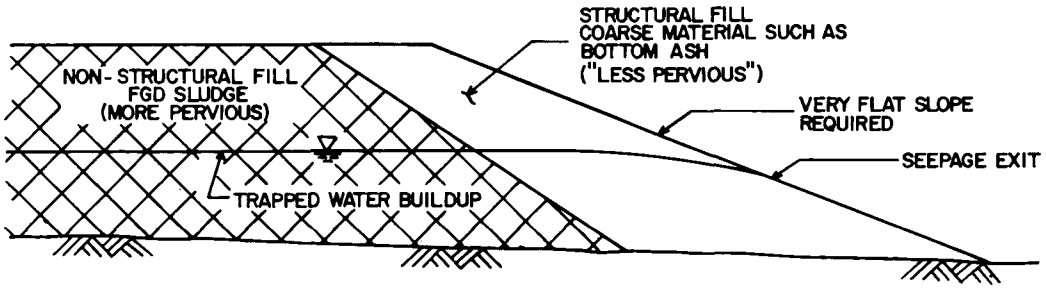
Rainfall Runoff. Appropriate temporary and permanent drainage facilities must be provided to control surface runoff. As discussed in the previous section, Site Development Plan, these facilities must be designed to accommodate precipitation falling directly on the site and runoff flowing onto the site. In most cases the facilities are designed to channel surface runoff around or through the site in a pipe or culvert.



(a) Chimney Drain Arrangement



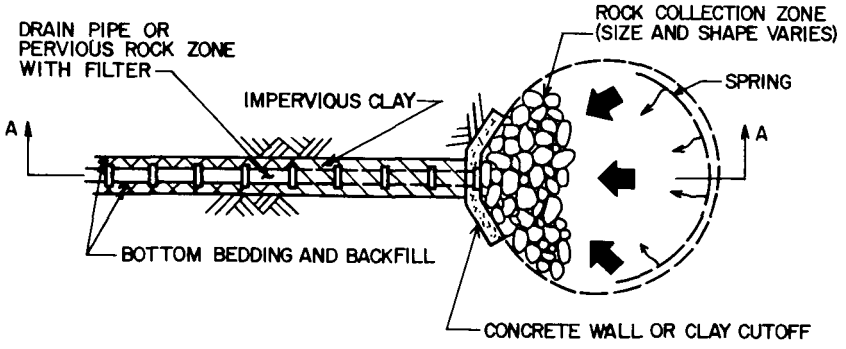
(b) Blanket Drain Arrangement



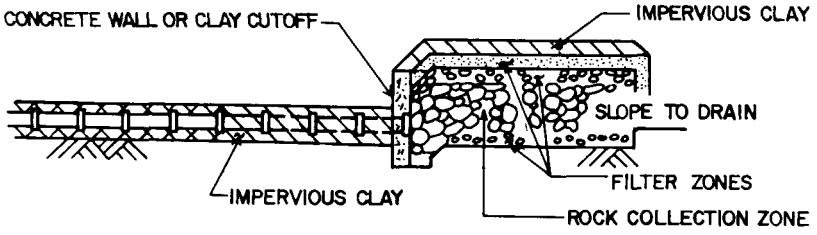
(c) Condition with No Underdrain

Figure 8-28. Underdrain Schemes for Landfills without Impoundments.

Source: E. D'Appolonia Consulting Engineers, Inc., Engineering and Design Manual, Coal Refuse Disposal Facilities, U. S. Department of Interior, Mining Enforcement and Safety Administration, 1975.



(a) Plan



(b) Section A-A

Figure 8-29. Typical Spring Collection Device.

Source: E. D'Appolonia Consulting Engineers, Inc., Engineering and Design Manual, Coal Refuse Disposal Facilities, U. S. Department of Interior, Mining Enforcement and Safety Administration, 1975.

Open channels or ditching are commonly used to carry the surface water away. The size and construction materials are usually determined by computing the runoff resulting from the design storm and applying Manning's equation. (8-18,33,49) The calculation of runoff quantity was discussed earlier in the subsection Hydrologic Inflow Determination under POND DESIGN.

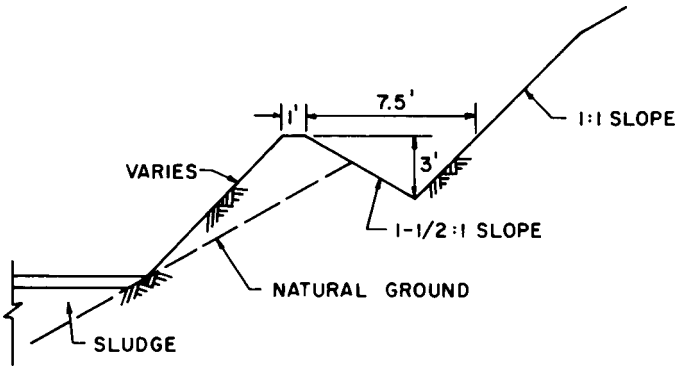
Depending on expected flow rates, the channels can be constructed of earth, lined with asphalt or rubble, or half sections of concrete or corrugated metal pipe. Figure 8-30 shows typical design details. Earthen ditches or split corrugated metal pipe are commonly used for temporary drainage facilities. Earthen ditches are advantageous because they are simple to construct with conventional earthmoving equipment; however, they are limited in the maximum tolerable velocity. Split corrugated metal pipe is popular because it can be placed fairly quickly and relocated conveniently.

Final drainage facilities are, in principle, the same as temporary facilities except that they must be designed to last. Grassy swales or ditches, stone center ditches, and concrete ditches are all commonly used.

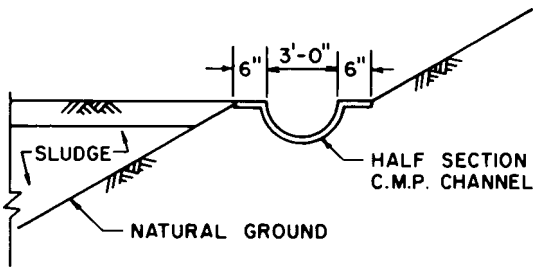
Facilities carrying surface runoff from the fill should be graded so that excessive erosion will not result during heavy flows. These grades will vary depending on the type of material over which the water will flow. For easily erodible materials, these grades may be as flat as 0.5 to 1.0%. Where runoff must be conveyed down steep slopes to the base of the landfill, paved ditches, rock channels or closed conduit may be necessary to prevent erosion. For such cases, consideration must also be given to the erosive nature of the high flow velocities that will result at the discharge point near the sedimentation pond.

The completed surface of the landfill should be maintained at a slope of not less than 2% to insure runoff of direct precipitation into the drainage system. Side slopes will be variable from 2:1 to 4:1, depending upon the engineering properties of the sludge or regulatory agency requirement. Exterior embankment slopes greater than about 50 ft in height should be benched to control surface runoff and improve embankment stability. Benches are typically constructed at 20 to 30 ft vertical intervals and are at least 10 to 12 ft wide to facilitate slope maintenance.

If the sludge is properly placed and compacted, little settling is expected to occur. However, if surface cracks or depressions occur, these should be regraded



(a) Earthen Drainage Channel



(b) Drainage Diversion Channel

Figure 8-30. Typical Design Details for Drainage Facilities.

Source: Sanitary Landfill, American Society of Civil Engineers, New York, NY, ASCE-Manuals and Reports on Engineering Practice - No. 39, 1976.

and revegetated to eliminate accumulation of water on the surface, reduce seepage and prevent erosion.

Sedimentation Pond

All surface runoff, particularly from the active portions of the landfill operation, should be collected and conveyed to a sedimentation pond. The sedimentation ponds used to clarify the landfill runoff may also be used to further treat the runoff water, if necessary. Sediment ponds are often excavated below grade into natural soil and rock materials. The capacity of the pond may be dictated by local regulatory requirements. Generally, however, excavated sediment ponds should have a minimum capacity to store 0.125 ac-ft/ac of disturbed area in the watershed. Sediments should be removed from the pond when the accumulation of sediment approaches 60% of the design capacity.

Ground Water Protection

The above methods of controlling surface water in and around the disposal site prior to the disposal of the waste materials, will help to provide for the long-term stability of the landfill when constructed and will reduce surface and ground water contamination by preventing this water from contacting the sludge.

According to the proposed EPA guidelines for non-hazardous waste disposal (8-56), disposal facilities overlying usable ground water should be at least 5 feet above the seasonal high water table to prevent direct contact of FGD sludge and the ground water. However, depending on the quality of the ground water table at some prospective disposal sites, and the soil and rock conditions at the site, further ground water protection may be necessary.

The migration of leachate pollutants into the ground water should be prevented where ground water quality is suitable for municipal and industrial use. In some cases, natural hydrogeologic conditions at the disposal site are capable of reducing leachate contaminants leaving the landfill to an acceptable level in the ground water. A design providing acceptable levels of leachate migration may be accomplished in hydrogeologic environments where on-site soils are impermeable (clays). Clays may remove pollutants and create longer retention time for leachate within the landfill to allow for more on-site purification. Clayey soils generally reduce the total dissolved contaminants content of leachate by one or two orders of magnitude in traveling a distance of a few feet.

According to the EPA proposed guidelines resulting from RCRA, if the natural hydrogeologic conditions at a disposal site overlying usable ground water are unable to prevent contamination of the ground water, artificial means of leachate control must be provided. Depending on the attenuation capabilities of the in-situ soil cover, leachate control should be accomplished by one of the following methods.

- Where natural hydrogeologic conditions are unable to improve the total quantity of leachate and prevent ground water contamination, the bottom and sides of the area to receive the FGD fill should be lined with suitable low permeability material. Liners delay and control leachate infiltration. Clay liners not only control leachate infiltration but also provide some degree of attenuation.
- Where natural hydrogeologic conditions provide only minimal leachate improvement, it will be necessary to reduce the quantity of leachate allowed to infiltrate the underlying soils by removing leachate intercepted by the liner material.

  To facilitate leachate removal, the liner should be sloped and covered with a layer of highly permeable material. The design of this layer should be in accordance with the criteria for filter design, previously presented during the discussion of The Embankment Foundation Design for POND DESIGN.
- Where the natural hydrogeologic environment is incapable of providing leachate improvement and the underlying ground water is particularly valuable, it will be necessary to prevent leachate from entering the natural soils. This may be accomplished by incorporating into the landfill design multiple liners and constant drainage systems to collect the leachate. The installation of a slightly permeable liner provided with a granular cover for leachate removal overlying a less permeable liner also designed for continuous removal of leachate should prevent the escape of leachate from the lowest liner.

Liners

Impervious liners may be required at pond and landfill disposal sites to stop or delay the flow of leachate and thereby prevent or minimize contamination of the underlying ground water. Liners chosen to control leachate, however, must be compatible with the FGD wastes in order to be effective. Although the effectiveness of available linings in contact with FGD waste is as yet unknown, the Waterways Experiment Station, U.S. Army Engineers and EPRI under RP 1457 are currently investigating the compatibility of several liner materials with this waste. (8-53)

Generally, three types of liners are considered for disposal facilities: admix liners, clay liners, and synthetic membrane liners (see Section 7 - LEACHATE). These liner types may be installed at disposal facilities provided that, through laboratory testing, the liner is determined to be impermeable and compatible with

FGD waste. A permeability equal to or less than 0.1 foot per year (10^{-7} cm/sec) is recommended where it is necessary to significantly restrict the flow rate of leachate from the landfill. The minimum thickness for any type of liner should be based on the degree of quality control and construction practice necessary to provide the required protection.

Admix Liners. Admix liners are prepared by mixing chemicals and/or clay minerals with soil. A laboratory testing program should be conducted by either the manufacturer or other qualified testing laboratory to determine the quantity of admix to be incorporated into the soil. Permeability should be the prime concern. Admix liners are generally installed by covering the area to receive the lining with the chosen amount of additive, mixing it with the required thickness of underlying soil (depth necessary to achieve the required liner thickness) and compacting. A protective earth covering of 12-inch minimum thickness should then be provided. Where removal of leachate collected on the liner is necessary, this covering should consist of free draining granular material as discussed previously.

Prior to placement of the liner, the area to be treated should be smooth, graded to promote proper leachate drainage and cleared of all vegetation and debris. Also, prior to compaction, the soil moisture level should be near optimum in order to achieve the required density.

Clay Liners. Clay liners are installed by placing and compacting the clay on a smooth surface free of vegetation and debris in not more than 6-inch layers until the required liner thickness is achieved. The thickness of the blanket will depend on the properties of the clay (see Section 7 - LEACHATE) in addition to the hydraulic head expected on the liner. Clay blankets require protection from cracking that results from drying or freezing and thawing. An earth cover, 12 to 18 inches thick, placed over the blanket may be used for this purpose. Where required, this blanket should consist of free draining granular material.

Synthetic Membrane Liners. Another method of leachate control consists of lining the disposal area with an impermeable compatible, synthetic membrane. Thin membrane liners should only be placed on surfaces that have been properly graded and cleared of all vegetation, roots, sharp stones or other objects that would tend to puncture the membrane. If the material over which the lining is to be placed is stony or of very coarse texture, it should be covered with a layer of fine material (fine sand) before the lining is installed. Membranes should be placed loose and

enough slack provided to prevent differential soil settlement from rupturing the membrane. Differential soil movement may be limited by compacting the soil prior to placement of the liner. All seams and any punctures or holes in the membrane must be sealed in accordance with the manufacturer's specifications prior to covering the liner with earth, to ensure proper performance of the membrane. All membrane liners should be provided with free draining granular cover to protect the liner from mechanical damage and provide a drainage blanket for leachate collection.

Summary. Liners can provide leachate control if necessitated by regulatory requirements. It is recommended that competitive liners be evaluated in terms of compatibility, regulatory authority acceptability, availability and cost. Most suppliers and manufacturers provide free or low cost technical services to assist in special design details and installation procedures for their particular product. Judicious use of this information can often be very beneficial in the final selection of a liner for any specific site.

Access Roads

If the sludge is to be transported to the landfill by truck, an all-weather access road must be provided to the site. This road should be designed to accommodate the anticipated volume of truck traffic. The road should normally be wide enough for two lanes of traffic and strong enough to carry the trucks. A typical landfill access road for on-highway trucks is shown in Figure 8-31.

The pavement configuration will vary depending on local conditions and use. The access road is typically constructed with some type of bituminous covering because its location will not be changed for a long time. Usually, a soil surface, gravel, crushed aggregate, or bottom ash road will be appropriate for haul roads on the site. Sometimes the requirements for dust control will require haul road surface treatment with lime, portland cement, or asphalt as binders.

The roadway width, curve dimensions, site distances, and other physical features of haul roads are primarily a function of the physical dimensions and probable speed of the trucks. Table 8-13 presents criteria for radius of curvature and superelevation for various speeds and grades.

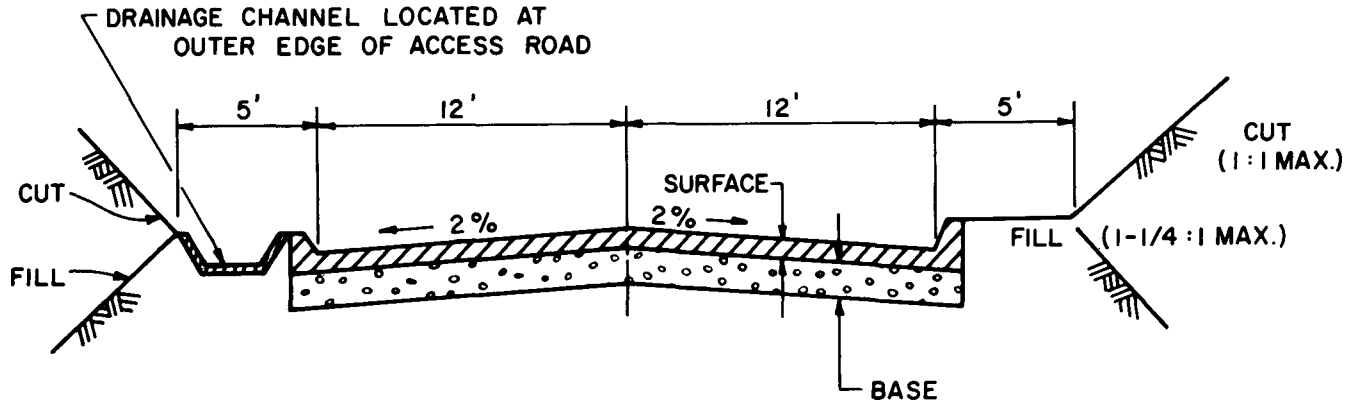


Figure 8-31. Typical Access Road.

Source: Sanitary Landfill, American Society of Civil Engineers, New York, NY, ASCE - Manuals and Reports on Engineering Practice - No. 39, 1976.

Table 8-13

SUGGESTED HAUL ROAD DESIGN CRITERIA

OPERATING DESIGN SPEED, MPH	10	10-20	20-30	30-40	40-50
Maximum sustained grade	9%	8%	8%	7%	6%
Minimum radius of curvature, ft	50	150	300	600	1000
Superelevation, ft/ft of width	0.04	0.05	0.06	0.06	0.05

Source: Pflieder, E. P., ed. Surface Mining, p. 678, AIME, New York, 1968.

Entry points to the site from a public road should be carefully designed to reflect traffic volumes and safety requirements. These considerations should be cleared with the local highway authority. The access point should be designed to: (8-49)

- Minimize traffic interference on the public road
- Minimize turn around time
- Assist in screening the site from the public
- Present an attractive point of entry

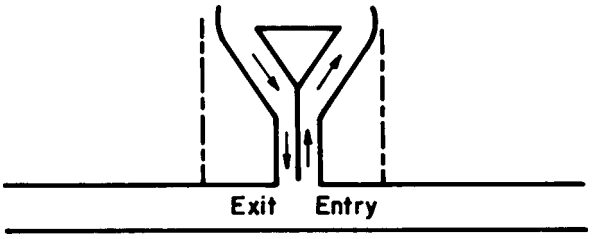
Ideally, separate entrance and exit roads should be utilized to minimize traffic congestion and increase safety. If the access easement is wide enough, the roads can be offset 20° to 50° to improve traffic flow. If the easement is narrow, it is usually feasible to plan a wide access road with a central island. Figure 8-32 shows some suggested arrangements.

Fencing

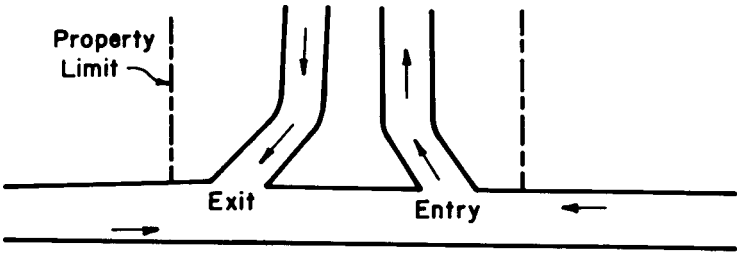
Fencing should be provided to control and limit access to the landfill site. Permanent woven or chain link fencing is commonly used for these purposes. A gate should be provided at the site entrance and should be closed and locked when the site is unattended. This is required by some regulatory agencies.

Buildings

Equipment used at the landfill should be provided with a shelter. In northern states, the facility should provide protection against freezing temperatures. This is particularly true if the landfill is remote from the power station. A single building or shed may be provided for both equipment maintenance and storage. If



(a) Single entry/exit road.



(b) Separate entry and exit roads.

Figure 8-32. Alternative Site Entry Configurations

Source: Noble, G., Sanitary Landfill Design Handbook, Technomic Publishing Company, Inc., Westport, CT, 1976.

the landfill is adjacent to the power station, a central facility for all major earth-moving equipment may be utilized. Even if this is the case, it may be advantageous to have an enclosed area on-site where routine maintenance can be conducted. The size of the building utilized and the equipment in the building will depend upon how much maintenance is anticipated to be conducted there.

Appropriate sanitary facilities should be provided for the landfill operators. Portable chemical toilets can be utilized for this purpose. At larger sites, workers should be provided with shower, locker, and lunchroom facilities. The size of the facility will depend upon the number of people employed and regulatory requirements. Often, mobile trailers can be adapted for employee facilities.

Utilities

The landfill should preferably be provided with power, water, and telephone or radio. Power is used for operating on-site equipment and lighting. Water is needed for drinking and sanitary purposes, for machine maintenance, and for dust control. A telephone or radio is necessary for communications, particularly in the event of a fire or accident at the fill. Fire extinguishers should be provided in accordance with local safety codes and OSHA regulations.

Other Facilities

A knowledge of the amount of sludge placed in the fill is important to control the operation and monitor the progress of fill and may be required by regulations. Provision should, therefore, be made to monitor and record the number of loads placed in the fill. It is not ordinarily necessary to weigh every vehicle loaded with sludge. Rather, periodic weight surveys will usually suffice to monitor sludge volume and density. Scales already available at the power station, such as those used for weighing coal vehicles, are often suitable. If these are not available, portable scales can be used periodically. The scales should be large enough to weigh the largest transport vehicle and simultaneously weigh all axles.

LANDFILL OPERATION

General

It is good practice to develop a general operating plan for the landfill operation. This plan should include explicit, written details regarding:

- Operating instructions
- Hours of operation
- Weighing procedures
- Traffic routing
- Periodic maintenance schedules
- Contingency plans
- Safety procedures
- Records required

It is especially important that the operational sequence and methodology be adequately described. While these items are outlined in the maps and drawings constituting design of the landfill, they are often too complicated or too detailed to be of value to the site manager or equipment operator. It is generally recommended that simplified concept sketches be prepared for the equipment operators as part of the operational plan. By this means, the operator can visualize the overall concept and work towards it.

Personnel

The day-to-day success of the landfill operation depends on the person who manages the site and the equipment operators. A well-trained and motivated supervisor is necessary to conduct an adequate operation. The supervisor must be able to interpret the operating instructions and convey these clearly to the equipment operators. He is also responsible in large measure for the training and motivation of the other workers.

The operation of the landfill is repetitive and can, therefore, become frustrating at times. This should be recognized and provided for in management-employee relations, task assignment and training.

The number of people required at a site will depend on the size of the operation, the hours of operation, the type and size of equipment, and similar parameters. In addition to the site manager and equipment operators, stand-by personnel may be necessary as gate attendants, equipment mechanics, and laborers.

Equipment

The type and reliability of equipment used in the filling operation is as important as the personnel. In selecting the proper equipment, consideration should be given to the following points: (8-48)

- Quantity and characteristics of the sludge being placed
- Distance sludge must be moved
- Site cleaning requirements
- Auxiliary tasks such as maintaining roads and drainage
- Maintenance needs
- Stand-by or equipment backup needs
- Lower equipment reliability with age
- Variation in sludge quantities
- Variation in weather conditions
- Availability of parts and maintenance
- Capital and operating costs
- Operator comfort and safety

Equipment size, numbers, and types will vary with the factors mentioned above and back-up or stand-by equipment must be available to assist if necessary.

The reliability of the equipment depends on the frequency and quality of maintenance and care in the use of the equipment. A specific plan for routine maintenance should be prepared and a dated record of maintenance performed should be maintained.

In most situations, two types of equipment will be necessary: spreading equipment and compacting equipment. The spreading equipment takes the tailgated sludge and spreads it into a thin layer. The compacting equipment firmly tamps down the sludge.

Spreading Equipment

A variety of equipment is available for spreading: dozers, loaders, scrapers, and graders. Of these, the tractor (crawler) dozer is usually preferred. It can efficiently spread sludge in layers and provide a firm grip regardless of weather conditions. Rubber-tired vehicles have also been used but have a tendency to lose traction on the sludge in wet weather. Track vehicles are also popular because of their ability to perform excavating operations during the construction of drainage devices and other similar appurtenances. Rubber tired vehicles are sometimes preferred because of their greater speed and maneuverability. A more detailed comparison of rubber tire versus track-type vehicles is provided in Reference 8-50.

Compaction Equipment

Compaction, which increases both the density and strength of the sludge, is usually required to achieve maximum stability. A certain amount of compaction is achieved by the action of the haulage vehicles and the spreading equipment travelling across the fill. However, if this compaction is inadequate, equipment designed specifically for compaction must be utilized.

Various types of compaction equipment are available; however, either rubber-tired rollers, segmented pad (tamping foot) or vibratory compactors are usually effective. Which types to use is best determined by experience with the sludge on site. Equipment manufacturers can provide current information and test vehicles.

Both vibratory and non-vibratory compactors are manufactured as self-propelled and towed models. Usually, where placement rates exceed 300 to 600 t/hr, a self-propelled model is justified. (8-50)

On-Site Roads

Good maintenance of on-site roads is mandatory. Potholes and clogged ditches should be corrected, and debris should be removed as soon as possible. Mud should be removed from roads for safety and efficient vehicle movement. If mud or sludge will be carried onto public roads from trucks travelling from the landfill, then provision must be made for clearing the wheels or cleaning the road at regular intervals. Good maintenance of access and public roads is necessary for the utility to maintain good relations with the public.

Method of Operation

The general method of operation is the same for all sites. Sludge is brought to the site (by truck, conveyor, rail, or other means), spread into thin layers usually less than two ft thick, and compacted for maximum density and strength. The spreading should be confined to as small an area as possible to maximize equipment utilization and control dust or mud. In order for the equipment to operate effectively, the sludge must be placed in relatively thin, horizontal layers.

The size of the working area will vary with the amount of sludge delivered, but generally square areas are most efficient. In some cases, two working areas will be utilized alternately. Trucks will haul to one work area while the dozer spreads sludge in another area. The dozer will then move to the new piles of sludge while

the trucks bring sludge to the area vacated by the spreader. Ordinarily no soil cover is required at the end of a day's operation. However, if a partially completed section will be left idle for several months, it should be covered with soil and vegetated to reduce erosion and dust.

Inclement Weather

Depending on location, the landfill operator may have to cope with prolonged periods of wet or freezing weather. In cold areas, the equipment must be winterized and care must be taken in cleaning the undercarriages and in parking. Equipment should be moved more slowly over frozen soil or fill to avoid impact damage. A heated storage area for the equipment will also be necessary. Snow cover should be removed and not incorporated into the fill.

Wet weather, especially when prolonged, causes more difficult operating problems. The sludge will tend to reliquify, particularly if it has only been stabilized, and will be difficult to spread and compact. Vehicles will generate mud at the working face and will carry it to the on-site roads and possibly the approach roads. Provisions should be made for wheel cleaning by automatic tire spraying equipment or other similar devices. Road maintenance should be particularly well conducted during these periods. FGD sludges are slippery when wet and can cause hazardous driving conditions if spilled on public roads in wet weather.

Erosion problems may also be severe during inclement weather, and the operator should be vigilant to inspect for erosion frequently and take appropriate steps to check its progress. Erosion control measures suitable to local site conditions can be obtained from the local office of the Soil Conservation Service or the Local Agricultural Extension Service.

Dust

During dry periods or in arid regions, dust will inevitably develop as a problem, particularly in urban or suburban areas. Dust will be generated on the access roads due to occasional spillage and sloughing of material from vehicle bodies and tires during wet periods. Dust will also be developed at the working face of the fill due to equipment activity. Dust from access roads is the more usual source of complaints from neighbors.

Dust control measures must be employed as appropriate. Usually a simple spray truck with a spraybar at the back will suffice for controlling road dust. In some cold, dry areas, calcium chloride crystals will be effective.

For controlling dust on the fill itself, a periodic fine water spray will reduce dust at the working face. Wind erosion of the fill can be reduced by various methods including:

- planting or erecting wind breaks
- using chemical sealants
- providing natural vegetative cover

Safety

Hazards resulting in injuries at a landfill are primarily related to the equipment being operated. Hazards include:

- direct injury from explosion or fire
- falls from vehicles
- accidents associated with operation of the equipment
- accidents associated with attempting to repair equipment with the engine running
- traffic accidents

In some cases, exposure to extremes of heat or cold are a potential hazard.

To prevent injury and the loss of life, utilities should incorporate an accident prevention program at the landfill which complements that at the station proper. An accident prevention program should include safety training, maintenance of safety records, provision of protective clothing and equipment. The current regulations of OSHA should be consulted for specific procedures which may be applicable. The Construction Industry Manufacturers Association can provide manuals of safety for equipment operation. All personnel should be thoroughly trained in safety and first-aid, and a well-stocked first-aid kit should be maintained on-site.

MONITORING

Any sludge disposal area, whether pond or landfill, should be the subject of an on-going monitoring program. There are several reasons for such a program:

- Protect the utility against unfounded accusations, claims and suits

- Provide warning if the site is not being managed properly, or if some man-made or natural malfunction occurs
- Satisfy the requirements of the regulatory agencies
- Determine if the design concepts were correct or indicate where changes are needed or when maintenance is required
- Assure that the environmental acceptability and structural stability of the site are maintained, both while active and after completion

Such a program should preferably be implemented before any construction or placement has started, in order to obtain base values and to record original conditions. It should be continued during operation of the site and be maintained for some period after completion and closure. The length of that period cannot be definitely stated. It will vary with the particular site conditions, especially insofar as stability and erosion of landfills, pond dikes or dams are concerned. The base values, as compared to on-going monitoring results, may provide a good indication of the duration of the period. Added to this will be the existing regulatory requirements, as well as those which may evolve from RCRA.

Monitoring should include:

- Sampling and analysis of water from monitoring wells, runoff and underdrains
- In-place measurement of the density of landfilled sludge
- Pipeline leak detection
- Maintenance of records of readings from surveys of and instrument readings in dikes or dams
- Visual observation of general site conditions

Sampling and Analysis of Water

Surface-Water Bodies. Surface-water bodies on or near disposal sites should be monitored frequently and discharge points for potentially contaminated ground water located. Implementing such a monitoring program will not only provide means for detecting surface water quality degradation, but will also enable preliminary ground water flow patterns to be developed. Since pollution of surface water by leachate may not be detected by visual inspection, water samples should be obtained and analyzed to establish the presence of leachate. In order to indicate the locations from which samples should be taken, the following in-situ characteristics of the surface-water bodies should be determined by preliminary samples:

- Specific conductance
- Temperature
- pH

Although leachate dilution may prevent surface-water monitoring from providing useful information, such monitoring can be an inexpensive means of estimating the environmental impact of FGD waste disposal facilities. Care should be taken, however, to ensure that the surface-water bodies being monitored are not subject to contamination from other sources.

Run-off. Run-off water from landfills should be channelled, as previously specified, so as to prevent surface washing and erosion. As currently required by some agencies, this run-off will be directed to a stilling or settling basin and samples of influent and effluent taken for analysis. If not directed to a single basin, run-off can be sampled at drainage ditches or trenches.

Underdrains. If the pond or landfill is fitted with underdrains, it is recommended that samples be taken of the effluent at the point of discharge.

Groundwater. The purpose of monitoring groundwater is to determine if there has been migration of leachate from a disposal area. Some state agencies currently require such monitoring, and future regulations may make it generally obligatory. At this time, there are few explicit guidelines for the number, location or depths of monitoring points. Most attention to this time has been directed toward groundwater monitoring at municipal waste landfills. There are numerous good reference sources concerning those landfills which can provide guidance to the utility operator of an FGD sludge disposal area. Most of the information which follows has been obtained from two of those sources. (8-51,52)

The first step in establishing a monitoring network is to determine the rate and direction of groundwater flow. Geologic data and aerial photographs obtained during site selection are invaluable for estimating the direction of flow. It will probably be necessary to secure the services of a hydrogeologist to interpret these data and, in conjunction with test borings, establish the flow rate as well as direction.

The rate of groundwater flow is dependent upon the porosity and permeability of the aquifer as well as the hydraulic gradient at the site. Therefore, groundwater rate of flow may be estimated from Darcy's Law.

$$v = \frac{ki}{n}$$

WHERE: k = Permeability
i = Hydraulic Gradient
n = Porosity

The existing hydraulic gradient of the water table at a disposal site may be estimated from observation wells or piezometers. Piezometers resemble screened wells and are normally used for monitoring water pressure in aquifers. A typical arrangement for determining the hydraulic gradient is presented in Figure 8-33. As shown in this figure, at least three wells are needed to determine the magnitude and direction of the hydraulic gradient in an area. After the groundwater level in each well has been determined and piezometric gradients between wells (Figure 8-33) developed, the piezometric surface is established by means of contour lines. A piezometric surface is the surface defined by all the values of piezometric head in the aquifer of interest. The piezometric head is equal to the sum of the pressure head at a point (indicated by the water level in a well) and the elevation of that point above an arbitrary datum.

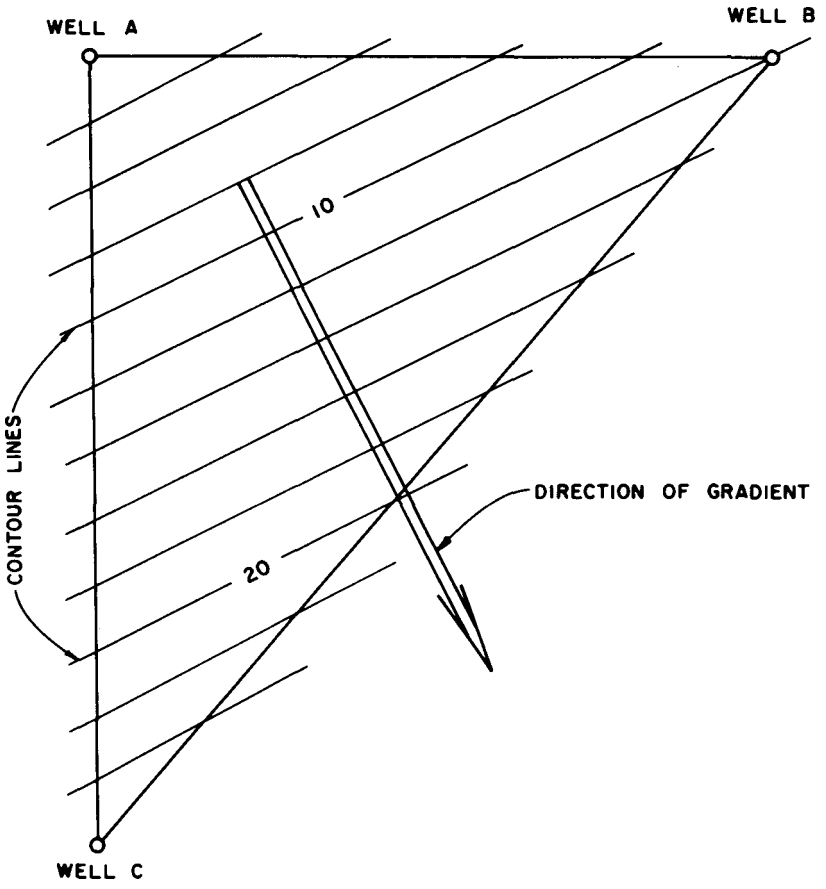
Field measurements of aquifer permeability may be made by conducting pumping tests on wells. Reference 8-6 provides well installation and field pumping test details. To conduct these tests, a well is pumped at a uniform rate, q, while water level readings are obtained in several nearby observation wells. The test is continued until steady conditions are reached. The coefficient of permeability, k, may then be approximated by using the simple well formula: (8-6)

$$k = \frac{2.3q \log_{10} (r_2/r_1)}{\pi (h_2^2 - h_1^2)}$$

Where: r_1, r_2, h_1, h_2 = dimensions illustrated in Figure 8-34.

A typical arrangement for determining soil permeability by a well pumping test is shown in Figure 8-34. Pumping tests can also be used for sloping water tables by drawing the bottom boundary of the aquifer parallel to the original water table. The computation may then be carried out as in the case of a level water table.

The well formula presented above is based on several assumptions; therefore, the realiability of well pumping tests will depend on how accurately those assumptions are fulfilled. The assumptions are:



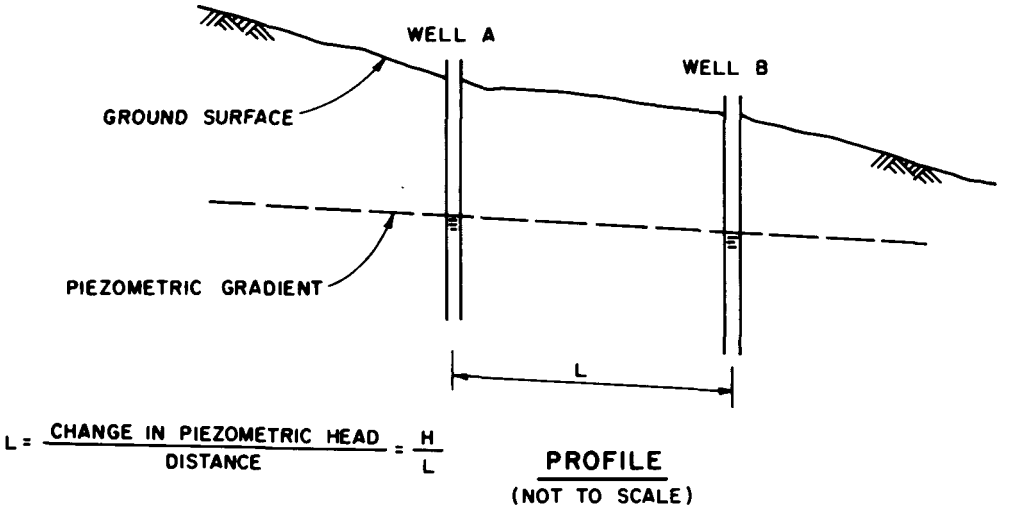
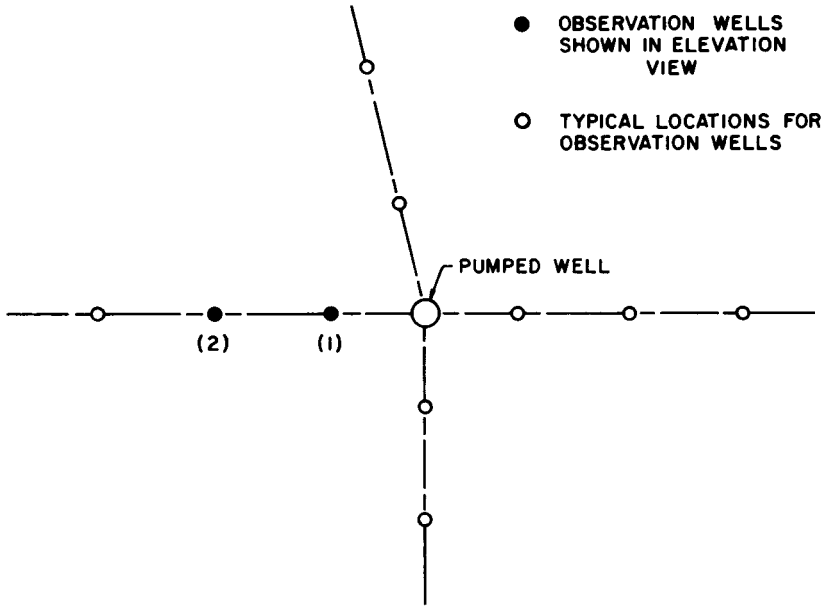
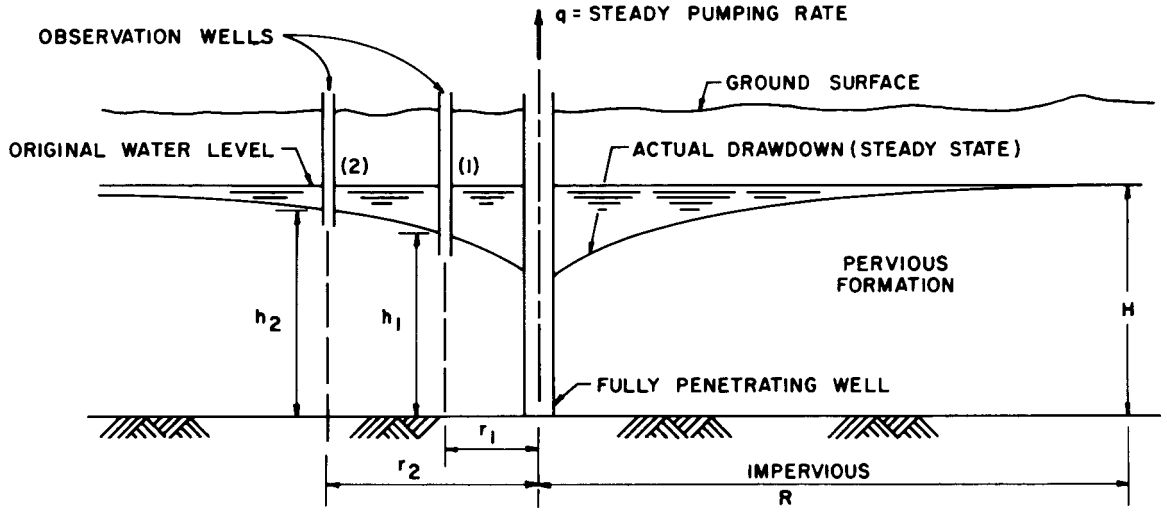


Figure 8-33. Typical Plan for Determining Magnitude and Direction of the Hydraulic Gradient



PLAN VIEW



ELEVATION VIEW

Figure 8-34. Typical Plan for Determining Aquifer Permeability by Well Pumping

After: Harry R. Cedergren, Seepage, Drainage, and Flow Nets, 2nd Edition, John Wiley & Sons, Inc., New York, NY, 1977.

- The aquifer is not under artesian conditions. That is, the upper surface of the aquifer is represented by a free water table.
- The pumping well completely penetrates the aquifer and the drawdown in the well is small compared with the thickness of the aquifer.
- A steady-state flow condition exists.
- The water-bearing formation is homogeneous, isotropic, and extends an infinite distance in all directions.
- The Dupuit assumption that the hydraulic gradient at any point is a constant from the top to the bottom of the aquifer and is equal to the slope of the water surface is valid. (This assumption is considered accurate at moderate distances from wells.)

Complete penetration of an aquifer by a well is rarely encountered in the field; however, the well formula gives reasonably good results for partial penetration if r is greater than 1.5H. (8-54)

Another method of estimating the groundwater rate of flow consists of introducing a tracer into a well and measuring the time for the tracer to reach a downstream well. Seepage velocity can then be calculated by dividing distance, L, by time, t. Presented below are the two most common tracing methods used to determine the velocity of groundwater flow.

- Use of an electrolyte, such as common salt, and galvanometers to detect the time required for the electrolyte to pass a known distance through the soil.
- Insertion of dye into a test hole and observation of the time required to emerge in a test hole located downstream. When dyes are used as tracers, test holes must be placed along flow lines. Since tracer concentration decreases rapidly with distance, the downstream sampling points should be near the point of application. Some dyes are unsuited for use in aquifers containing clay fractions because of base exchange and absorption phenomena.

Although tracer methods give only a rough evaluation of the groundwater velocity, well pumping tests are expensive and should only be made when dependable permeability information is necessary.

Once the rate and direction of groundwater flow at the disposal site has been established, a monitoring well network should be installed to detect and evaluate potential or existing groundwater degradation. A typical monitoring network is shown in Figures 8-35 and 8-36. This well network includes:

- One background monitoring well up-gradient from the disposal site ("A" Well)

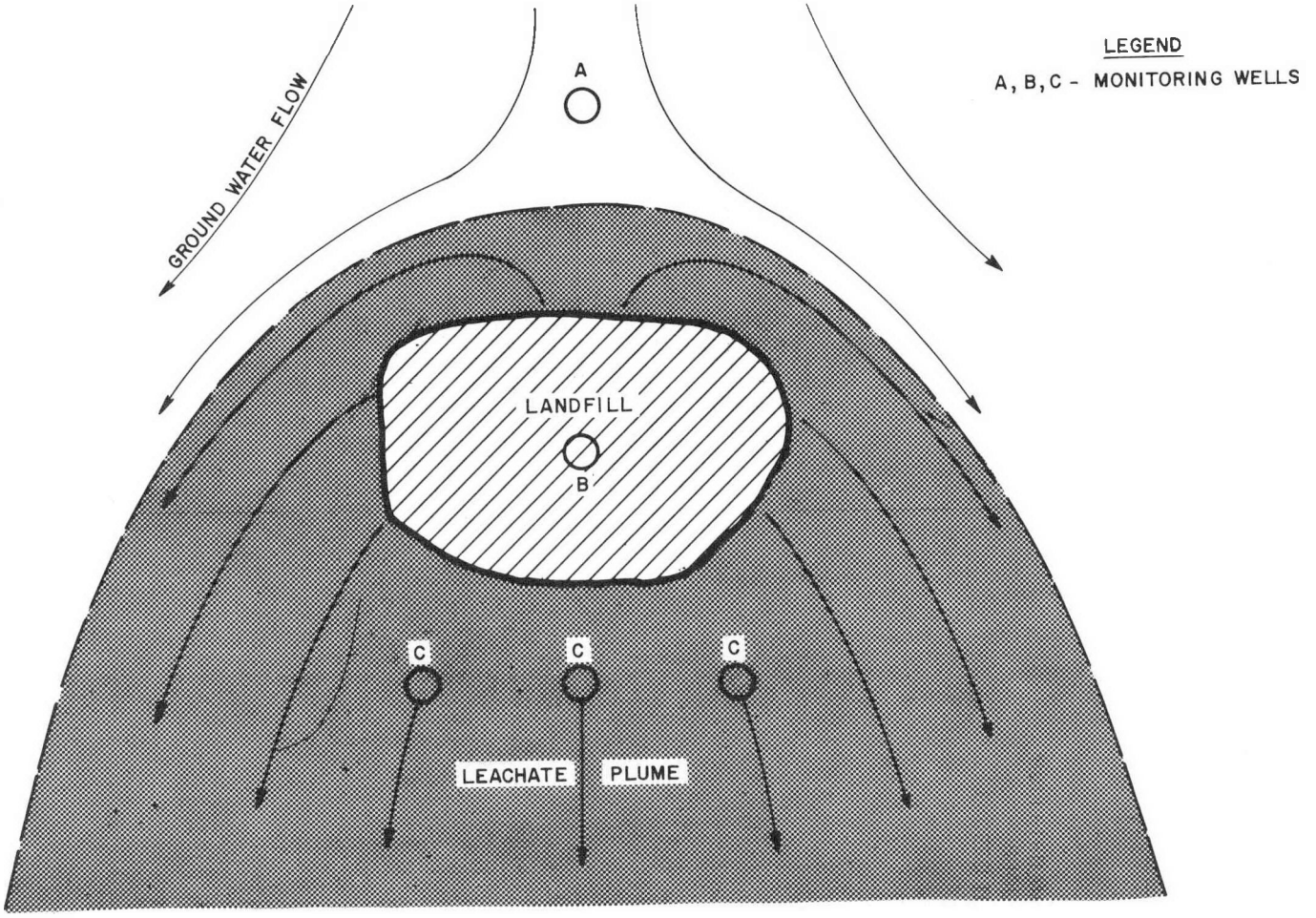


Figure 8-35. Typical Monitoring Network.

Source: Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities, EPA/530/SW-611, August, 1977.

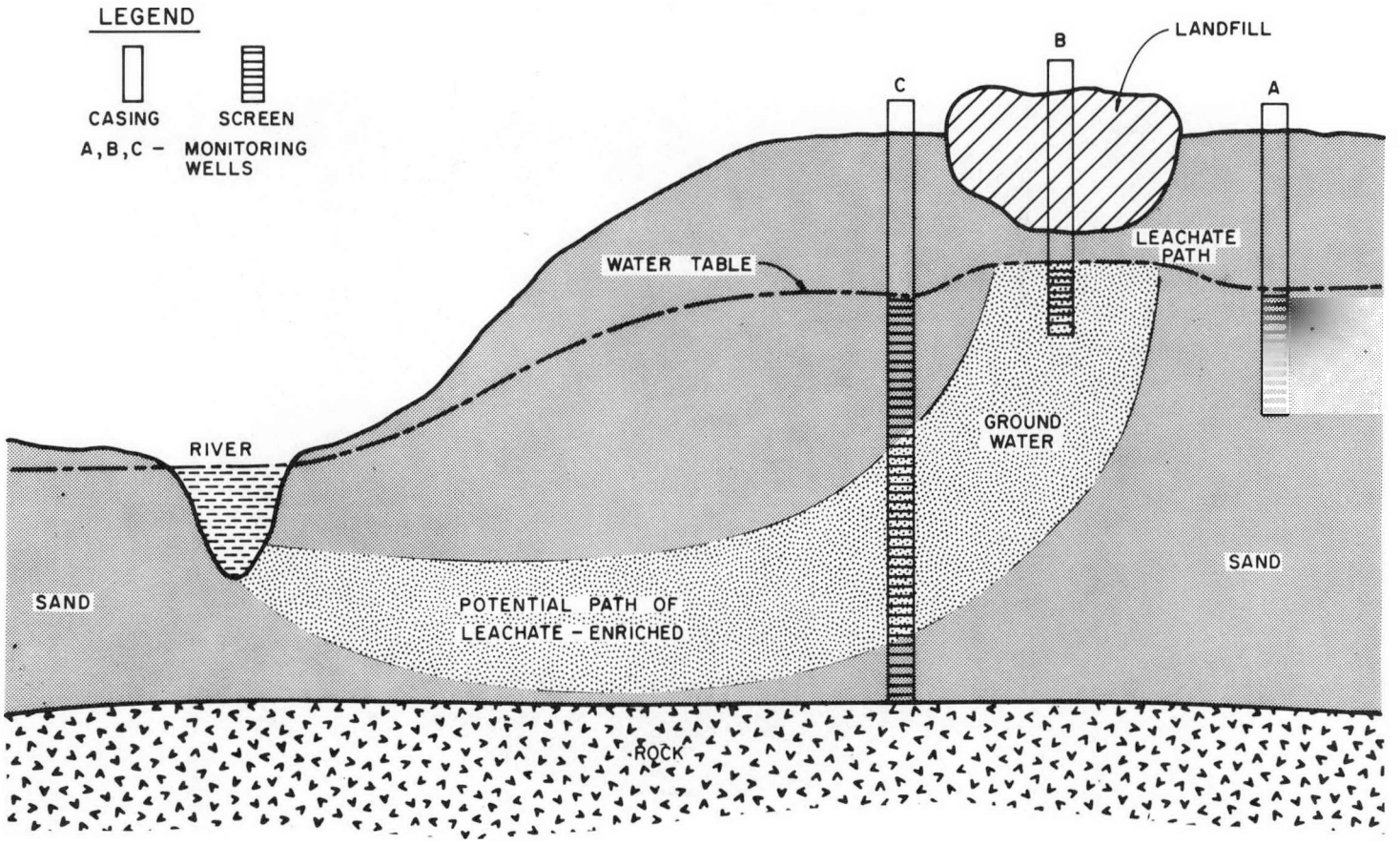


Figure 8-36. Monitoring Network for Aquifers with Intergranular Porosity - Vertical Flow Patterns

Source: Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities, EPA/530/SW-611, August, 1977.

- One well adjacent to or within the disposal area for early warning of groundwater quality degradation ("B" Well)
- At least three down-gradient wells located close to the disposal site to detect the leachate plume as soon as possible ("C" Wells)

Wells indicated as "A" and "C" are also applicable to pond disposal. The number of down-gradient wells should be sufficient to give a representative sampling of the area. In the case of landfills, additional wells may be necessary as the area is enlarged during the life of the site.

Casings for monitoring wells should be of PVC rather than steel to avoid contamination of the sample. A typical well configuration is presented in Figure 8-37. Water samples are generally removed from wells by bailing or pumping.

Leachate migration into groundwater tends to enter as a plume, rather than being dispersed. There is no way of predicting the location of the plume in the aquifer, and single-depth sampling may fail to sample the plume, if present. The monitoring device should, therefore, collect water over the entire saturated thickness of the aquifer. To lessen the possibility of missing the plume, the well should either be screened through the full thickness of the aquifer or the well-cluster technique adopted. Well-clusters are groups of closely spaced, small diameter wells completed at different depths. Although screening wells over the entire thickness of an aquifer simplifies construction, dilution could conceal the presence of leachate. Another problem with this type of construction is that the well could contribute to the vertical spread of contaminant.

These problems can, however, be overcome by drilling clusters of wells to various depths. Well clusters are the most common and successful technique for delineating groundwater contamination. From these wells, water samples that are representative of the different horizons within the aquifer can be collected. One disadvantage with well clusters, however, is that unsampled intervals exist through which leachate may pass undetected.

As indicated in Reference 8-55, monitoring wells were installed in the Conesville FGD Disposal Facility of the Columbus and Southern Ohio Electric Company to detect potential leachate migration into the groundwater. A total of thirty monitoring wells were installed. Four wells were installed primarily as observation wells for drawdown measurement during pump tests. The remaining twenty-six wells were designed for determining water quality and aquifer potential; however, two were used ini-

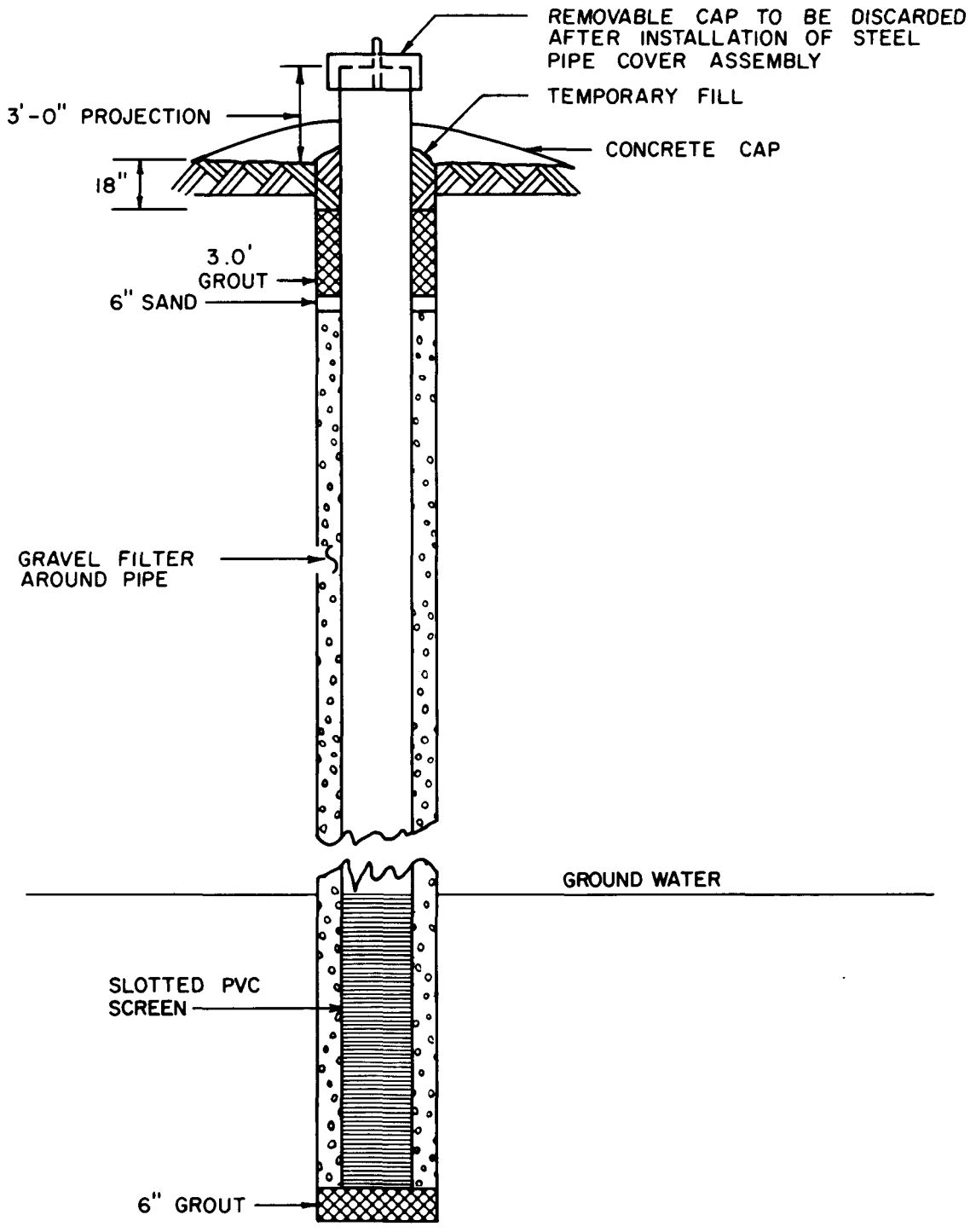


Figure 8-37. Example of Monitoring Well.

tially during pump tests for drawdown measurements. Four of the wells installed for monitoring will be used as background water quality wells. The nine remaining wells will be used for leachate detection; two of which were located within the disposal area.

Each well was constructed by placing polyvinyl chloride (PVC) pipe having a plugged bottom and slotted section into a pre-drilled, cased hole. The space between the casing and the PVC pipe, around the slotted section, was backfilled with pea gravel and a bentonite seal provided above the backfill. After the casing was withdrawn, the annular space above the bentonite was filled with native sand and gravel auger cuttings with the exception of the top few feet, which was sealed with bentonite.

The wells were generally located in clusters of two. It appeared that the probable path of the leachate plume would remain in the shallow flow system within the aquifer; therefore, each well cluster consisted of a shallow well just intercepting the groundwater table and a well slotted ten feet deeper. One deeper well was screened only near the base of the aquifer to detect any deeper leachate plume.

The Bruce Mansfield FGD waste disposal area is located southwest of Georgetown, Pennsylvania on the Pennsylvania/West Virginia border, and is known as the Little Blue Run Reservoir. This impoundment was created by a 400-foot high impoundment dam. To detect potential leachate migration into the groundwater, ten monitoring wells were installed around the perimeter of the reservoir prior to construction of the dam. Each well is 4 inches in diameter and was installed in a manner similar to the wells installed at the Conesville facility.

Two wells are situated beyond the downstream toe of the dam. One well is approximately 15 feet deep and is intended to monitor groundwater movement in the soil overburden. The other well extends 100 feet below the ground surface into bedrock to monitor groundwater movement through the rock. Eight wells surround the remainder of the impoundment. These wells extend to various elevations and range from 100 to 300 feet deep. Each of these wells is used for monitoring groundwater movement in a special strata.

As previously stated, piezometers are pressure measuring devices used to monitor water pressure in earth dams or aquifers. Well-type piezometers that are normally used to monitor water pressure in aquifers may also be installed for shallow groundwater quality monitoring. These piezometers are identical to wells screened over

a single interval except that the piezometer is provided with an impermeable annular seal immediately above the screen. This seal not only isolates the underlying well screen for the measurement of vertical head differences, it also minimizes the movement of leachate in the annular material. Any well constructed without this seal cannot be considered a piezometer.

Typical engineering piezometers that are used to monitor earth dams have been modified to serve as in-situ water sampling devices and greatly resemble lysimeters in construction (see Figure 8-38). Lysimeters are devices generally used to obtain samples of in-situ soil moisture within the zone of aeration (unsaturated zone above the water table). Either piezometers or lysimeters can be installed in clusters at different depths to explore vertical leachate distribution. As shown, the water samples are removed by applying vacuum/pressure to the sample chamber. High purity nitrogen has been used for pressurizing in some cases when it was desired to protect trace concentrations in the water samples from contamination.

Leachate Monitoring in Zone of Aeration. A leachate monitoring system may be installed within the zone of aeration underlying disposal facilities to check the effectiveness of the engineering design. Governmental regulations may require such a monitoring system. By monitoring the zone of aeration, the downward percolation of leachate can be traced before it reaches the water table and data can be provided on the soil attenuation capabilities.

Pressure-vacuum lysimeters may be used to monitor the unsaturated zone and obtain samples of in-situ soil moisture. This device consists of a porous ceramic cup, a small-diameter sample accumulation chamber, and two sampling tubes leading to the surface. After installing the lysimeter at the desired depth, a vacuum is applied to the cup. As a result, soil moisture moves into the sampler and accumulates. When the vacuum is released, pressure is applied, forcing the accumulated water to the surface through the sampling tube. Lysimeters should be installed prior to disposal of the waste in order to avoid drilling through the pond or landfill. Impermeable seals should be installed above the lysimeters and at the surface to prevent the downward migration of leachate through the material backfilled during lysimeter installation.

Frequency of Samples. As a minimum, it is recommended that samples be taken on a quarterly basis. However, regulatory requirements or site conditions may dictate more frequent sampling.

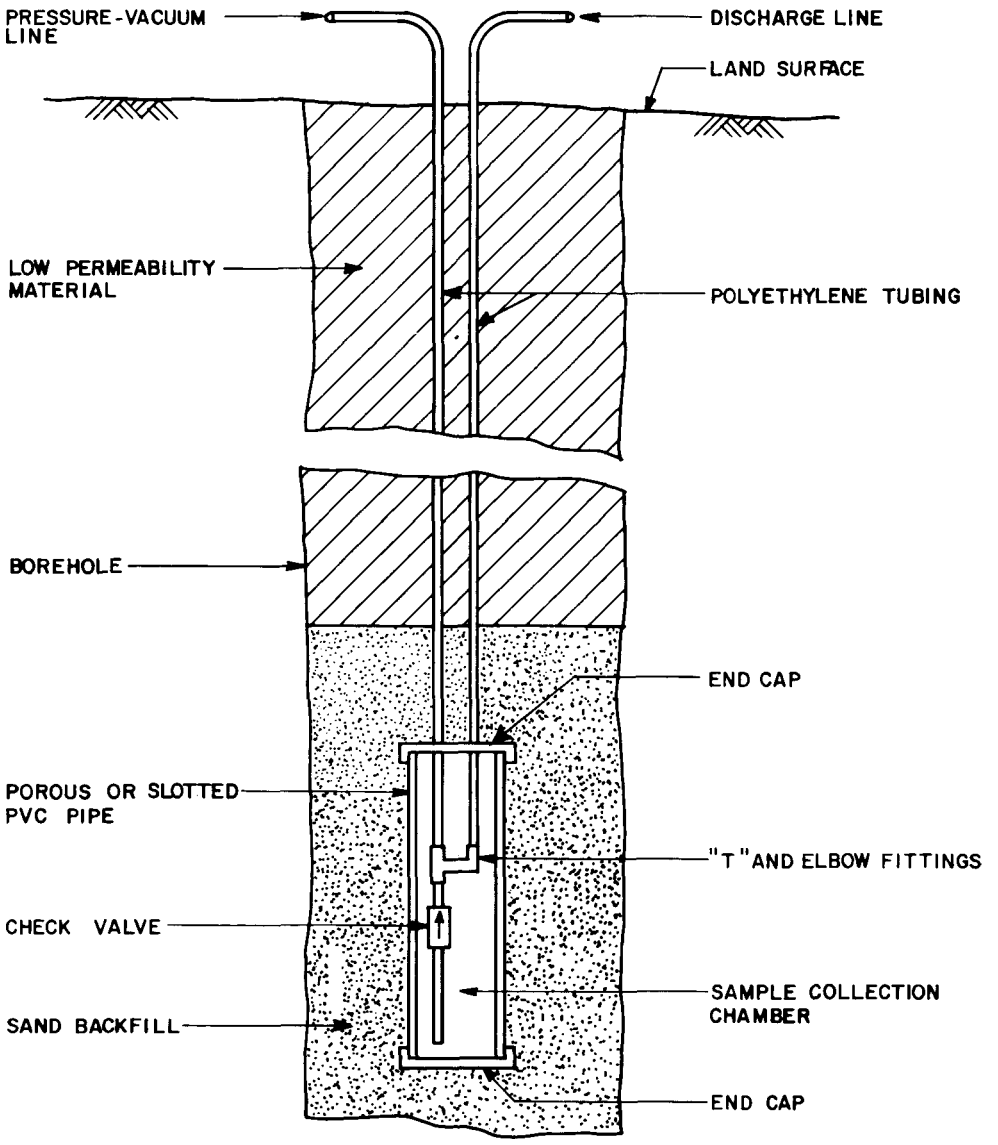


Figure 8-38. Piezometer Modified for Collection of Water Samples.

Source: Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities, EPA/530/SW-611, August, 1977.

Parameters to be Measured. In practically all discussions of leachate or run-off quality, comparison to drinking water standards is made. Table 8-14 presents a possible list of parameters for analysis. Regulatory agencies may require additional and/or other analyses.

Table 8-14

SUGGESTED ANALYTICAL PARAMETERS FOR WATER SAMPLES

pH	Arsenic
Specific Conductance	Barium
Alkalinity	Boron
Acidity	Cadmium
Iron, total	Chromium, total
Calcium	Lead
Magnesium	Mercury
Sulfate	Selenium
Sulfite	Silver
Chemical Oxygen Demand	Total Dissolved Solids

Analytical Methods. In order to gain credence for the analytical results, it is recommended that EPA-endorsed procedures be used. (8-44) These methods are discussed along with precautions for sample preservation in Reference 8-51.

Physical Measurements

Density Determination. Periodic determination of the density of landfilled material is advisable to assure that the proper degree of compaction and, in turn, optimum strength is obtained. Typical dry bulk densities are shown in Table 8-15.

Table 8-15

TYPICAL DRY BULK DENSITY VALUES OF LANDFILLED FGD WASTES

MATERIAL	DRY BULK DENSITY lb/ft^3
Compacted Flyash	70 to 90
Calcilox-Stabilized Sludge	33 to 44
Poz-O-Tec	70 to 90

Method of Determination. Procedures of the American Society for Testing and Materials are recommended.

The laboratory tests are:

ASTM D-698 Moisture-Desity Relations of Soils Using 5.5 lb Rammer and 12-in. Drop (Standard Proctor).

ASTM D-1557 Moisture-Density Relations of Soils Using 10 lb. Rammer and 18-in. Drop (Modified Proctor).

The field tests are:

ASTM D-1556 Density of Soil in Place by the Sand-Cone Method.

ASTM D-2167 Density of Soil in Place by the Rubber-Balloon Method.

Pipeline Leak Detection

Prompt discovery of pipeline leaks is essential in order to:

- Avoid environmental impacts resulting from water contamination, fugitive dust from dried spills and damage to the pipeline right-of-way
- Assure maximum delivery of sludge to the processing or disposal area
- Avoid erosion damage to pipeline components

Two suggested means of detection are:

Instrumental. Pipeline pump pressure will normally be logged or recorded. Operators should be alerted to the significance of a sudden drop in pressure and instructed to check for leaks immediately. Pressure sensors, depending on the type and provision for flushing, can be rendered inoperative by sludge deposits. Frequent routine maintenance and cleaning should be scheduled.

Visual. Frequent (once per week, at least) walking inspections are recommended for revealing leaks, especially those which are too small to register a significant change in pressure. It is suggested that such "walk-bys" be logged to assure adherence to schedule. Operators should also observe for vandalism which might develop into sizable leaks in off-site, above-ground pipelines.

Dam and Dike Instrumentation

Dam and dike integrity are being scrutinized closely by regulatory agencies. Instrumentation is being required for large impoundments, such as that at the Mansfield Plant. (8-43) Data from the Mansfield instruments are forwarded to the Pennsylvania Department of Environmental Resources, Division of Dam Safety. Whether or not re-

quired by regulations, the utility might find instrumentation of this type to be a good investment in preventing dam or dike failures. A thorough discussion of such instrumentation has been presented by MESA. (8-45)

Visual Observation of Site

Whether landfill or pond, the site should be inspected routinely (once per week is suggested) for general condition. Integrity of dikes, dams and slopes is especially important. Condition of overflows and diversion ditches/pipes/troughs should also be noted, as well as any indication of erosion or fugitive dust. It is suggested that a check list could prove an advantage, especially if the area is subject to periodic regulatory inspection. A file of such completed check lists would also aid in supervising site operation. A suggested form for a check list is given in Table 8-16 for ponds and in Table 8-17 for landfills.

FINAL LAND USE

One aspect of FGD waste disposal that should be factored into the early plans for sludge processing and into siting studies is the final disposition or use of the disposal area. This can be an important factor from the viewpoint of:

- Financial benefit from sale of the site
- Public relation or employee relation value
- Obtaining regulatory and/or public acceptance of the site
- Possible future use of disposed material as a natural resource (gypsum or sulfur recovery)
- Long-term responsibility for monitoring and maintenance
- Benefit from utility use of the site

The final land use will be governed by two main factors: type of sludge disposal and location of site.

Types of Sludge Disposal

The types of sludge disposal can be categorized as:

- Dry disposal with stabilization/fixation
- Wet disposal with fixation
- Dry disposal without stabilization/fixation
- Wet disposal without fixation

Table 8-16

POND INSPECTION CHECK LIST

DATE: _____ BY: _____ APPROVED: _____

Item		OK	Attention Required	See Remarks
No.	Identification			
1.	Inlet			
2.	Outlet Structure			
3.	Discharge Water			
4.	Diversion Ditches			
5.	Dams, Dikes - exterior			
6.	Dams, Dikes - interior			
7.	Equipment			
8.	Instrumentation			
9.	Freeboard			
10.	Underdrains			
11.	Fences, Gates			

NOTE: Where a need for attention is indicated, an explanation must be given under following:

Item No.	Remarks

Table 8-17

LANDFILL INSPECTION CHECK LIST

DATE: _____ BY: _____ APPROVED: _____

Item No.	Identification	OK	Attention Required	See Remarks
1.	Access Roads			
2.	Dust Problem			
3.	Active Area			
4.	Slopes			
5.	Equipment			
6.	Diversion Ditches			
7.	Completed Area			
8.	Underdrains			
9.	Foreign Material			
10.	Undergrowth			
11.	Fences, Gates			

NOTE: Where a need for attention is indicated, an explanation must be given under following:

Item No.	Remarks

Of the four types, only the first two have definite possibilities for end use of the site. The other two types may yield a stable fill only if the waste product is gypsum, either with or without flyash inclusion from the scrubbing process.

Location of Sites

Adjacent to or on the Plant Site. This site location may have low potential for end use, depending on the proximity to active plant areas. Regardless of the end use, few utilities would be willing to permit public access because of the potential for accidents or vandalism. It is possible that the utility itself could put the area to use when access could be limited to its own employees, with the site developed for one of the uses listed later.

Off-site. A site of this nature would have much greater potential for use, especially if title could be transferred to another entity. This is an advantage of off-site areas that should receive serious consideration during siting studies.

Site Closure

Landfills. Landfills should be graded and contoured throughout active life with a view to end-use. In addition, as areas are completed, they will preferably have been covered with acceptable soil and vegetated. With such a procedure, wind and water erosion will be minimized, and the problems associated with runoff and infiltration will be reduced.

The amount of cover to be used may be dictated by a regulatory agency. In some cases, the depth has been set by the requirements for sanitary landfills; these regulations have been used in the lack of specific rules for sludge and/or ash fills. Future regulations will hopefully be made specific for coal ash and scrubber sludges, with full consideration being given to the properties which differ widely from those of sanitary and municipal wastes. Existing regulations often specify 24 inches of top cover, whereas six inches is generally sufficient for vegetation of most FGD waste fills. This cover will preferably have been stockpiled from preceding site preparation, so the expense of offsite procurement and of hauling can be avoided.

The particular type of plant growth for vegetation may be specified by a regulatory agency. If not, consultation with local agronomists, perhaps with establishment of a number of trial plots, may be advisable. Hydroseeding has proved to be an excellent way to obtain good results in vegetation, especially on slopes.

Pending a decision on final reuse of the disposal site, it will be necessary to provide facilities for public exclusion from off-site areas. Indiscriminate use of recreational vehicles and dumping of various household and industrial wastes could imperil plantings and the structural stability of landfills. In addition, if still under utility ownership, suits for liability for injuries and for ownership of a public nuisance could be lodged. It is assumed that on-site disposal areas would be adequately protected from trespassing.

Ponds. An impoundment of fixed sludge can be drained and the area prepared as described above, or it can be left covered with water for use as a pond or lake. Both of these possibilities will be considered by the Pennsylvania Power Company for the end use of the Mansfield Plant impoundment.

An impoundment or pond of unfixed sludge may lend itself to closure either as a landfill, after draining or evaporation, or as a permanent pond. Whichever course is followed, it will be necessary to assure that there is sufficient stability to provide for the safety of humans and wildlife. If this cannot be assured, facilities for permanent exclusion and posting of warning signs will be necessary. Precautions concerning water quality, as discussed below, will also be necessary.

Monitoring of water quality in such ponds should be initiated and continued for a period of long enough duration to establish a trend. There should be assurance that neither the public nor wildlife could be endangered by dissolved solids from the cured sludge. If such assurance cannot be determined, closure as a landfill might be a more desirable course to follow.

Possible End-Uses

Recreation. This is probably the end-use which first comes to mind when considering the closure of sludge disposal areas. Reasons for this include:

- The wide diversity of use that is possible
- The good public relations that can be advanced by such use
- The possibility for transfering title with or without financial return

Types of recreational use for landfills or drained impoundment areas are almost limitless. For an undrained impoundment of stabilized sludge, the use of the completed area as a recreational pond may be the best possible use. Fishing, hunting,

swimming and boating can all prove to be good public relation uses, if the water quality is satisfactory.

Restrictions to dry land use are minimal. Any recreational structures that might be built should be of such size as to exert loadings well within the permissible limits of either fixed or flyash-stabilized sludge. Some uses that might be considered are ballfields, tennis courts, skeet shooting, model plane ports, swimming pools, picnic grounds and small game lands. These, as well as other possible uses, are listed in Table 8-18. Consideration should be given to transferring ownership for the property. There may be some financial advantages to this--both monetary and in relief from maintenance responsibility and cost. If this is undesirable, care must be taken to preserve the integrity of the land cover and to continue the monitoring that state regulations or RCRA may require.

Building Sites. Fixed sludge disposal areas should provide good sites for building activities--both residential and light industrial. The financial return from such uses could be substantial. Participation in regional planning activities could well pay off for the utility, not only in final land use, but in obtaining initial public acceptance of the site.

Utility Company Utilization. Depending on the activities and needs of the particular utility, utilization of the closed site might prove to be an answer for additional land for company use. Either fixed or stabilized landfill is suitable, depending on the particular use. Fixed sludge will usually be necessary for higher loadings. Material storage and store rooms, lay-down areas, district garages, and satellite headquarters are all possible end-uses.

Long-Term Monitoring

As with all other FGD sludge disposal practices, there is no indication at present as to the requirements of RCRA or related state regulations as affecting monitoring after closure. It would be advisable to maintain knowledge of developing regulations in this area. Some discussion to this time has involved completely unreasonable durations of time for continuing monitoring activities. Such requirements have primarily concerned chemical and radioactive disposal sites. However, as with other regulations, these requirements could be expanded to cover the disposal of more innocuous materials.

Table 8-18

SOME RECREATIONAL FEATURES SUITABLE FOR LANDFILL AREAS

ACTIVITY	ADVANTAGES	DISADVANTAGES
Play areas	Popular. Small area requirements	Flat areas. Somewhat difficult to drain
Court games	Popular	Large flat areas required--differential settlement may be a problem
Putting green	Popular	See above
Golf course (18/9 or miniature)	Popular. Good natural drainage characteristics	Settlement creates maintenance problems
Nature/hiking trails	Popular	Some tree cover required--care required in tree selection
Golf driving range	Very popular. With careful contouring could be ideal for drainage control. No heavy traffic to impair grass growth	Expensive. A great deal of pre-planning may be necessary
Archery/Rifle range	Fairly popular	Flat area requirements pose drainage problems
Model Airplane flying	Shortage of areas set aside for this use	Inclined to be noisy--some flat areas required
Garden plots	Growing in populatiry	Slope requirement presents a problem.
GoKart track	Popular	Flat--Noisy--Not conducive to maintaining grass cover
Motorcycle scramble	Very popular. Good natural drainage	Noisy--Not conducive to maintaining natural cover
Open air zoo	Very popular. With careful design good natural drainage could be achieved	Extensive paved areas could be a problem due to differential settlement. Maintaining natural vegetation might be difficult in some penned areas

Source: Noble, G., Sanitary Landfill Design Handbook, Technomic Publishing Company, Inc., Westport, CT, 1976.

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Section 9

PROCESSING ALTERNATIVES

PURPOSE

This section will briefly review the various processing alternatives to prepare sludge for wet or dry disposal and will provide guidance on how to determine which alternative is appropriate for a given situation. The results of example calculations to determine the disposal volumes resulting from the several alternatives are shown.

PRIMARY ALTERNATIVES

There are several alternatives available that may be used alone or in combination for the preparation or processing of FGD scrubber waste for wet or dry disposal. These processes are designed to make the waste more amenable to handling and disposal. The preparation or processing alternatives are divided into three principal categories which are described briefly here and are considered in detail in the following three sections of this Manual. The three broad processing alternatives are:

- Forced Oxidation
- Thickening/Dewatering
- Fixation/Stabilization

Forced Oxidation

Briefly, forced oxidation is a processing step incorporated as part of the scrubber cycle or the waste treatment cycle to intentionally oxidize the sulfite species to sulfate so that gypsum is the primary solid component of the waste.

Forced oxidation offers a number of advantages in obtaining a waste with near optimum qualities for dry disposal. The resultant gypsum dewaters readily by settling or thickening alone, or with subsequent filtration or centrifugation to about 80% solids, thereby reducing the volume of product to be handled, transport costs, land area requirements, land acquisition costs, and disposal costs. It can also be disposed by stacking as shown in an EPRI-sponsored test at the Scholz Plant

of Gulf Power Company and discussed in Section 16 - GYPSUM STACKING. The product has good structural properties and can be easily landfilled. Furthermore, it may have a market outlet in building material or in agricultural uses.

Thickening/Dewatering

Thickening/dewatering is designed to remove water from the sludge and can be accomplished by one or a combination of thickeners or settling ponds, and vacuum filters, centrifuges, or cyclones. Removal of water reduces the volume of waste, which results in lowering transportation costs, disposal area requirements, land acquisition costs, and disposal costs. Dewatering is also used to reduce the moisture content so that dry handling and disposal are possible.

Thickeners and Ponds. Because of inherent simplicity, thickeners and/or settling ponds are justified in most cases. They are used almost universally on the scrubber bleed stream to concentrate the scrubber solids. Thickeners are usually preferred to settling ponds because of efficiency in solids removal, flexibility in location, and smaller space requirements. However, thickeners are usually more expensive than ponds and require more operator attention and maintenance.

The primary advantages of interim ponding include low capital cost and a minimum of mechanical equipment and operating manpower. Disadvantages include the difficulties and cost of excavating the dewatered material, the requirement for land area preferably near the plant, the need for careful dike construction and continued surveillance, the possible need for expensive liners and the necessity in some locations for providing for human and animal exclusion:

Thickeners, like ponds, employ gravity for settling sludge. They accelerate the separation process, require less land area than ponds and fit well into further treatment steps. As disadvantages, more mechanical equipment and operating and maintenance manpower are required, an area close to the scrubber site is necessary, and spare capacity, redundancy or by-pass must be provided. Freeze-up of idle thickeners has occurred in colder areas, and malfunctions have resulted in completely filling thickeners with sludge of high solids content.

Vacuum Filters, Centrifuges and Cyclones. When used, vacuum filters or centrifuges generally follow thickeners or settling ponds to effect an additional increase in

solids content of the sludge. In Japan, it is common practice to use such devices directly on the bleed stream with no preliminary settling.

Vacuum filters can be either the drum or belt type, with the former appearing to be more popular with utilities. Performance is more satisfactory with predominantly sulfate sludges; flocculant addition may be necessary in some cases. Vacuum filters require an indoor or protected location; maintenance requirements have been high at some installations due to mechanical and filter media problems; redundant equipment is a necessity; and operator attention is required.

Centrifuges have been sucessfully used in chemical and manufacturing processes, but have seen only limited use with FGD sludge. Table 2-2 shows that more applications are planned. Protection from the elements will generally be necessary, as well as precautions to minimize noise and vibration. The installation at the Martin Lake Plant of Texas Utilities Generating Company and with the Chiyoda 101 prototype at the Scholz Plant of Gulf Power Company have given good results.

Cyclone separators have also been proposed and will be seen in future installations.

Fixation/Stabilization

There is no clearcut difference between the terms stabilization and fixation as used in the industry. They are often used interchangeably and the terminology is somewhat confusing. Stabilization in a broad sense is any chemical and/or physical treatment designed to improve the chemical and/or physical properties of the sludge. Strictly speaking, this definition could include thickening/dewatering. However, stabilization is generally understood to mean addition of dry flyash, soil, or other dry additive to reduce the moisture content and improve handling characteristics without a chemical interaction between the sludge components and the additive. It is used in this context throughout this Manual.

Fixation or chemical treatment is defined as a type of stabilization which involves the addition of lime or other reactive material, such as blast furnace slag, alkaline flyash, or portland cement, to result in cementitious-type reactions in the sludge. These reactions bind the sludge particles together, thus increasing shear strength and reducing permeability. The structural stability and environmental characteristics of the waste product are thereby improved.

Mixing with Flyash. Mixing with dry flyash can significantly improve the physical properties of FGD sludge, facilitating waste handling and enabling landfill disposal without dikes or dams. In the case of non-alkaline flyash, the mechanism improving product properties is solely physical, resulting from a decrease in moisture content and change in overall particle size. No chemical reactions are involved.

A number of western coals and lignite yield flyash that contains appreciable quantities of free alkaline materials--as high as 30 to 40% as calcium oxide. When mixed with the sludge, these alkaline materials may react in a pozzolanic manner with the sludge and other flyash components, resulting in fixation.

Ideally, the sludge/flyash blend should have a moisture content that will allow the material to be handled as a solid and to be placed in a landfill at its maximum bulk density. The physical characteristics of the mixture are similar to that of moist flyash. As such, it is suitable for handling with conventional earth moving equipment, is compactible into a stable, dense fill, and has sufficient moisture to prevent fugitive dust problems during disposal. For all practical purposes, the desired moisture content is the Optimum Moisture Content. This engineering parameter is determined by laboratory test and is defined as the water content at which a soil or soil-like mass can be compacted to a maximum dry unit weight by a given compactive effort.

In addition to the advantages obtained from a dry disposal system, stabilization or fixation by blending with flyash is the least expensive method of achieving dry disposal. With this system, no additives other than flyash are required. The expense of chemical reagents is thus eliminated. The capital and operating cost of blending equipment is relatively small as compared to dewatering equipment, although for most cases, some degree of dewatering is necessary to achieve the best results.

The disadvantages of stabilizing by blending with ash are: the final material is more permeable than those from fixation processes, thus increasing the potential for leachate production, and the final product is less physically stable. Good pozzolanic reactions with alkaline flyash will, of course, eliminate these factors. Another aspect receiving consideration is that the mixing of flyash and sludge will make future recovery of one or both materials difficult, if not impractical. The mixing of sludge with flyash is becoming more widely used as a disposal method as noted in Section 2 - CURRENT PRACTICE.

Blending with Flyash and Lime. IU Conversion Systems (IUCS) markets the Poz-O-Tec^{R} process which is based on the addition of lime and flyash to FGD sludge. This process is in use at or planned for 25 generating units, as of November 1, 1979.

Before blending with flyash and lime, the sludge should be dewatered to the degree required to obtain a mixture at or near the optimum moisture content for compaction. When the sludge is dewatered to this degree, the physical properties of the mixture are improved and the amount of lime required is reduced.

Blending with Calcilox^{R}. Dravo Lime, a subsidiary of Dravo Corporation, markets a fixating agent called Calcilox, derived from basic, glassy blast furnace slag. The slag is finely ground to increase its reactivity. When added to FGD sludge, lime is also added, if necessary, to increase the slurry pH to 10.5 to 11.0. The addition of lime and ground blast furnace slag to fixate the sludge is similar to adding slag cement.

Dravo recommends adding 5 to 10% Calcilox to sludge slurries to obtain fixation. After mixing, the sludge is disposed by a wet disposal method. Dravo has systems of this type in operation at the Bruce Mansfield Plant of Pennsylvania Power Company and the Pleasants Station of the Monongahela Power Company. For dry disposal systems, Dravo recommends dewatering by vacuum filtration and addition of Calcilox; however, no systems of this type are presently in operation. No flyash addition is necessary in any of the Dravo processes.

Mixing with Other Materials. There has been some testing of mixtures with overburden from strip mines in backfilling the cuts, and some utilities are planning such disposal methods. However, no full-scale mixing of sludge with such material to accomplish stabilization has been practiced. There has been limited application of layering the sludge with overburden in the reclamation of surface mines.

SELECTING APPROPRIATE PROCESSING

The preceding discussion provides a review of the primary processing alternatives available and the important advantages and disadvantages. A logical next step is to consider the quantities of waste that will result from the various processing alternatives. The following discussion will utilize the waste quantities derived in Section 4 to determine the extent of processing necessary to arrive at an overall processing system which will meet the requirements of a specific situation.

The results derived are accompanied by the equations which were used, thereby enabling similar calculations for other conditions.

Land Requirements

Consider the four examples which were described in Section 4 - WASTE QUANTITIES:

Example 1 - Typical plant burning 3.5% sulfur coal yielding non-alkaline flyash with the emissions scrubbed in a lime scrubber.

Example 2 - The same as Example 1 but with limestone used as the reagent in the scrubbing system.

Example 3 - The same as Example 2 but with forced oxidation of the scrubber sludge.

Example 4 - A plant burning sub-bituminous coal or lignite with the alkaline ash being used as the scrubber reagent.

Other assumptions for the plants are shown in Table 9-1 together with the waste quantities previously calculated.

The disposal options considered are:

- Landfill disposal of flyash and sludge
- Ponding of combined flyash and sludge

Other options are available, but these are considered typical of current and proposed practices. If disposed separately, the first option will allow for future recovery of one or both materials and appears to be the logical choice for forced oxidation systems which have upstream flyash removal. If the sludge and flyash are co-disposed, this would represent the one in which the sludge is stabilized with non-alkaline flyash or fixated with alkaline flyash or the IU Conversion Systems method. The second option involves the ponding practice most familar to utilities and widely used for the disposal of flyash and bottom ash.

Using the numerical method of calculation given in Section 4 - WASTE QUANTITIES, volume calculations for the options for each example are developed. The results are shown in Table 9-2, along with the method of calculation.

Table 9-1

ESTIMATION OF WASTE QUANTITIES

ASSUMPTIONS			
Plant			
Units		2 @ 500 Mw	
Capacity factor over 30-yr life		45%	
Example:	1	2, 3*	4
Fuel			
Heating value, Btu/lb	12,500	12,500	8,000
Ash content, %	12	12	8.5
Flyash/bottom ash	80/20	80/20	80/20
Sulfur content, %	3.5	3.5	0.6
Annual consumption, t @ 45% capacity factor	1,577,000	1,577,000	2,217,000
Air Quality Control System, AQCS			
Upstream particulate removal, %	99	99	N/A
Overall particulate removal, %	99.8	99.8	99.8
SO_2 removal efficiency, %	90	90	70
Scrubbing reagent	Lime	Limestone	Alkaline Flyash
Reagent Stoichiometry, %	110	130	NA
Thickener underflow solids, %	35	35	35
Sludge and flyash solids specific gravity	2.4	2.4	2.4

ESTIMATED WASTE QUANTITIES FROM SECTION 4				
Example:	1	2	3	4
Ash, t/yr				
Flyash	151,400	151,400	151,400	150,800
Precipitator Flyash	150,000	150,000	150,000	N/A
Sludge, dry t/yr				
SO_4/SO_3	20/80	20/80	90/10	60/40
$CaSO_4 \cdot 2H_2O$	53,450	53,450	240,500	30,060
$CaSO_3 \cdot \frac{1}{2}H_2O$	160,200	160,200	20,020	15,010
Excess and unreacted reagent, t as $CaCO_3$	43,400	102,500	102,500	N/A
Flyash	1,210	1,210	1,210	150,500
Total weight of dry sludge solids, t	258,300	316,300	363,200	195,600
Sludge, dry volume yd^3/yr	127,400	156,000	179,200	96,500

*Plant 3 conditions the same as Plant 2 except forced oxidation is utilized.

Table 9-2

DISPOSAL SITE VOLUMES AT 45% CAPACITY FACTOR

Example:	1	2	3	4
Landfill: Landfill of mixed sludge and flyash compacted to 80 lb/ft^3. Sludge dewatered to give 75% solids in mixture.				
Weight, tons/yr				
ash + sludge, dry solids	408,300	466,300	513,200	195,600
Water	136,000	155,300	170,900	65,140
Volume, yd^3/yr	504,000	575,600	633,400	241,400
Total volume ac-ft/30 yr @ 45% capacity factor	9,370	10,700	11,750	4,490
Ponding: Ponding of sludge and flyash. Settled solids from Plants 1 and 2--45%, Plants 3 and 4--60%.				
Volume, yd^3/yr				
ash + sludge, dry solids	201,300	230,000	253,000	96,430
Water	591,700	675,800	406,000	154,700
Total	793,000	905,800	659,000	251,100
Total volume, ac-ft/30-yr @ 45% capacity factor	14,740	16,840	12,250	4,670

Method of Calculation

Volume compacted waste, yd^3/yr =

(weight dry waste solids, t/yr + weight water in dewatered solids mix, t/yr) ÷ (compacted density, lb/ft^3 x 27 ft^3/yd^3 ÷ 2000 lb/ton)

Volume of dry waste solids, yd^3/yr =

(weight of dry waste solids, t/yr x 2000 lb/ton x .037 yd^3/ft^3) ÷ (62.4 lb/ft^3 water x specific gravity of solids)

Volume wet waste, yd^3/yr =

volume dry waste solids, yd^3/yr + volume water, yd^3/yr

Weight water in wet waste, t/yr = weight dry waste solids, t/yr x $\frac{\%\ \text{water}}{\%\ \text{solids}}$

Volume water in wet waste, yd^3/yr =

(weight water, t/yr x 2000 lb/t x .037 yd^3/ft^3) ÷ density water, lb/ft^3

Total waste volume, ac-ft/yr = total volume, yd^3/yr x 6.198 x 10^{-4} ac-ft/yd

For both lime and limestone scrubbing without oxidation, the data in Table 9-2 show that dry disposal of flyash and sludge significantly reduces the total disposal volume required, being roughly two-thirds of that required for ponding of both ash and sludge. These reductions may result in significant savings in the cost of land and related items. Similar but much lower reduction in disposal volume is shown for the oxidized and alkaline flyash sludge because of their better settling properties when ponded.

The effect of forced oxidation on the volume of limestone scrubber sludge is also shown. In the landfill option, there is about a 10% increase in the waste volume of the oxidized sludge/flyash because of the greater weight/volume of sulfate solids. This must be balanced against the better dewatering and handling properties of the gypsum. In the ponding option, the oxidized sludge/flyash requires about 25% less volume than the unoxidized sludge mix due to better settling properties.

While any reduction in disposal volume may result in significant savings in land costs and related items, it may be that the cost of additional processing to achieve the desired disposal option outweighs the savings in cost of land. Therefore, it is important to determine the processing necessary to achieve the disposal option desired. This factor is considered next.

Wet Disposal

The basic question to be answered is: Can a processing step be added to give a more cost-effective disposal method than direct ponding of the scrubber bleed stream? A logical step to be considered is that of thickening or partial dewatering to yield a pumpable waste with less water than before. A thickener provides a means to accomplish this, and the effect of incorporating it in the waste disposal scheme will be considered.

Fixation/stabilization will not reduce the ponded sludge disposal volume at all, so it is not considered until later in this analysis. Fixation/stabilization is primarily related to structural and environmental concerns and is not utilized for volume reduction.

The volume of FGD sludge expected from thickening is compared with the direct ponding option in Table 9-3. The figures shown do not include flyash disposal except in Example 4.

Table 9-3

VOLUME OF SCRUBBER SLUDGE PUMPED TO DISPOSAL POND

Example	1	2	3	4
1. Direct ponding of scrubber bleed @10% solids				
million yd^3/yr	2.883	3.531	4.054	2.183
million gal/day	1.594	1.952	2.242	1.207
2. Ponding of thickened scrubber bleed @35% solids				
million yd^3/yr	0.696	0.852	0.978	0.527
million gal/day	0.385	0.471	0.541	0.291
Reduction in volume of sludge, %	76	76	76	76

Method of Calculation

Volume bleed, yd^3/yr = Volume dry sludge, yd^3/yr + Volume water, yd^3/yr

Volume bleed, gal/day = (Volume bleed, yd^3/yr x 202 gal/yd^3) ÷ 365 days/yr

The data show that thickening alone or in combination with forced oxidation reduces the amount of sludge to be pumped by 76%. The relative costs and advantages/disadvantages of pumping the larger volume vs. thickening should be examined to determine which is more desirable. As indicated earlier in this section, a thickener is usually justified because of the significant volume reduction attained. It should be noted, however, that the final volume of settled sludge is not reduced.

The volume of pond supernatant returned is also an important variable. Table 9-4 shows the volume of pond supernatant expected with and without thickening. The actual supernatant will be greater or smaller depending upon losses from evaporation, seepage, and overflow and gains from precipitation and surface runoff. These factors are site specific but readily estimated from available data. (See Section 8 - DESIGN OF DISPOSAL AREAS.) For any wet disposal system, a water balance must be established as a major factor in conceptual and final design. Without a water balance, there is no certainty that either the scrubber system or the disposal system will perform as designed. It should be observed that little or no supernatant is expected in arid areas where evaporation of pond water is significant.

Table 9-4

VOLUME OF SUPERNATANT RETURN FROM DISPOSAL POND[a]

Example	1	2	3	4
1. Direct ponding of scrubber bleed[b]				
million yd^3/yr	2.382	2.917	3.588	2.057
million gal/day	1.317	1.613	1.984	1.137
2. Ponding of thickened scrubber bleed[c]				
million yd^3/yr	0.194	0.238	0.512	0.400
million gal/day	0.107	0.132	0.283	0.221
Reduction in supernatant return, %	92	92	86	81

[a]The figures shown are estimates at 45% capacity factor. Actual supernatant return would be greater or smaller, depending upon evaporation, seepage, and overflow losses and precipitation or runoff gain.

[b]Assumes scrubber bleed at 10% solids content settling to 45% solids for Examples 1 and 2 and 60% solids for Examples 3 and 4.

[c]Assumes thickener underflow at 35% solids settling to 45% solids for Examples 1 and 2 and 60% solids for Examples 3 and 4.

The results show reduction in supernatant volume from 81% for alkaline flyash scrubbing to 92% for both lime and limestone scrubbing, the latter without oxidation. Forced oxidation in Example 3 results in a slightly greater amount of sludge to be handled and more supernatant. Pumping costs can be expected to be slightly higher, therefore, with this system. However, as previously discussed, the primary advantage of forced oxidation is the better dewatering property of the oxidized sludge.

Dry Disposal

If a dry disposal system is to be considered, some additional processing will be required. Shown here are the results of a series of calculations which determine the processing options which can be used to produce a material suitable for landfill disposal for the four example power plants.

In general, sludge processing to facilitate landfill disposal is directed toward reducing the moisture content of the waste product. Ideally, the waste product would have a moisture content that would allow the material to be handled as a solid and be placed at its maximum bulk density in a landfill. For practical

purposes, the desired moisture content for landfill disposal is the "optimum moisture content," which is the water content at which a soil-like mass can be compacted to a maximum dry unit weight by a given compactive effort.

While large variations in optimum moisture contents have been reported for some unusual sludges, generally, the optimum moisture content is 30 to 40% for sludge and 20 to 30% for sludge/ash mixtures. These values correspond to solids contents of 77 to 84%; the higher solids contents are for sludges with a greater degree of oxidation. To insure that the dewatered waste will behave as a solid material suitable for landfilling, solids contents of 72 to 79% should be obtained, at least in the conceptual design of the disposal system.

Note that, in conformity with soils engineering, percent solids is expressed as the percent of the total weight of the sludge due to the solid constituents. In contrast, moisture content is calculated as the ratio of the weight of the sludge liquid to the weight of the sludge solids, expressed as a percentage.

For the illustrative plants, the solids content corresponding to an optimum moisture content for a sludge/ash mix is estimated to be about 80%. Allowing some excess moisture, it is assumed that 75% solids is the minimum solids content that can be tolerated for landfill disposal without a chemical reaction to fix the mixture. To obtain these solids, assume that all the flyash collected in the precipitators in Examples 1, 2 and 3 is available for mixing with the sludge and apply the following equation to determine the feasibility of dry disposal and the processing that is required:

$$\text{Solids content of mix} = \left[\frac{(\text{weight of precipitator ash}) + (\text{weight of sludge solids})}{\left(\begin{matrix}\text{weight of}\\ \text{precipitator ash}\end{matrix}\right) + \left(\begin{matrix}\text{weight of}\\ \text{sludge solids}\end{matrix}\right) + \left(\begin{matrix}\text{weight of}\\ \text{sludge water}\end{matrix}\right)}\right] 100$$

Note: These quantities have previously been determined in this section or Section 4 - WASTE QUANTITIES.

The simplest processing alternative is to take thickener underflow (assume 35% solids) and mix in the dry precipitator ash. In Example 4, no dry flyash is available. Using the equation above and the values shown in Table 9-1, the solids contents of the resulting mixes are calculated to be:

Example	Solids Content of Mix, %
1	46
2	44
3	43
4	35

In all cases, the solids content is too low and additional dewatering is necessary for dry disposal. Since for Example 4 it was assumed that the flyash is alkaline, the sludge/flyash mixtures may be self-fixating at a certain point in dewatering. As a result, dewatering may be all that is required for the alkaline ash examples. In such cases, pilot or demonstration testing would be warranted to determine if fixation does occur and at what solids content.

Another possibility is to allow long-term settling of the sludge to 45% solids content for Examples 1 and 2 and 60% for 3 and 4, followed by excavation and, in Examples 1, 2 and 3, addition of the precipitator flyash. The results of this processing are:

Example	Solids Content of Mix, %
1	56
2	54
3	68
4	60

Under these conditions, none of the mixtures has attained the 75% solids content, indicating that further processing is required, unless the sludge in Example 4 proves to be self-fixating.

Another possibility for these plants is to provide mechanical thickening followed by centrifugation or vacuum filtration to further reduce the moisture content. Assume the sludge from Example 1 is dewatered to 60% solids and in Examples 2, 3 and 4 is dewatered to 70% solids. The latter may be a conservative value since some pilot and test results have shown solids in the 80 to 90% range, especially for oxidized sludge. Mixing these sludges with dry flyash results in the following solids contents:

Example	Solids Content of Mix, %
1	70
2	77
3	77
4	70

The figure for Example 1 is now close to, but still less than, the suggested 75%. Experience has indicated that additional mechanical dewatering of the sludge is impractical. Therefore, additional flyash from another unit or plant would be necessary to further reduce the moisture content, or some fixation chemical must be added to provide a material suitable for landfill disposal. Examples 2 and 3

have more than the necessary 75% solids content. Once again, the mix in Example 4 may fixate at the 70% solids shown.

To facilitate planning for a new sludge handling system, Figure 9-1 provides a means of estimating the solids that will result from mixing various proportions of flyash to scrubber sludge of various solids content. For example, to obtain 75% solids for dry disposal, it would be necessary to mix two parts of flyash to one part of dry sludge solids when in a 50% slurry. Similarly, if the sludge were dewatered to only 40% solids, the same 2:1 mix would result in 67% solids. However, a sludge dewatered to 65% would require only about a ½:1 mix. It will be observed that in Examples 1, 2 and 3, the available flyash is about ½ the weight of the sludge solids, which indicates that dewatering to more than 60% is required in all cases.

In summary, for dry disposal at the four example plants, the available schemes are:

Example 1 - Thickening + secondary dewatering + blend dry flyash + add fixation reagent(s) or more dry flyash.

Example 2, 3 - Thickening or settling + secondary dewatering + blend with dry flyash with or without fixation reagents.

Example 3 - Thickening or settling + secondary dewatering of oxidized sludge. Dispose separately or mix with flyash.

Example 4 - Thickening or settling + secondary dewatering. If the sludge/ash mix is not self-fixating, an additive may be necessary.

Knowing what system is technologically viable should enable the utility engineer to develop cost comparisons for the available schemes and to plan accordingly.

CONCLUSIONS

It is evident from the above analysis that a cost comparison of wet vs. dry disposal options and the amount of processing necessary or desirable will vary depending upon the site-specific conditions. Which system to use will depend on a cost comparison and the relative advantages and disadvantages of the disposal options considered.

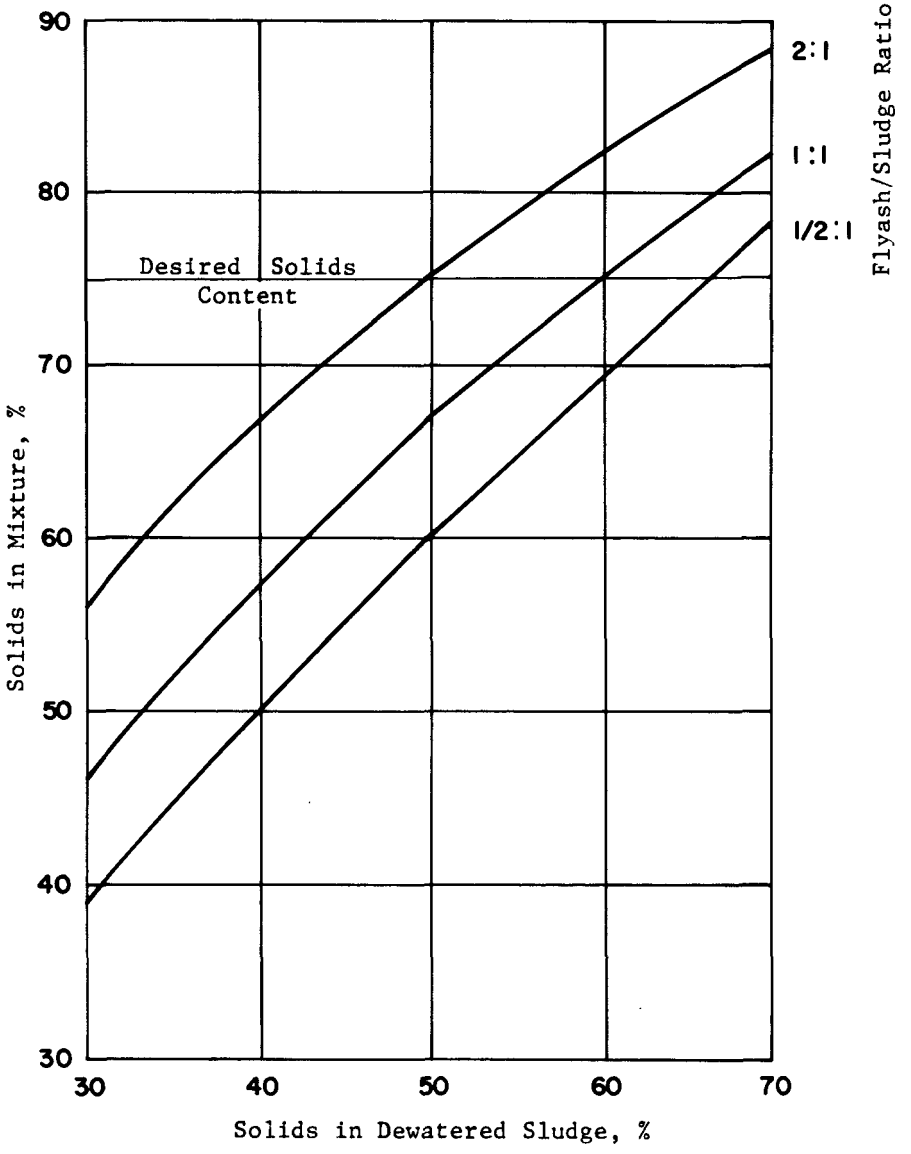


Figure 9-1. Percent Solids in Mixes of Flyash with Sludge of Various Solids Content

Section 10

FORCED OXIDATION

PURPOSE

The purpose of this section is to discuss the use and effect of the forced oxidation option on sludge processing and disposal. Advantages, disadvantages and cost factors are included in the discussion. Periodic update of this section will be necessary in order to reflect the developing technology.

BACKGROUND

In the earlier days of scrubber development, it was believed that satisfactory, scale-free operation could be obtained only by minimizing or eliminating calcium sulfate from the scrubber system. That was the reason attributed for the successful operation of the Louisville Gas and Electric Company Paddy's Run No. 6 Scrubber. With a better understanding of the chemistry of scrubbing, the completion of numerous laboratory and field tests, and the redesign of systems and use of reaction or delay tanks, the formation of sulfate has been found to be beneficial insofar as resulting in a better end product without scaling in the system. Beneficial effects on sludge include better dewatering properties and resultant smaller disposal volumes. Consequently, recent developments in scrubbing have included the use of forced oxidation to promote the formation of calcium sulfate in the sludge.

The process has been widely and successfully used in Japan because:

- There was a waiting market for the gypsum for use in wallboard or in cement.
- Most of their scrubbers are on oil-fired boilers, so flyash does not contaminate the gypsum for wallboard use.
- There is little land available for throwaway products.
- Environmentalists discourage disposal of calcium sulfite because of its chemical oxygen demand.

There has been limited application of the process in the U.S. However, with the advantages resulting from conversion of the sulfite to sulfate, wider use can be expected. Because of the limited experience with the process, recommendations on equipment type, size and placement in the cycle must come from the scrubber suppliers who offer the oxidation option with their systems.

The forced oxidation process involves the addition of air to the bulk of the scrubbing liquor, to the first loop of a two loop system or to a bleed stream from the recycle loop. The most important variable in the process is the pH of the liquor at the point of air introduction. The rate and extent of oxidation increase as the pH decreases, and is proportional to the sulfite concentration in solution. The use of magnesium oxide as an additive to the reagent has also been found to aid in sulfite solubility (1). Tests at the EPA/TVA test facility at the Shawnee Power Station of TVA (Shawnee) have shown good results in the pH range of 4.5 to 6.0 (2,3,4,5,6). One suggested method of pH control involves the addition of acid to a bleed stream before introduction to an oxidizer vessel. This method is used commercially in Japan but has only been tested in this country (2). A more favored method of control is the introduction of air to the low pH liquor after partial or complete absorption of SO_2 and before addition of make up reagent.

Air Introduction

Air for the oxidation process is normally supplied by compressors. Tests at Shawnee with an eductor were not as satisfactory as those with a compressor because of erosion of the rubber-coated eductor and high energy consumption. The oxygen stoichiometry requirements show wide variation as reported by various investigators, being higher when lime is the scrubbing reagent. This has been attributed to the higher pH normally found with lime scrubbers. An air stoichiometry of 1.0 with 97% oxidation was reported with limestone at Shawnee, the excellent response being attributed to the possible presence of an unknown catalyst. More normal values appear to be about 1.3 to 1.8. Air stoichiometry is defined as:

$$\frac{\text{atoms of oxygen fed to oxidizer}}{\text{moles of } SO_2 \text{ absorbed in scrubber}}$$

The air is introduced through various devices. In Japan, a "JECCO spinning-cup" is widely used. This device is a proprietary spinning air atomizer. In the U.S., the use of spargers in various configurations appears to be favored. At Shawnee, a sparger ring was installed directly below a turbine agitator, as shown in Figure 10-1. Trouble was reported with plugging of the sparger holes. Later tests with an open-end 3-in. pipe elbow discharging downward at the center and near the bottom of the oxidation tank gave good results when accompanied by adequate agitation.

A field test of a new Japanese concept involving a "jet bubbling" process has been conducted at the Scholz Steam Plant of Gulf Power Company (Scholz) under EPRI sponsorship (RP 536). A scrubber cross-section is shown in Figure 10-2. In this

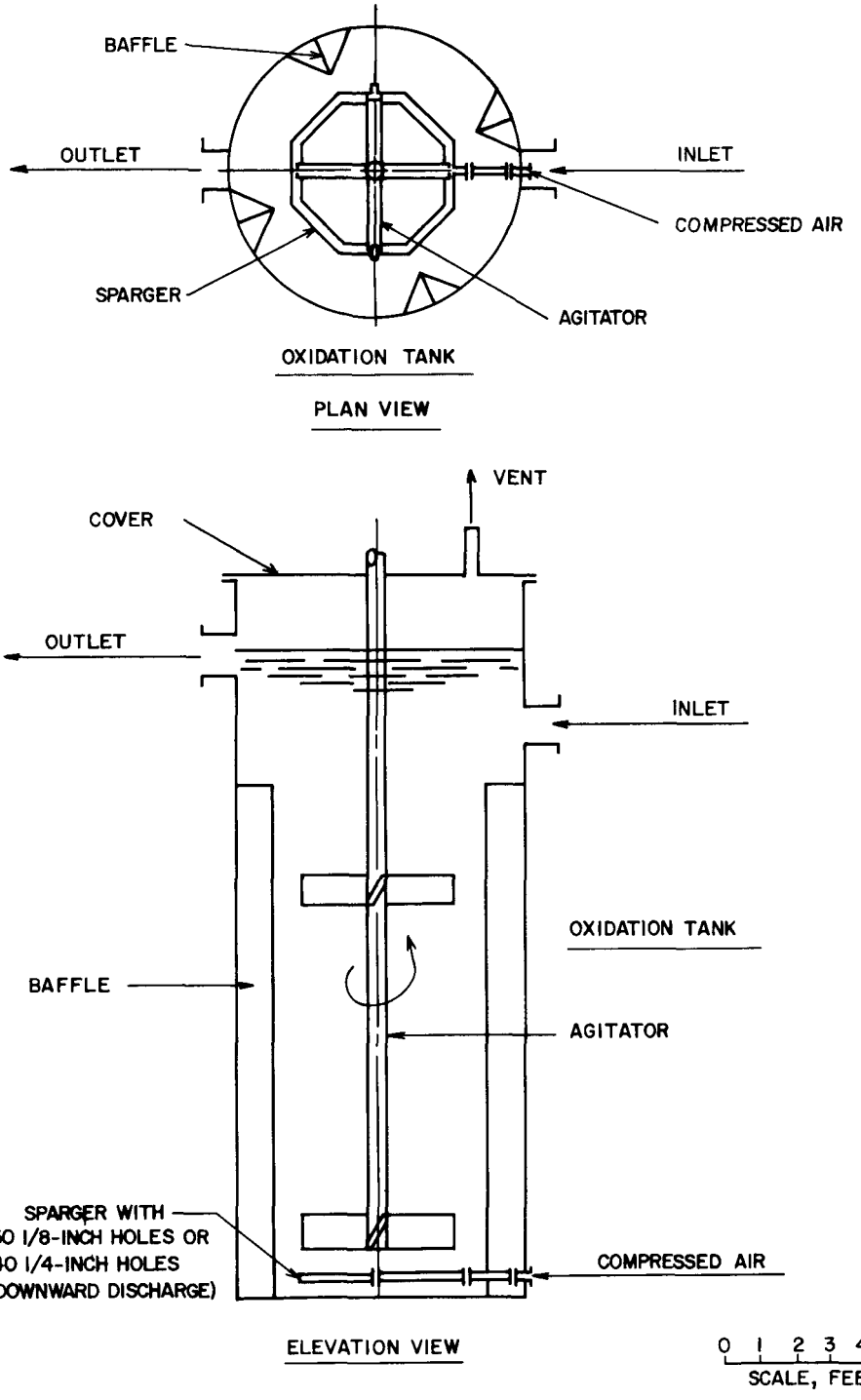


Figure 10-1. Arrangement of the Venturi/Spray Tower Oxidation Tank with Sparger.

Source: Head, H. N., et al., "Results of Lime and Limestone Testing with Forced Oxidation at the EPA Alkali Scrubbing Test Facility," EPA Symposium on Flue Gas Desulfurization, November, 1977, EPA 600/7-78-058a.

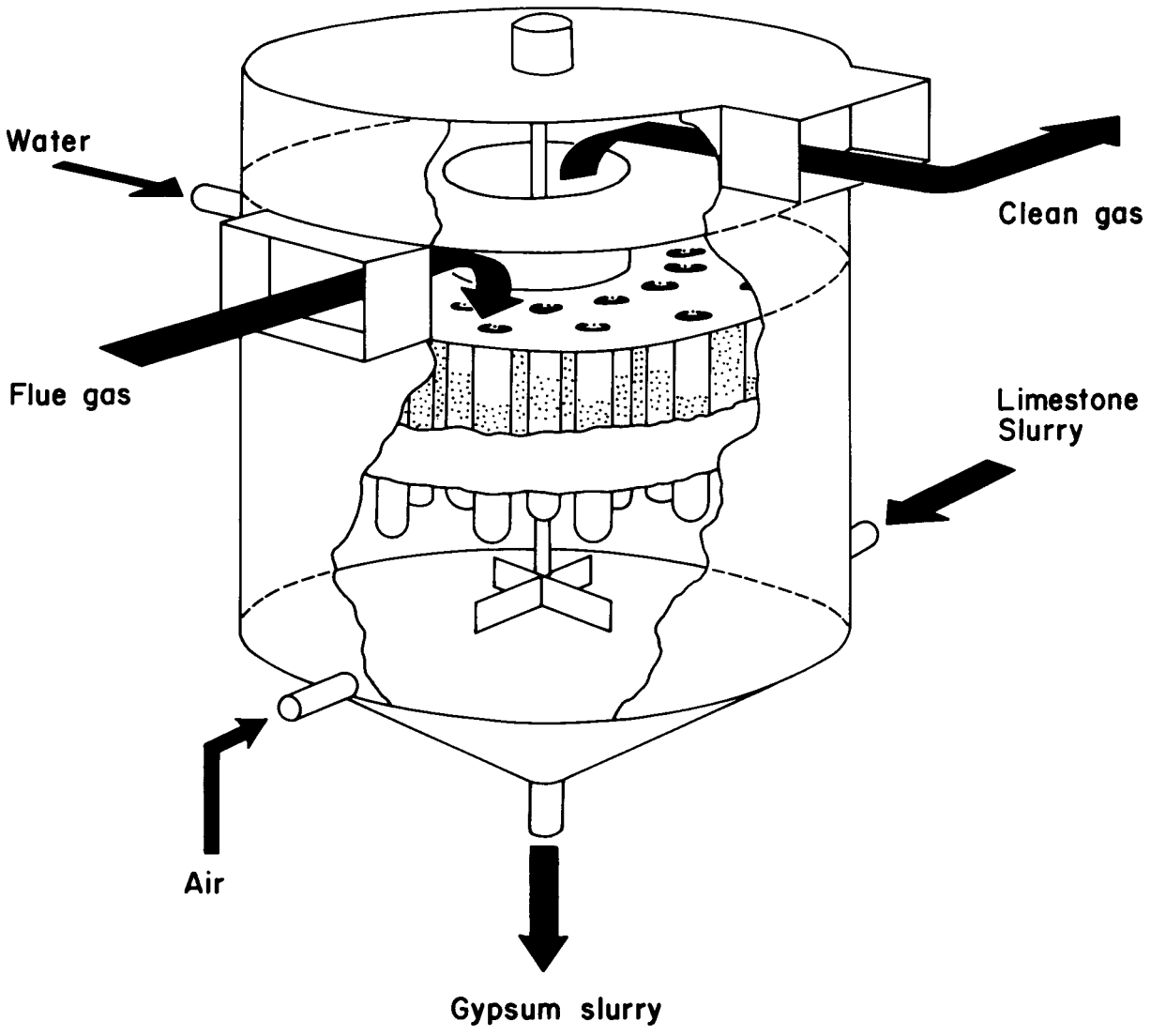


Figure 10-2. Jet Bubbling Reactor

Source: Clasen, D. D. and J. Idemura, "Limestone/Gypsum Jet Bubbling Scrubbing System," EPA Flue Gas Desulfurization Symposium, March 1979. EPA-600/7-79-167b.

system, the entire process of absorption, oxidation and neutralization is accomplished in one vessel.

EPA/TVA TESTS

Most of the investigation and tests of forced oxidation have been conducted by the EPA at Research Triangle Park and by EPA/TVA at the scrubber test facility at the TVA Shawnee Steam Plant, Paducah, Kentucky. A number of reports have been published on this work (1,2,3,4,5,6).

A recent EPA progress report summarizes results that have been obtained by:

- Oxidation in the first loop of a two-loop system
- Oxidation in a single loop TCA^R scrubber
- Oxidation of a bleed stream

Tests have involved the use of lime and limestone as reagents and MgO as an additive (6).

Two Loop System

Figure 10-3 shows the two-loop system in which the flow from the venturi section is isolated and directed to an oxidation tank. Upstream flyash removal may or may not be employed with little, if any, effect on results. Air is introduced to the oxidation tank which is equipped with an agitator. The stream next flows to a desupersaturation tank where the reaction proceeds, and a bleed stream is taken off to waste treatment. The main liquor flow in this loop is returned to the venturi scrubber. Isolation of the venturi and spray tower flows enables oxidation of the more acidic venturi liquor in the oxidation tank and isolates high chloride concentrations to only a portion of the system, where resistant materials can be employed.

The spray tower loop includes the spray tower, where SO_2 removal is completed, an effluent hold tank (EHT) and recycle pumps.

A bleed flow from the EHT supplies part of the make-up to the venturi loop. A portion of the make-up to both loops is also supplied by the clarified liquor return from the dewatering system. The balance of the make-up to the spray tower is supplied by fresh water through mist eliminator sprays.

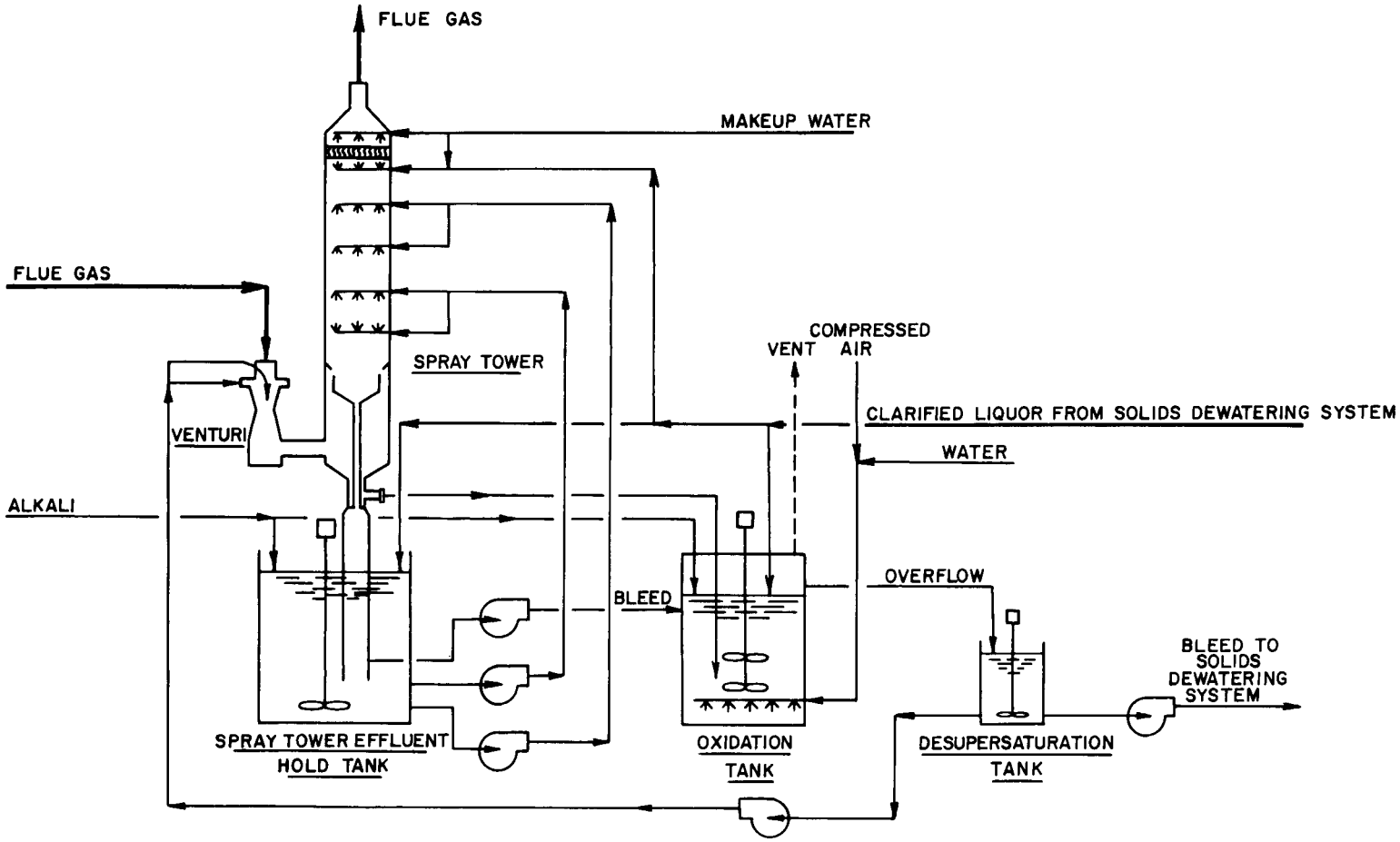


Figure 10-3. Flow Diagram for Two-Scrubber-Loop Forced-Oxidation Tests on the Venturi/Spray Tower System.

Source: Head, Harlan N. and Shih-Chung Wang, EPA Alkali Scrubbing Test Facility: Advanced Program, Fourth Progress Report, Vol. 1, November, 1979, EPA-600/7-79-244a.

When limestone was used, pH control was maintained by addition only to the EHT; with lime, addition to both loops was necessary. When MgO enhanced reagent was used, it was also added to the EHT.

Tests with limestone at an oxidation tank pH of 4.5 to 5.5, a slurry solids concentration of 15% by weight at the venturi inlet, and air stoichiometry of 1.4 to 2.8 averaged:

Oxidation	98%
Limestone Utilization	80-98%
SO_2 Removal	86%
Filter Cake Solids	87%

When the venturi inlet pH was lowered to 4.5, oxidation was 97% at an air stoichiometry as low as 1.0. When MgO was added, SO_2 removal was improved to 96%, with no significant change in other parameters, Operation without the desupersatuation tank had no adverse effect.

Tests with lime at an oxidation tank pH between 4.5 and 5.5, spray tower pH at 7.8, air stoichiometry at 1.5, and venturi solids at 15% showed the following:

Oxidation	98%
Lime Utilization	98%
SO_2 Removal	94%
Filter Cake Solids	85%

In these tests it was necessary to add lime to both scrubber loops.

Single Loop TCA System

Figure 10-4 shows the single loop TCA system with an oxidation tank and an effluent hold tank (EHT). The low pH scrubber liquor drains to the oxidation tank, with the overflow going to the EHT where the reagent and the makeup liquor are added. A bleed stream is taken off to waste treatment, while the recycle flow is pumped to the scrubber.

Results with limestone stoichiometry of 1.3, oxidation tank pH of 5.5 and air stoichiometry of 1.7 were:

Oxidation	94%
Limestone Utilization	81%
SO_2 Removal	80-90%

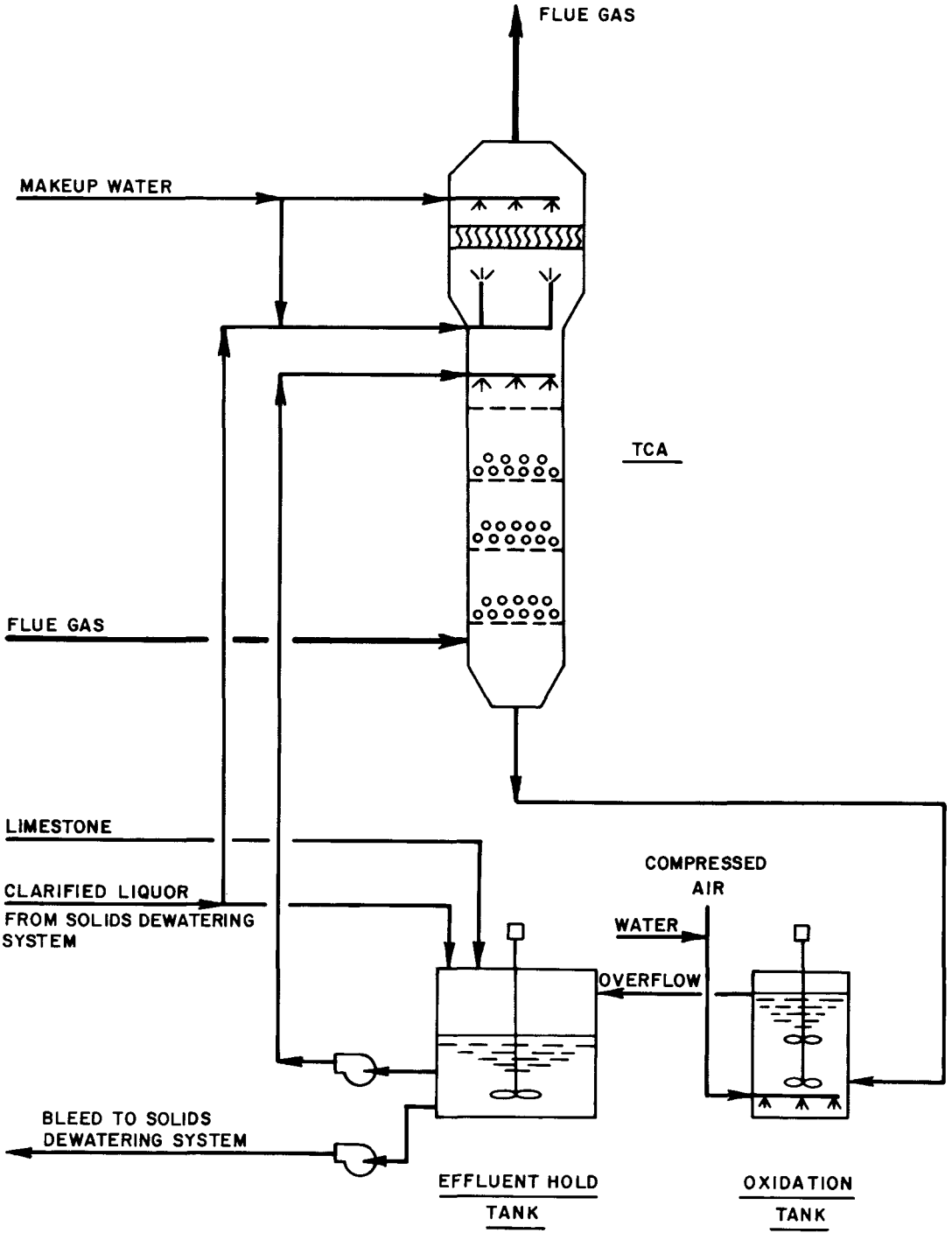


Figure 10-4. Flow Diagram for One-Scrubber-Loop Forced Oxidation with Air Sparger in the TCA System Using Two Tanks

Source: Head, Harlan N. and Shih-Chung Wang, EPA Alkali Scrubbing Test Facility: Advanced Program, Fourth Progress Report, Vol. 1, November, 1979, EPA-600/7-79-244a.

Tests with the EHT excluded from the cycle were less successful. Additional testing is planned.

Bleed Stream Oxidation

Figure 10-5 shows the system for bleed stream oxidation. This configuration is similar to that in Figure 10-3, except the venturi cycle is not isolated. A bleed stream is taken from the low pH spray tower drains to the oxidation tank. A bleed stream from the latter is sent to waste treatment; the overflow returns to the EHT, where the limestone and makeup return liquor are added. MgO was also added to the EHT and is said to serve to buffer the pH against residual limestone dissolution and to increase the dissolved sulfite concentration.

With limestone stoichiometry of 1.4, oxidation tank pH of 5.4 to 6.3 and air stoichiometry of 1.6, tests showed:

Oxidation	96%
Limestone Utilization	62%
SO_2 Removal	88-95%
Filter Cake Solids	84%

It was stated that bleed stream oxidation is not expected to work with either lime or limestone without MgO addition or acidification of the bleed stream to increase sulfite solubility. This is the system most adaptable to existing scrubbers and for that reason is to be investigated further.

STATE-OF-THE-ART

As shown in Tables 2-1 and 2-2, forced oxidation is or will be used at eight plants. Four of the systems use the Combustion Engineering, Inc. (CE) process, two are Research Cottrell (RC), one is Pullman Kellogg and one is Chemico. The most experience has been logged on the CE scrubbers on Northern States Power Sherburne County Generating Plant (SherCo) Unit Nos. 1 and 2. The No. 1 unit was placed in service in May, 1976; No. 2, in April, 1977. Only one other system was available for service as of November 1, 1979. This was on the Kansas Power and Light Company Lawrence Energy Center No. 4 Unit. It is also a CE system which was placed in service in January, 1977. The oxidation system is not normally used because gypsum formation is reported to be satisfactory without it.

The SherCo sludge shows good settling properties and appears stable when ponded. A recent report states that air stoichiometry is 350% and the pH is in the range

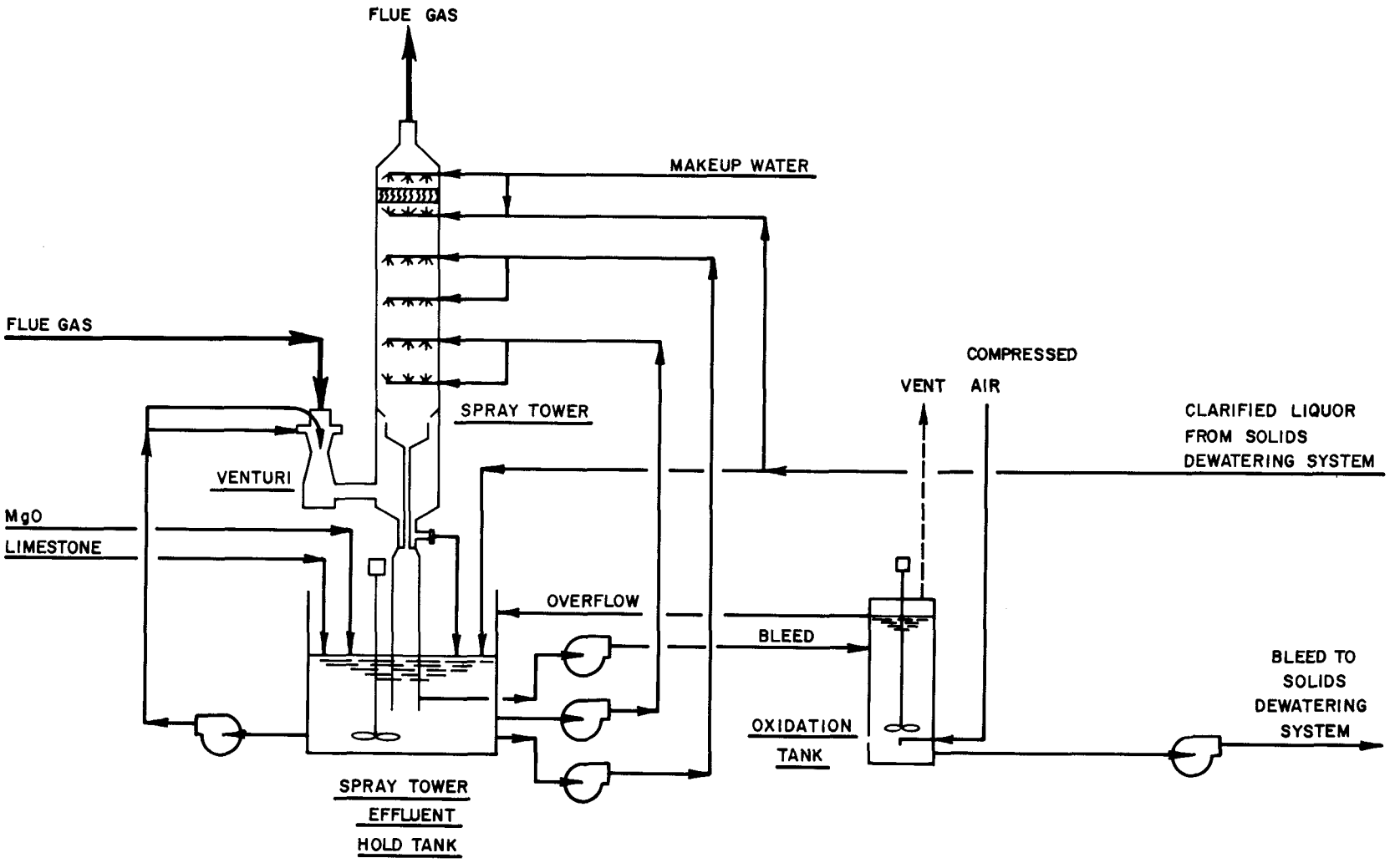


Figure 10-5. Flow Diagram for Bleed Stream Oxidation in the Venturi/Spray Tower System

Source: Head, Harlan N. and Shih-Chung Wang, EPA Alkali Scrubbing Test Facility: Advanced Program, Fourth Progress Report, Vol. 1, November, 1979, EPA-600/7-79-244a.

of 5 to 5.5 (8). These systems, as well as Lawrence 4, employ alkaline flyash supplemented by limestone as the scrubbing reagent. As noted previously, the use of limestone (with normally lower pH) enhances the oxidation of sulfite. A report on Montana Power Company's Colstrip Station scrubbers attributes the same effect to alkaline flyash (9). Additional information should be forthcoming from the work at Shawnee and at TVA's Widow Creek Steam Plant (4).

Of the U.S. scrubber suppliers offering a forced-oxidation option, Combustion Engineering, Inc., normally oxidizes the scrubbing liquor in the reaction tank, as shown in Figure 10-6, which shows the SherCo flow diagram. However, the installation on Lawrence No. 4 has separate, external tanks for the two scrubber sections, viz, the rod section and the absorber and tests have been made with forced oxidation in either and both tanks. In the Pullman Kellogg system, Figure 10-7, air is added to a bleed stream in an oxidizer which operates at near-atmospheric pressure. This manufacturer also recommends the use of "magnesium-promoted" slurry in order to eliminate scaling, improve SO_2 removal efficiency and enhance oxidation. No full-scale installation of this company's oxidizer is in service, but laboratory tests have been performed. Good results were reported, with 99% oxidation being obtained (1).

ADVANTAGES

The advantages of oxidation of calcium sulfite to calcium sulfate include:

- Better settling and filtering properties
- Less disposal space required
- Good structural properties of the disposed waste
- Potential for utilization of the gypsum
- Minimal chemical oxygen demand of the disposed material

Dewatering Properties

Calcium sulfate has the property of settling faster from water than the sulfite form. This may permit the use of considerably smaller thickeners, as shown in Figure 10-8. It has also been reported that sulfite/sulfate mixed slurries show settling rates of 40 to 60 lb/day-ft^2, compared to 200 to 350 for oxidized slurry (10). Shawnee reported filter cake solids of 80-85% after forced oxidation. The same test report stated that optimum settling required at least 90% oxidation. The previously referenced progress report gave additional data (6). It was reported that, in oxidation tests, the average initial settling rate ranged from 0.7 to 1.2 cm/min,

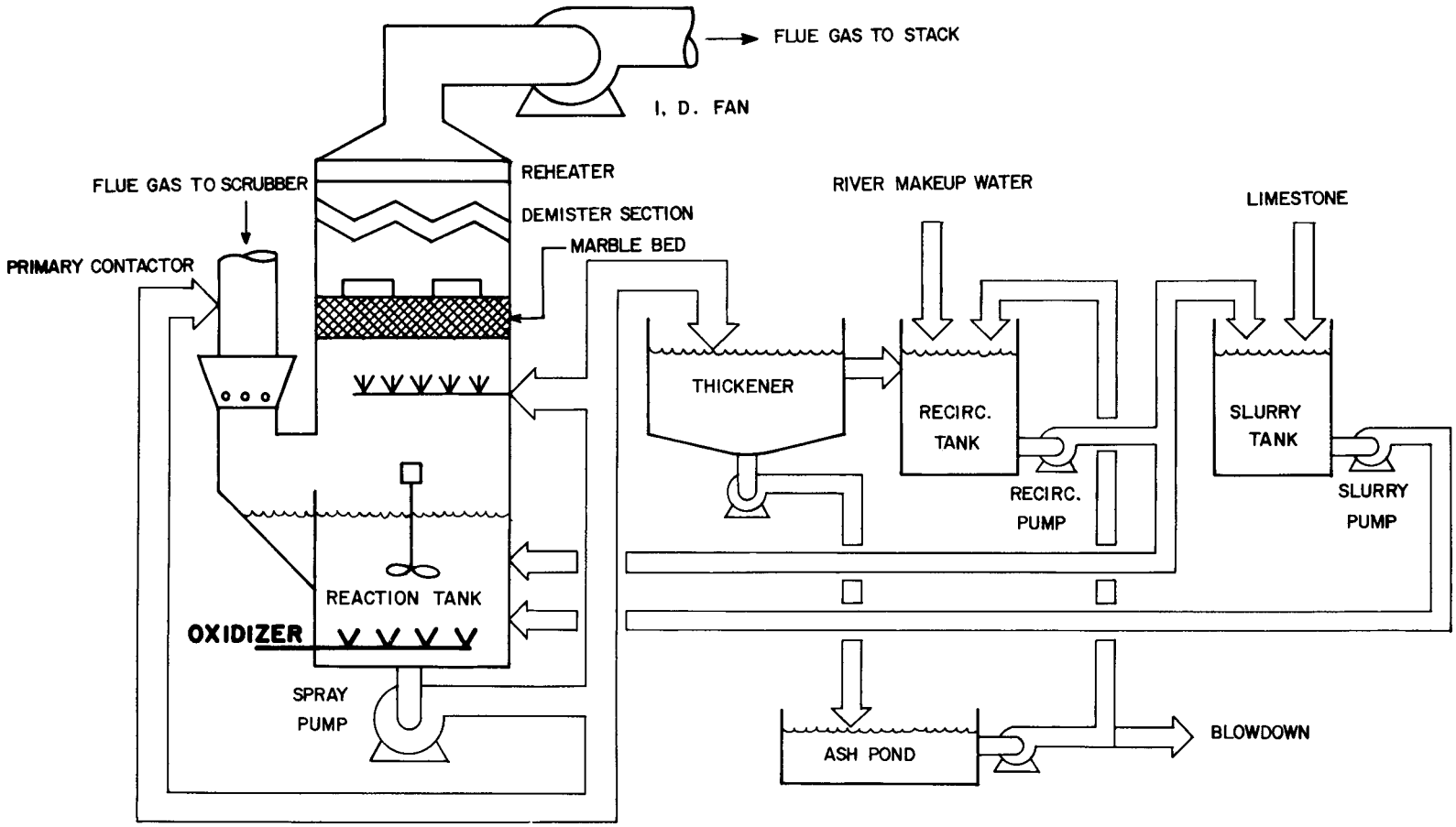


Figure 10-6. Sherburne County Wet Scrubber System.

Source: Kruger, R. J., "Experience with Limestone Scrubbing," Symposium on Flue Gas Desulfurization, November, 1977, EPA 600/7-78-058a.

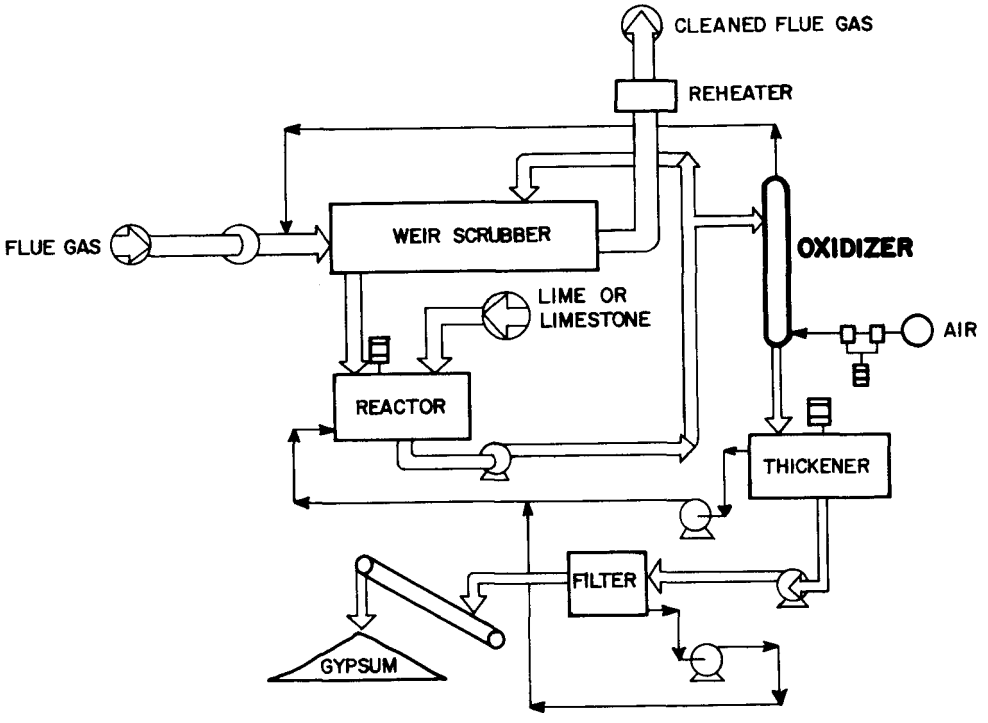
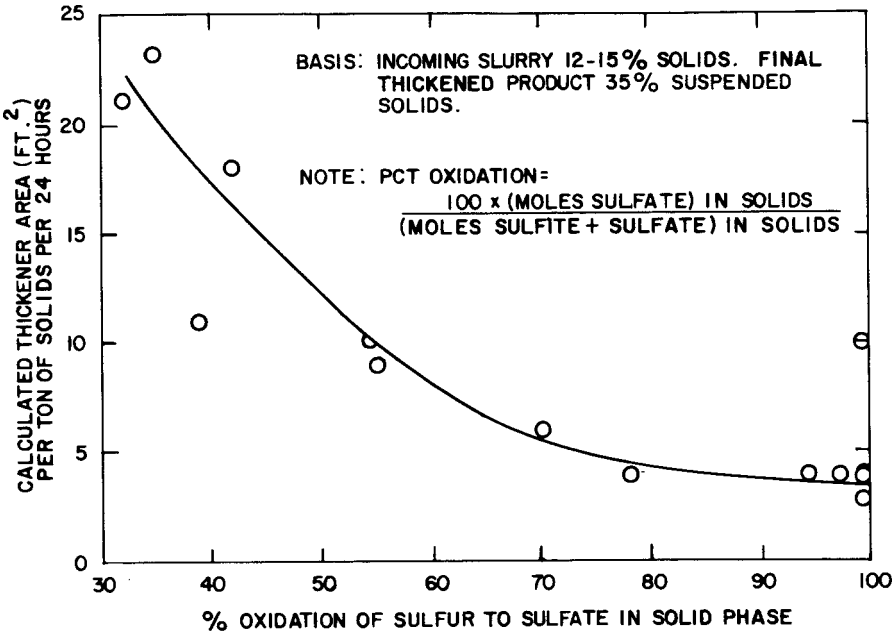


Figure 10-7. Kellogg Scrubbing System.

Source: KELLOGGRAM, 1976 Series, Issue 2.



Note: Data obtained from pilot plant operation with sludge composed of about 20% $CaSO_3/CaSO_4$ and 80% flyash.

Figure 10-8. Oxidation and Its Sludge Thickening Characteristics.

Source: Raben, I. A., et al., "Particulate and SO_2 Removal at the Colstrip Station of the Montana Power Company," Proceedings of The Second Pacific Chemical Engineering Congress, August, 1977.

compared to 0.2 to 0.4 cm/min for unoxidized slurry. The initial settling rate indicates the rate at which solids fall during the unhindered portion of settling; the value of this parameter is necessary in the sizing of thickeners. Figure 10-9 illustrates the data that were obtained.

The same report stated that use of MgO reduced the initial settling rate. This was attributed to the increased viscosity and density of the liquor resulting from the greater concentration of total dissolved solids. Flyash in oxidized slurry is said to have a similar effect, apparently because its particle size (smaller than gypsum) slows the settling rate.

The improved settling properties also show in ponding, where settled solids of 60% and better are obtained. While the mechanism is different, the settling properties are illustrated by the Florida phosphogypsum piles, which are built by pumping the slurry into a settling area at 15 to 20% solids. Combined settling and evaporation result in a dry solid which can be pulled to the pond side for raising the banks as shown in Section 5, DISPOSAL ALTERNATIVES. Phosphogypsum is a waste product from the manufacture of phosphate fertilizer. Similar satisfactory results were obtained in the Scholz Plant Chiyoda 121 tests. See Section 16, GYPSUM STACKING.

In the Shawnee tests, oxidized sludge with low concentrations of flyash was ponded at 35% solids. With an underdrain system, the sludge dewatered to about 80-86% solids in one day with a bearing strength of about 300 psi. A loss of 25-30% in bearing strength was experienced upon wetting, but the original value was regained after draining (4).

Mechanical dewatering is likewise improved. Excellent results were obtained by centrifuging the gypsum product from the Chiyoda 101 scrubber at the Scholz Station as shown in Section 5, DISPOSAL ALTERNATIVES. This gypsum product showed 85% solids.

Structural Stability

Calcium sulfate is more amenable to dry disposal than calcium sulfite. The crystalline nature of gypsum is decidedly different; it is blocky, easily dewatered and stacks well, as noted above for phosphogypsum and in the Chiyoda 121 tests. This waste material is reported to demonstrate relatively strong cementation, which improves with age and is said to provide safety against deep shear failure of the subgrade soils (11).

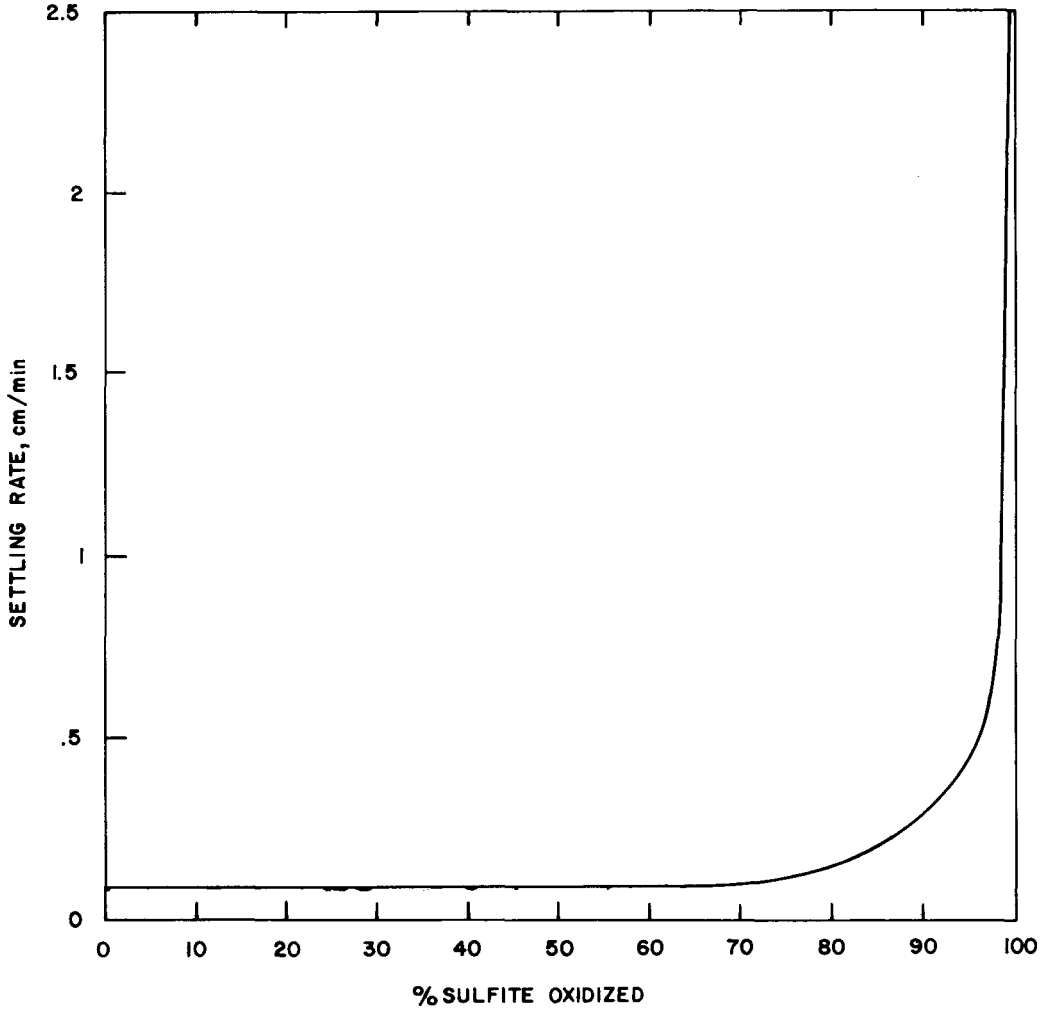


Figure 10-9. Effect of Oxidation on Initial Settling Rate

Source: Fourth Progress Report: Forced Oxidation Test Results at the EPA Alkali Scrubbing Test Facility, EPA-625/2-78-018.

Environmental Considerations

Gypsum is a naturally occurring mineral which is widely distributed around the world. It is mined or quarried and is sometimes found as a loose earth called gypsite. It is also the white "sand" which comprises the White Sands National Monument in the State of New Mexico. As a natural material, it appears acceptable for landfill disposal. It has a higher solubility than either the sulfite or carbonate form, and for that reason it is advisable to avoid surface washing by means of diversion ditches and by covering with soil and vegetating. Permeability of the "cemented" phosphogypsum pile described above was reported as about 8×10^{-4} cm/sec.

A concern in the disposal of scrubber sludge has been the chemical oxygen demand of calcium sulfite as being deleterious to ground and surface water. By oxidizing this component of the sludge to sulfate, the concern over deoxygenation of water is eliminated.

Landfilled phosphogypsum is subject to dusting in traffic areas. However, when undisturbed, it develops a crust which is resistant to both wind and water erosion. Results representative of scrubber gypsum have been reported in the gypsum stacking tests conducted under EPRI sponsorship at Scholz Plant and in the Shawnee tests (5).

Product Utilization

The gypsum product from SO_2 throwaway-type scrubbing appears to have more potential for utilization than any other by-product. This is more thoroughly discussed in Section 15 - UTILIZATION. Briefly, trial runs with FGD sypsum have resulted in the production of acceptable wallboard and the successful use as a soil amendment in the growing of peanuts. Because of possible greater utilization in the future, consideration should be given to the stockpiling of flyash-free gypsum in planning for future scrubber installations.

DISADVANTAGES

The primary disadvantage appears to be that of lack of full-scale experience in the U.S. As noted previously, there are only three scrubbers currently equipped for forced oxidation in this country: SherCo Nos. 1 and 2, and Lawrence No. 4. However, Table 2-2 shows that it is planned for use on an additional eight scrubbers. There have been no unfavorable reports on the in-service systems, and a good sludge product appears to be produced.

High total dissolved solids in leachate or run-off from gypsum disposal areas may present a problem. However, good area design and management should minimize this. The advantages of gypsum as a structurally-stable waste or as a by-product that has potential for utilization may outweigh the disadvantages.

COSTS

In considering the incremental costs involved with the forced-oxidation option, care must be taken to be assured that system comparisons involve the same battery limits. For example, some estimates have included certain equipment in the oxidation system, while other estimates include the same equipment in the disposal cost. For example, air compressors in some cases are charged to the scrubber system, while in others they are considered part of the disposal system. Other factors that should be considered in evaluating costs include:

- Sulfur content of the coal and the efficiency of SO_2 removal--affect the number and capacity of air compressors required.
- Location and type of oxidizing vessel--oxidation in a separate vessel rather than in the scrubber or hold tank would increase the cost.
- Oxidation of a bleed stream or of the entire scrubber stream--affects the size of compressors, oxidation tank and pumps.
- Efficiency of oxidation--affects the compressor capacity required.
- Improved characteristics of gypsum for water removal--dewatering costs should be reduced; the use of thickeners may be unnecessary or the size could be reduced or ponding could be used. In Japan, the gypsum slurry is sent directly to centrifuges.
- Credit for gypsum sales--if a market can be developed, the proceeds would offset some of the disposal costs.
- Eliminate the need for fixation--the nature of the by-product gypsum may be satisfactory for disposal without chemical treatment.
- Solubility of gypsum--this may act to increase disposal costs by necessitating both water exclusion/diversion facilities as well as protection against leaching.

An Aerospace report estimates the incremental capital cost of providing forced oxidation for new units of 500 and 1000 MW capacity. Burning coal with 3.5% sulfur, the incremental cost for the 1000 MW unit was $10,090,000, for the 500 MW unit, $6,640,000 (11). The major equipment included air compressors, oxidation tanks and vacuum filters. It was assumed that there were upstream electrostatic precipitators and that thickening equipment had been installed.

In regard to operating costs, TVA reports state that landfill disposal of sludge in the gypsum form has the lowest annual revenue requirement of any of the options considered. The processing options included: untreated, Dravo, IUCS, Chemfix, untreated sludge-flyash blending and gypsum (4,13,14). The data show the incremental increase in revenue requirements when considering the upgrading of pond disposal to landfill with these alternatives:

- Commercial fixation with additives--0.6 to 1.1 mill/kWh.
- Blending sulfite sludge with flyash--0.7 mill/kWh
- Forced oxidation--0.2 mill/kWh

Note that all of these are incremental costs over ponding. Forced oxidation is clearly the winner in this evaluation.

Additional data, Tables 10-1 and 10-2, show the capital cost of disposal systems and the annual revenue requirements for various processing options at a typical plant. These data show that, for the options considered, the gypsum process--forced oxidation--is lowest in capital investment requirements for disposal only, being 45% that of ponding and 72% of the nearest competitor--IUCS--on a $/kW basis. When considering annual revenue requirements for disposal only on a mills/kWh basis, it once again is lower than all but untreated ponding. It is 125% that of ponding and 78% that of the IUCS process. In considering capital costs of scrubbers and disposal, the gypsum process is 82% that of ponding and 94% that of the IUCS system. Looking at annual revenue requirements, the gypsum process is 106% as much as ponding and 93% as much as the IUCS process.

SUMMARY

The use of forced oxidation to convert calcium sulfite to the sulfate appears to be a growing trend for the reasons which have been discussed and are listed in the following:

- A more easily disposable end-product results.
- Less disposal space is required.
- The cheaper, more easily available limestone reagent can be used.
- Excellent utilization of the reagent has been shown in tests.
- Better water balance results from the water separation characteristics of the gypsum.
- Utilization potential for the gypsum is favorable.
- The in-service systems in Japan have been very satisfactory.
- The in-service systems in the U.S. have given satisfactory results.

- Landfill disposal should be acceptable.
- Conceptual operating economics favor forced oxidation over the unoxidized processes.
- With better dewatering and decreased quantity of water in the disposed gypsum, higher total dissolved solids will be found in the scrubber liquor.

Table 10-1

CAPITAL INVESTMENT FOR BASE-CASE WASTE DISPOSAL PROCESSES

Process	Disposal Only $/kW	Scrubbers and Disposal[a] $/kW
Gypsum	15.4[b]	88.2
IUCS	21.4	94.2
Dravo Landfill	25.3	98.1
Chemfix	27.1	99.7
Untreated Ponding	34.4	107.2
Sludge - Flyash Blending	36.4[c]	109.2
Dravo Ponding	48.2	121.0

Basis: New 500-MW midwestern plant; 3.5% sulfur, 16% ash in coal removed to NSPS; one mile to disposal site. Costs scaled to mid-1979.

a. Basic limestone scrubber cost is $36,368,000 (72.7 $/kW).
b. Air oxidation cost of $2,303,000 (4.6 $/kW) included.
c. ESP cost of $9,614,000 (19.2 $/kW) included.

Table 10-2

ANNUAL REVENUE REQUIREMENTS FOR BASE-CASE WASTE DISPOSAL PROCESSES

Process	Disposal Only mills/kWh	Scrubbers and Disposal[a] mills/kWh
Untreated Ponding	0.94	4.32
Gypsum	1.18[b]	4.56
IUCS	1.51	4.90
Sludge - Flyash Blending	1.64[c]	5.02
Dravo Landfill	1.89	5.27
Dravo Ponding	1.91	5.30
Chemfix	2.00	5.38

Basis: New midwestern 500-MW plant; 3.5% sulfur, 16% ash in coal removed to NSPS; one mile to disposal site. Costs scaled to mid-1980.

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes, February, 1979, EPA-600/7-79-069.

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Section 11

THICKENING/DEWATERING

PURPOSE

This section provides descriptive and design information relating to primary and secondary dewatering processes applicable in FGD sludge disposal systems.

FUNDAMENTALS

The main purposes of dewatering are:

- To reduce the volume of sludge for transport and disposal, thereby reducing transport costs, land area requirements, land acquisition costs, and disposal cost.
- To reduce the moisture content so the waste can be handled and disposed of dry.
- To recover sludge for utilization and/or liquid for further use.

In addition to above purposes, depending on the sludge characteristics, the thickening/dewatering may also be beneficial to sludge blending, sludge flow equalization, sludge storage, and the reduction of chemical requirements for sludge conditioning.

Figure 11-1 shows the effect of dewatering on the total disposal volume. As the water is taken out and the solids content increased, the volume for disposal is substantially reduced. It is evident, therefore, that transport and disposal costs can be reduced by reducing the volume of water carried to the disposal site.

On the other hand, the size and cost of dewatering equipment increases as the level of dewatering increases. As a result, there is an economic trade-off between the disposal cost and increasing the dewatering cost. Similar trade-off situations also exist for other purposes of sludge thickening and dewatering. For any given situation, an optimum (lowest cost) system can be determined through an evaluation of appropriate alternatives. Section 9 - PROCESSING ALTERNATIVES shows examples of some of the computations necessary to determine what level of processing is required to achieve the necessary sludge volume reduction.

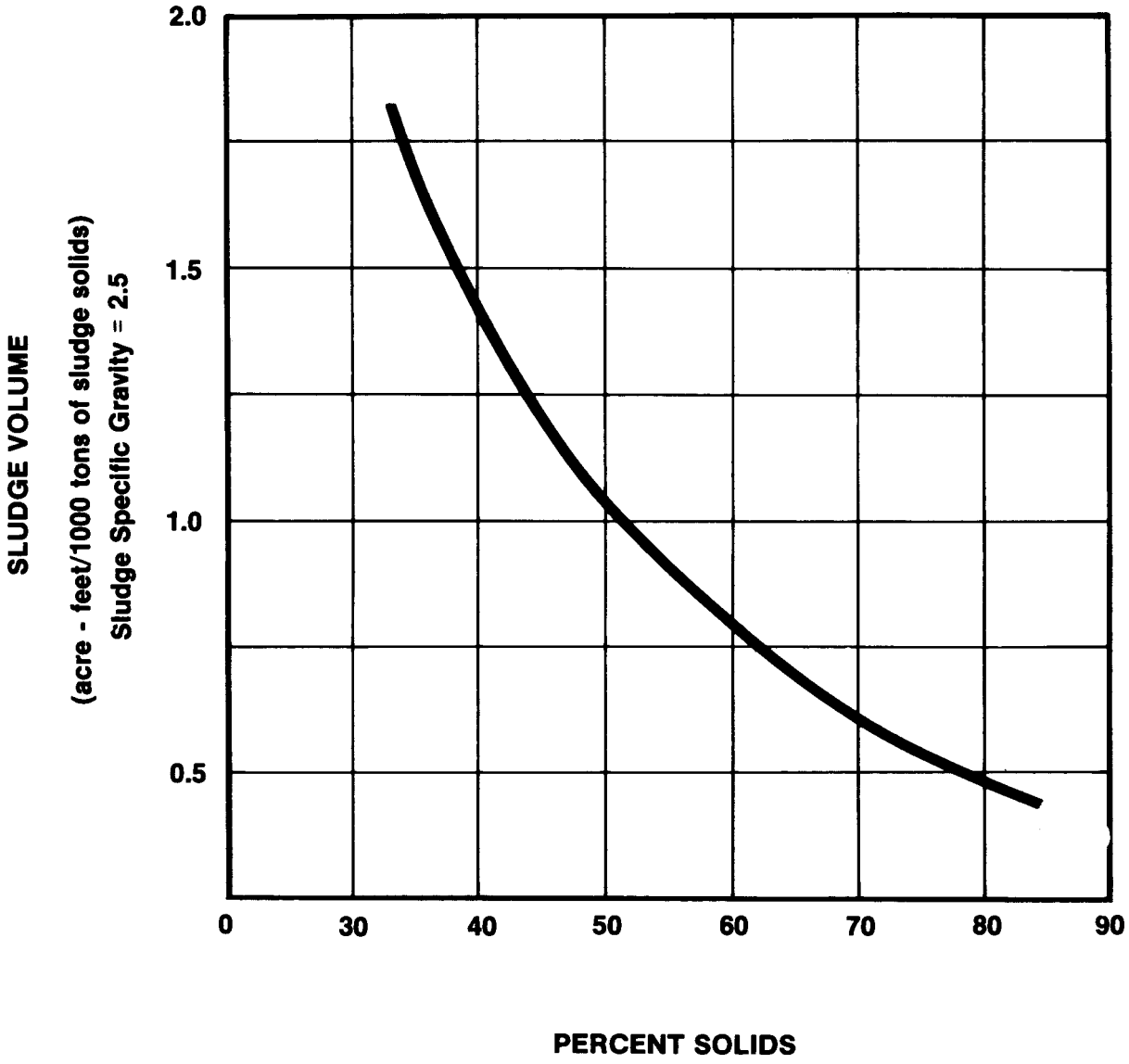


Figure 11-1. Relationship Between Sludge Volume and Solids Content.

The FGD sludge processing activities may be classified into groups: primary dewatering and secondary dewatering. The primary dewatering process uses scrubber bleed as input and performs liquid-solid separation as an initial step and usually attains sludge solid concentration within the range of 40 to 50 percent. The secondary dewatering process is capable of dewatering sludge up to a solids concentration of 65 to 85 percent. There are exceptions to the above classification. For example, some processes such as centrifugation have been claimed to be capable of processing direct scrubber bleed to attain a solids content in sludge of higher than 50 percent (1). In other words, this equipment performs both primary and secondary dewatering in one step and in one unit. Figure 11-2 contains a flowsheet showing the various methods involved in the sludge thickening and dewatering processes.

Hence, thickening/dewatering can be accomplished by any one or combination of the following processes:

- Settling ponds
- Gravity Thickeners
- Vacuum Filters
- Centrifuges

Table 11-1 summarizes the various dewatering practices for operating utility scrubbers.

Table 11-1

SUMMARY OF FGD SLUDGE-DEWATERING PRACTICES

	NO. OF PLANTS/TOTAL CAPACITY, MW				
	SO_2 REMOVAL		SO_2 AND FLYASH REMOVAL		FLYASH REMOVAL
	LOW S COAL	HIGH S COAL	LOW S COAL	HIGH S COAL	LOW S COAL
Pond Settling	3/1570	1/550	2/1085	2/885	7/1220
Thickening	2/365	3/185	3/2185	1/1650	3/865
Thickening and Pond Settling	-	-	-	-	2/1175
Thickening and Filtration	3/1045	6/2515	-	-	-
Thickening and Centrifugation	1/1585	-	-	-	-

Source: Midkiff, L., "Disposing of Flue-Gas Cleaning Wastes," Power, Sept., 1979.

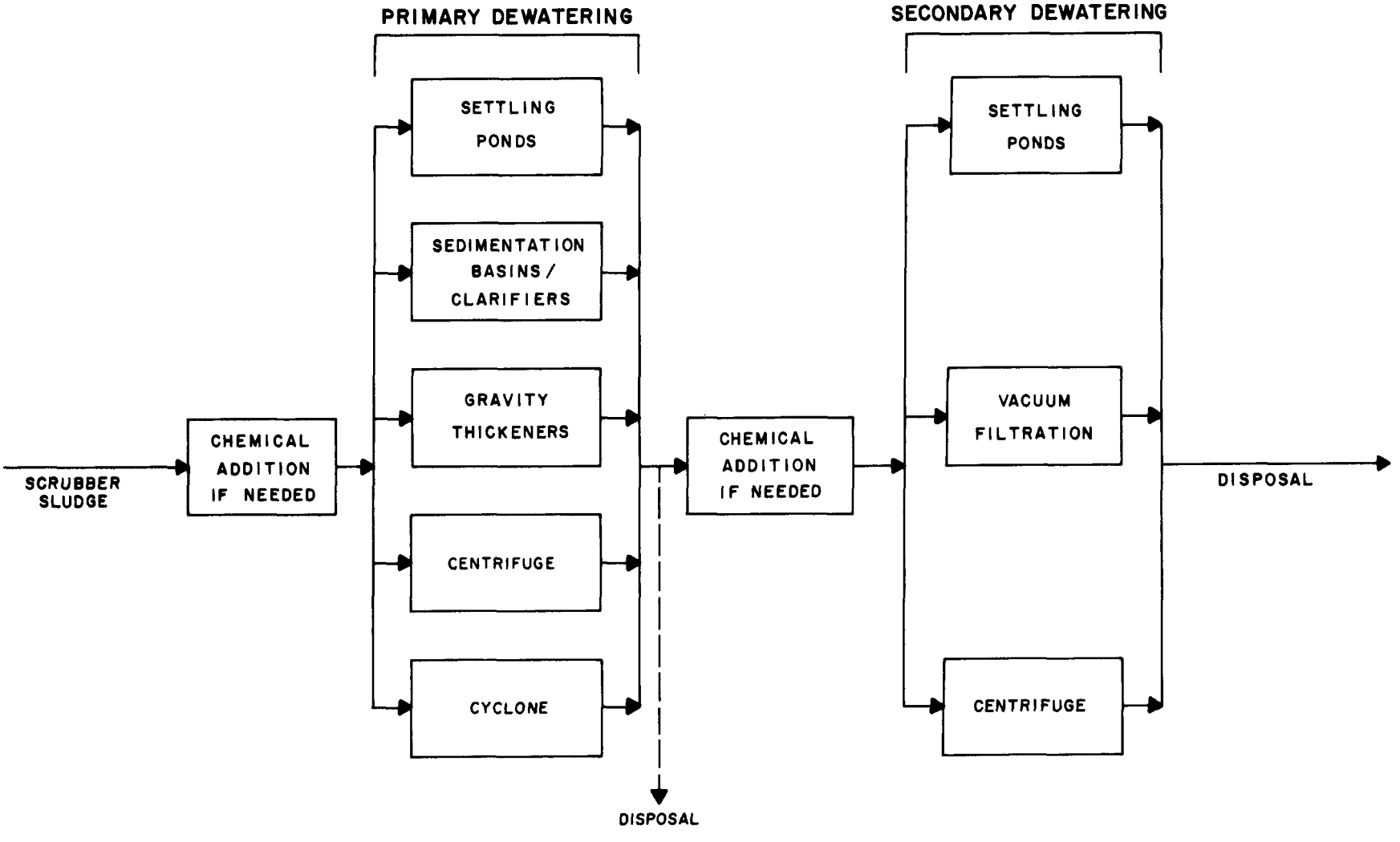


Figure 11-2: Sludge Processing Flow Sheet.

The choice among these methods depends on the characteristics of the sludge, the method of disposal, the availability of land, and the economics involved. Table 11-2 shows the level of solids concentration which can be achieved by each of these processes.

Table 11-2

TYPICAL SOLIDS CONCENTRATIONS OF FGD SLUDGES

	LIME TREATED SLUDGE	LIMESTONE TREATED SLUDGE	DUAL-ALKALI SYSTEM SLUDGE
Scrubber Bleed	5 to 15%	5 to 15%	5 to 15%
Settled Sludge (thickeners or settling ponds)	40 to 53%	47 to 67%	37 to 44%
Vacuum Filtration	56 to 57%	53 to 80%	55 to 58%
Centrifuge	34 to 62%	60 to 77%	50 to 62%

Because of their inherent simplicity, thickeners and/or settling ponds are almost always justified and, hence, are used nearly universally on the scrubber bleed to concentrate the scrubber solids. This primary dewatering can increase the scrubber bleed (5 to 15% solids) to about 40 to 53% solids (gypsum sludges will settle to 60 to 67% solids). Although possibly more expensive, thickeners are usually preferred to settling ponds because of increased ease and flexibility in solids removal, flexibility in location, and smaller space requirements. An EPA Manual on the treatment and disposal of sludge from wastewaters provides a good reference for mechanical dewatering equipment (5).

Where used, vacuum filtration or centrifuging follows thickening or settling ponds to effect an additional increase in solids content. Vacuum filtration or centrifugation can increase the solids content of sulfite sludges to 50 to 60% solids. If sulfate is predominant in the sludge, the solids content increases to 80 to 85% solids.

Dewatering facilities should be placed as close as possible to the scrubber facilities. This will reduce the length of large-diameter piping required to convey scrubber bleed to the dewatering facility and to return that portion of the liquid fraction which is removed. Placing a settling pond close to the scrubber may not be possible because of the relatively large commitment of land required for a pond.

Dewatering facilities may be installed singly, in parallel, or in series, depending upon the degree of treatment required. Mechanical equipment should be sized to allow sufficient storage or sufficient surge capacity should be provided to permit flexible operation. Sufficient equipment should be provided to assure uninterrupted operation of the scrubber during either planned or unscheduled downtime due to process or equipment failure in the sludge processing system. Usually this means providing redundant equipment, utilizing oversized equipment, or installing a by-pass with emergency storage facilities.

SETTLING PONDS

Settling ponds are usually flat-bottomed impoundments created by constructing an earth-fill dike or excavation in a rectangular configuration. Figure 11-3 shows a typical installation. Where topography permits, construction may be simplified by building a dam across a natural valley. In either case, the functional aspects of the facilities are identical. Scrubber bleed is introduced at one end of the pond. As it flows the length of the impoundment at extremely slow velocities, gravity acts to separate the settleable solids from the liquid fraction. At the opposite end, the supernatant is drawn off and returned to the scrubber.

Ponds can be emptied of sludge by using a floating dredge or similar device to reslurry the concentrated solids and pump them to a final disposal area. Alternatively, two or more ponds can be used. While one is in service, the other can be drained and the sludge excavated by a front-end loader or clamshell bucket for further processing and disposal. This latter method is operation-intensive and is usually the more costly of the two methods.

Interim ponding for sludge (in some cases with flyash) dewatering is currently used by at least six full-scale operating stations. It has proven to effectively dewater all sludges that may normally be expected from lime/limestone FGD scrubbing systems, concentrating the solids up to a maximum of about 50% solids. Dewatering ponds are advantageous because they are less sensitive than thickeners to variations in scrubber bleed flow and solids content, and are relatively inexpensive to maintain. Ordinarily, they do not have to be taken out of service for periodic maintenance.



Figure 11-3. Removing Settled Sludge from Settling Pond - Will County Station - Commonwealth Edison Company.

In terms of disadvantages, ponds require a substantial commitment of land; they are usually closely scrutinized by regulatory agencies; they are generally unpopular with environmentalists; and it is often difficult, time consuming and expensive to remove sludge.

For a detailed discussion on pond design, see Section 8 - DESIGN OF DISPOSAL AREAS.

Thickening and ponding are both types of sedimentation, which is a process of solid-liquid separation which separates solids from liquid under the effect of gravity. The difference in the densities of liquid and solid causes the denser material (solids) to settle and occupy the lower space of the container.

Nearly all commercial equipment is built for continuous sedimentation in relatively simple settling tanks. A distinction is commonly made depending on the purpose of separation. If the clarity of the overflow is of primary importance, the process is called clarifying. If thick underflow is the aim, the process is called thickening. The feed slurry in the latter process is more concentrated.

A detailed presentation of the sedimentation or the clarification process is outside the scope of this section. However, in many processes such as the conventional gravity thickener and the lamina-type clarifier, the clarification and thickening take place in the same vessel.

LAMINA-TYPE CLARIFIER/THICKENER

Description

In lamina-type clarifiers, the inclined plates or tubes are used to increase the settling surface area. The settling volume is divided into many shallow chambers. A typical inclined plate clarifier appears in Figure 11-4.

In the unit, the wastewater flows up through the spaces in between parallel inclined plates. The plates provide surface area for gravity settling. The flow is directed against the bottom of the plates and the coalescing solids slide down into the sludge thickening chamber. A rake in the collection chamber collects the sludge which is pumped off as required.

Design

The use of inclined plates and tubes increases the necessary surface area for solids settling. The plates also serve as contact surfaces for separation of moving

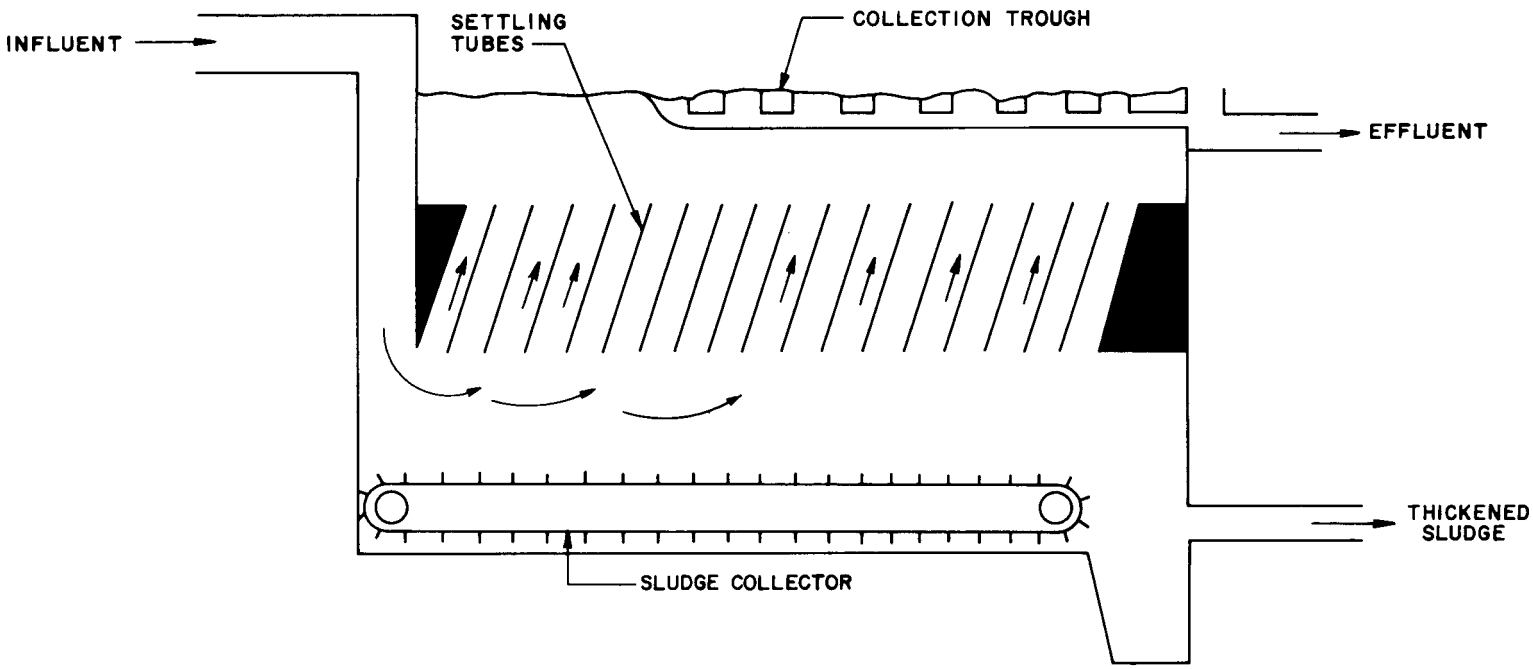


Figure 11-4. Lamella Clarifier/Thickner

particles suspended in liquid. The intent is to minimize the conventional clarifier area and at the same time to provide efficient separation of solid and liquid. Recently various manufacturers are marketing proprietary processes with varying efficiencies in solid recovery and thickening. Many compact units are available within the capacity range of 10 to 1000 gpm (6,7).

The use of the process on FGD slurry is still in the introductory stage. Where tubes are used, they are square in cross-section and sloped at a 60-degree angle (8). Tarrer, et al. studied various design and operational variables which affect the dewatering efficiency of a lamina-type clarifier/thickener (9). FGD scrubber slurry was utilized in the study. The results indicated that the dewatering efficiency of the lamina-type clarifier depends on the angle of inclination of the tubes or plates, the location of the feed port, the feed concentration and the rate of solid feeding into the clarifier. The highlights of the results were:

1. Locating the feed port near the top rather than the bottom of the clarifier significantly improves the process performance.
2. Feed solid concentration and solid loading rate were observed to be two important operational variables. For steady operation and clear overflow, the underflow rate has to be increased or decreased with changes in the amount of solids fed into the thickener.
3. Underflow concentration is very sensitive to the underflow rate or thickener solid retention time.
4. The efficient angle of plate inclination was found to be 30-degrees.
5. Solid separation efficiency increased almost linearly with increase of settling area. In other words, the increase in tube or plate length or an increase in number improves the solid separation efficiency. However, it does not affect the underflow concentration to any great extent.
6. The results indicated that FGD slurry can be thickened to a concentration of 25% solids by using a lamina-type clarifier.
7. The achieved efficiency indicated the lamina-type clarifier may be a good pre-thickening process.

THICKENERS

Description

A conventional gravity thickener is shown in Figures 11-5 and 11-6. The unit operates very much like a settling tank; the feed solids entering in the center are distributed radially, and the sludge solids are collected as underflow in a sludge sump. The effluent exits the top over weirs.

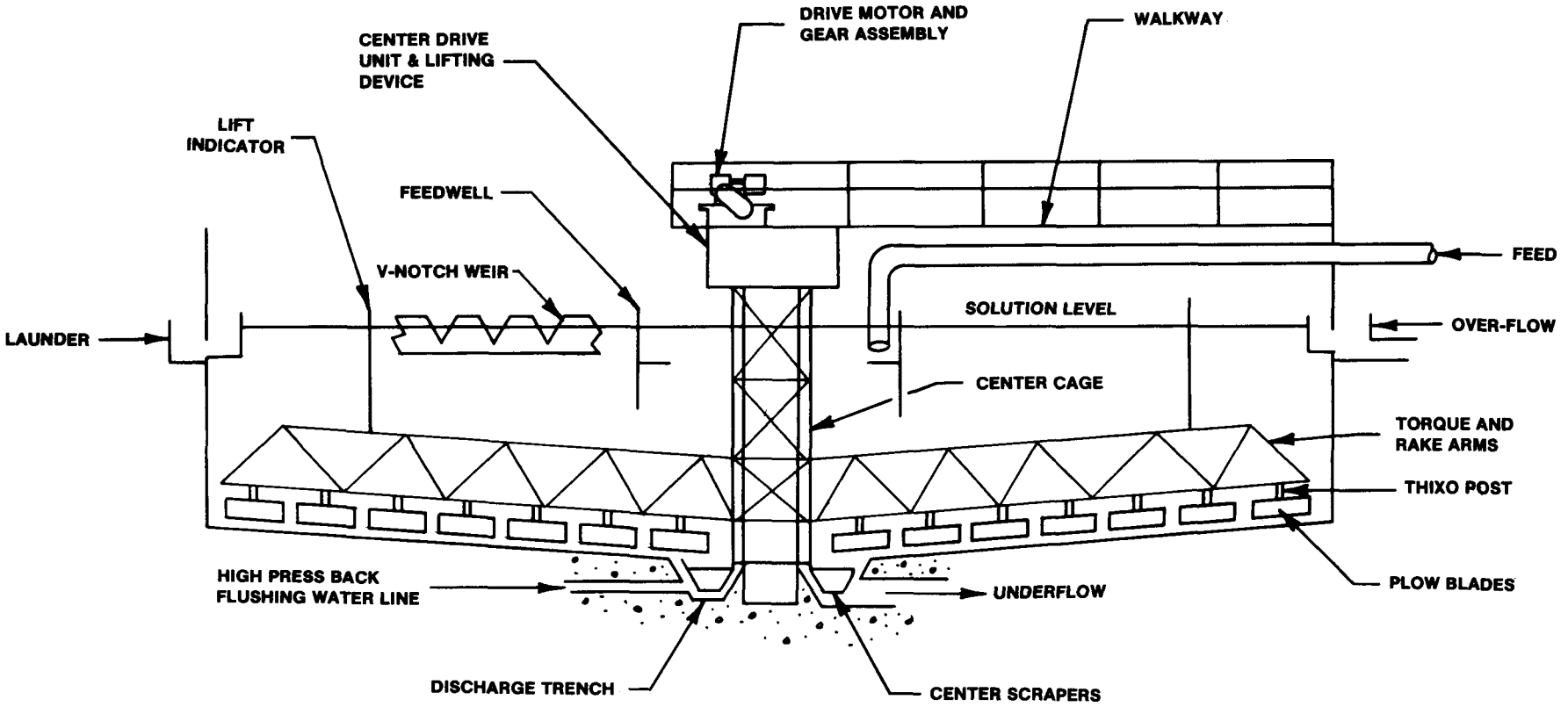


Figure 11-5. Cross-Section of a Conventional Gravity Thickener.

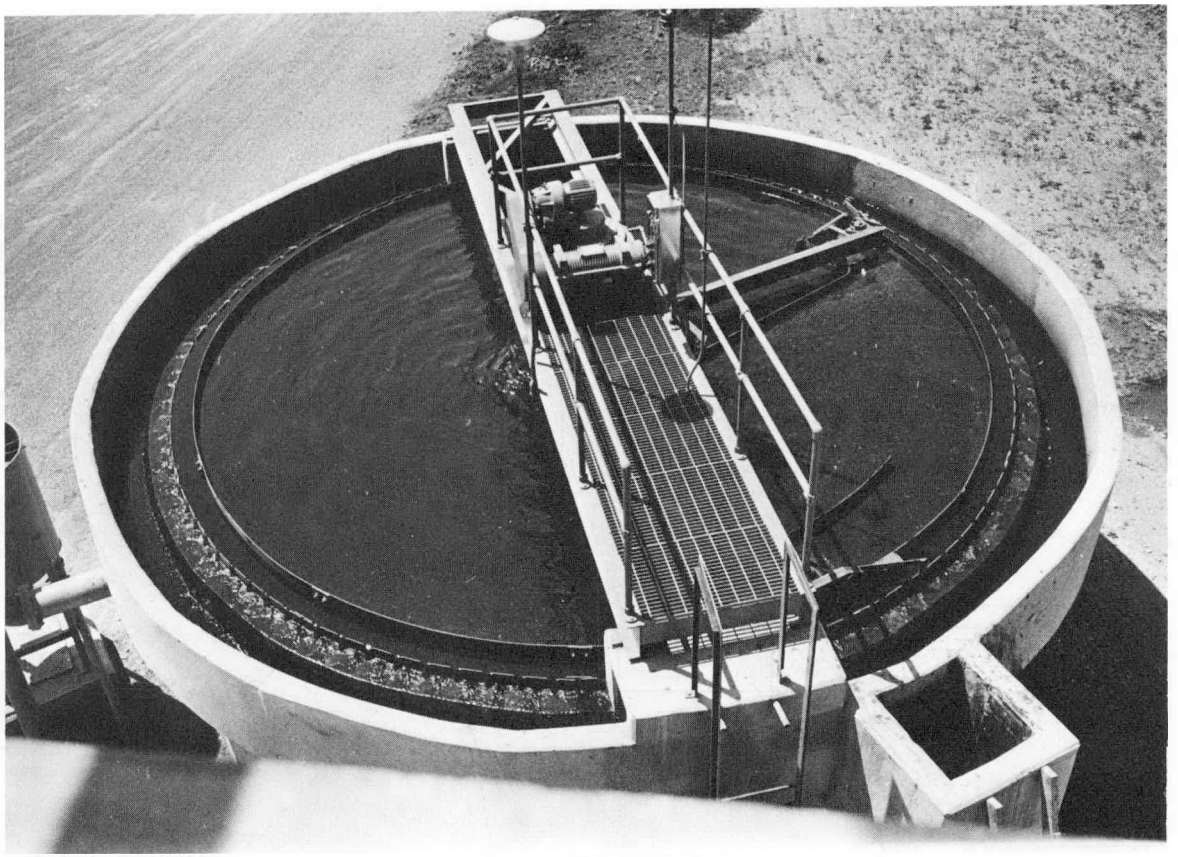


Figure 11-6. Typical Gravity Thickener.

Courtesy: Dorr-Oliver, Inc.

The concentration of solids with a continuously-operated thickener is shown in Figure 11-7. There are three very distinct zones in such a thickener. The clear zone on top is composed of liquid that eventually becomes the effluent escaping over the weirs. This liquid has a very low solids concentration. The next zone is called the feed zone, although it is not necessarily at the same concentration as the feed solids. It is characterized by a uniform solids concentration. Below the feed zone is the compaction zone, characterized by an increasing solids concentration to the point of discharge (10).

A typical thickener consists of a large holding tank with a central vertical shaft. The shaft is supported either by a center column or by a bridge. Two long, radial rake arms, with the option of two short ones, extend from the lower end of the vertical shaft. Plow blades are mounted on the arms at an oblique angle and have a clearance of 1.5 to 3 in. from the bottom of the tank. They can be arranged so that the bottom is swept either once or twice during each revolution. The bottom of the tank is usually constructed to a slope of 1.75:12 from the center. The settled sludge forms a blanket on the bottom of the thickener tank and is pushed gently toward the central discharge outlet. Center scrapers clear the discharge trench and move the solid deposits toward the underflow discharge point.

In normal operations, scrubber slurry is fed through the feedwell into the thickener at a concentration of 5 to 15% solids and at a maximum rate of 1000 gal/min. The sludge is discharged as underflow at a concentration of 20 to 45% solids. Thickener underflow concentration for typical full scale thickeners generally ranges from 20 to 40% solids for lime scrubbing sludges and from 25 to 45% solids for a limestone scrubbing system (3). If sulfate is the predominant species, underflow concentration may reach as high as 65% solids (11). The addition of polymer is reported to be very effective in reducing the unit area of a conventional thickener used for FGD sludges (3). Anionic polymers are usually most effective and are applied at a dosage of 0.001 to 0.03 pounds per ton of dry solids.

Major Components

A thickener consists of several major components, not all of which are supplied by thickener vendors. Components that can be purchased from vendors include the center drive unit, torque control and alarm system, rake arm mechanism, lifting device, lift indicator, feedwell and internal piping, anchorage ring or bottom flange for structures with center-column support, and the walkway. Vendors can provide design specifications; however, they usually prefer not to design or supply the tank, nor do they

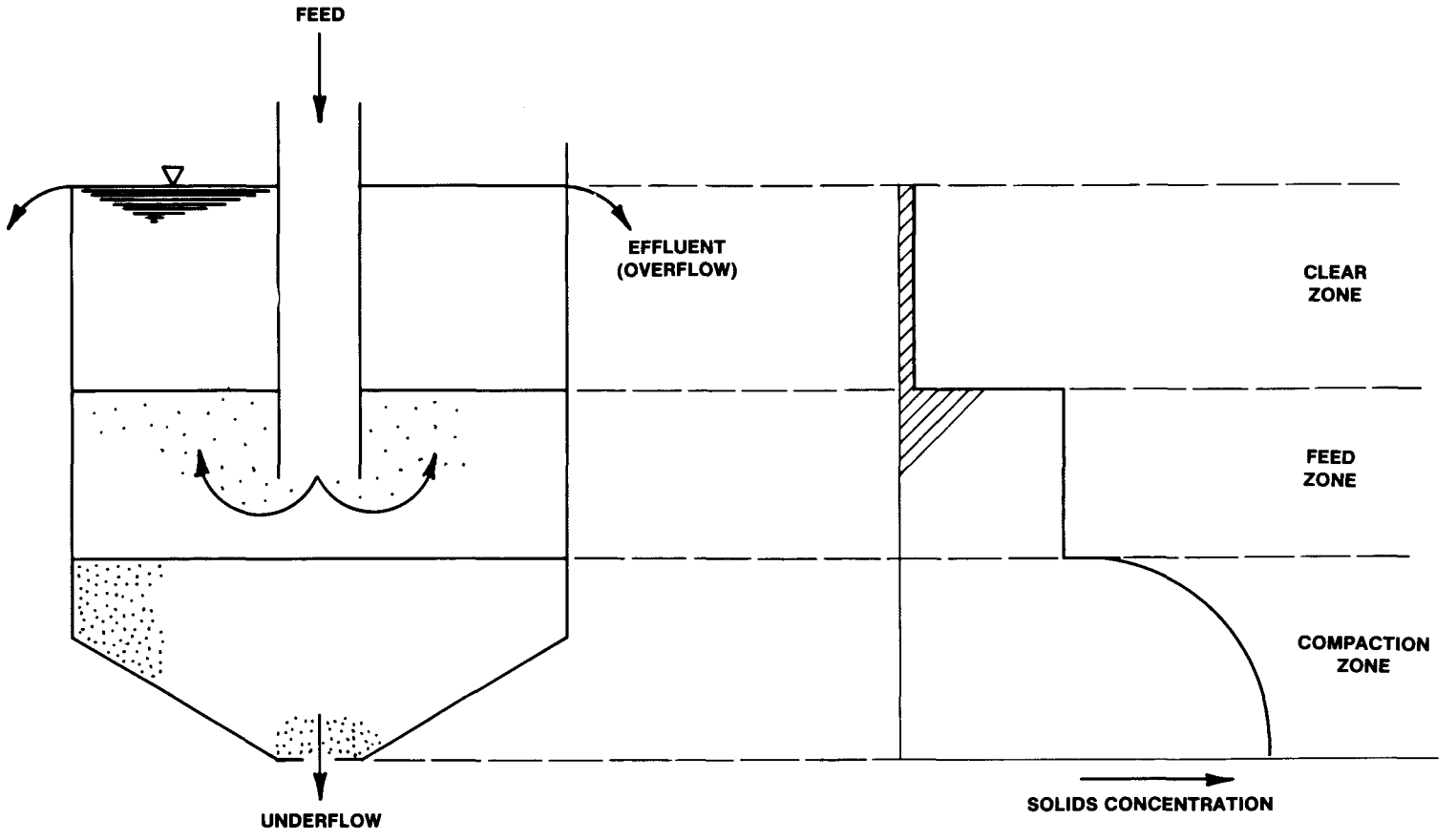


Figure 11-7. Thickener Flow Pattern and Concentration Zones.

provide items such as external piping, the electrical conduit and wiring, weirs, baffles, and overflow launders. Design considerations for components and associated auxiliary equipment are as follows:

Center Drive Unit. The center drive unit is the workhorse of the rotating rake arm mechanism. Choosing the right one from several available designs depends on the size of the thickener and the torque requirements of the thickened solids. The center drive unit consists of a primary worm gear motor, an intermediate worm gear reduction box with torque control and alarm system, and a main spur gear.

When the rake arms travel through the sludge, it resists the movement and the torque is transferred to the center drive unit. The normal design torque requirement of a thickener is empirically expressed as:

$$\tau = KD^2 \qquad (1)$$

where: τ is the torque in ft-lb,
D is the diameter of the thickener in ft, and
K is a constant.

In most FGD scrubber sludge disposal systems, K should be selected in the range from 15 to 20 ft-lb/ft^2. When ordering a center drive unit, the design engineer should specify momentary peak torque of the drive gear in addition to design torque of the complete mechanisms. Peak torque of the drive gear is generally four times the design torque of the mechanism to ensure that the drive gear is not damaged by sudden torque spikes. In any case, the peak torque should not approach the yield strength of the gear metal.

During the thickener operation, the settled solids may bed in around the rakes and cause excessive torque. A torque overload control is, therefore, an important auxiliary for the protection of the drive unit. Three types are available: hydraulic, electromechanical, and electrical (12). Each can be adjusted to sound an alarm and stop the equipment at a predetermined load limit. One or more torque control units can be used simultaneously and coupled with a visual torque readout.

Feedwell. The feedwell, a crucial component in the tank center, quiets the incoming flow before it enters the tank. Current designs dissipate high inlet velocity by creating small eddies and a radially uniform flow. In a well-designed feedwell, solids settle rapidly with minimal disturbance due to turbulence.

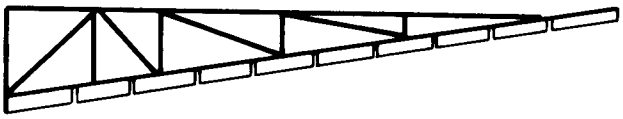
Rake Arm Mechanism. The main function of the rake arms is to move the settled solids to a central discharge point. Bridge-supported and column-supported designs generally employ two long arms with the option of two short ones, the latter added when necessary to rake the inner area.

Rake arms must be strong enough for the required torque, although their design also depends on the nature of the solids. They come in two main types: a truss-type and a rod-type. The truss-type arm is a conventional design (Figure 11-8a) that also acts as a torque arm. Its blades are bolted to the bottom chord of the truss structure. When sludges reach high density and high viscosity, the blades and the rake arm structure tend to form the sludge into an immobile "donut" or "island." Proper blade angles and extension of the blades below the raking arms by means of vertical posts, Thixo posts in Figure 11-8b, help eliminate this phenomenon by leaving fewer structural members to move through the sludge in the critical center area. In larger thickeners (300 to 400 ft diameter), the center depth would be excessive if a single slope were employed. The double sloping design, Figure 11-8c, eliminates this problem.

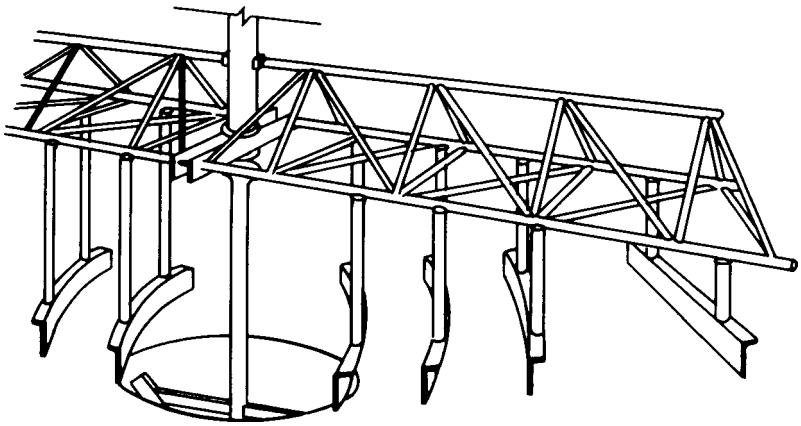
The rod-type of rake arm has a hinged design, as shown in Figure 11-9. The arm is simply a long pipe pivoted at the center column either by a single tilted pin (Swing Lift, EIMCO), or by two pins, one horizontal and one vertical (Cable Torq, Dorr-Oliver). The rake arms are suspended and dragged by cables from torque arms, which rotate 30° to 45° ahead of them. The interesting feature of this design is that the pivot pins allow the rake arms to swing over heavy deposits of coarse material. This design has further advantages over the truss-type in that it also offers lighter dead load, less drag, and less tendency for scale buildup in the rake arms.

The diameter of a lift-arm thickener is usually limited to 150 ft, since even a small lifting action near the center creates excessive swing at the tip of the rake arms. The lack of positive control of the lifting and lowering action is another problem with this design.

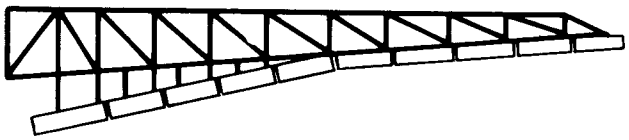
Lifting Device. Most thickeners are installed with some type of device for lifting the arm. This device permits continuous operation without excessive torque by lifting the rakes over coarse, settled solids and lowering them as these solids are removed. Hinged rake arm designs do not require a separate lifting device because of the unique design mentioned earlier. It should be noted, however, that this design does not have positive control of the lifting action.



a.) CONVENTIONAL DESIGN

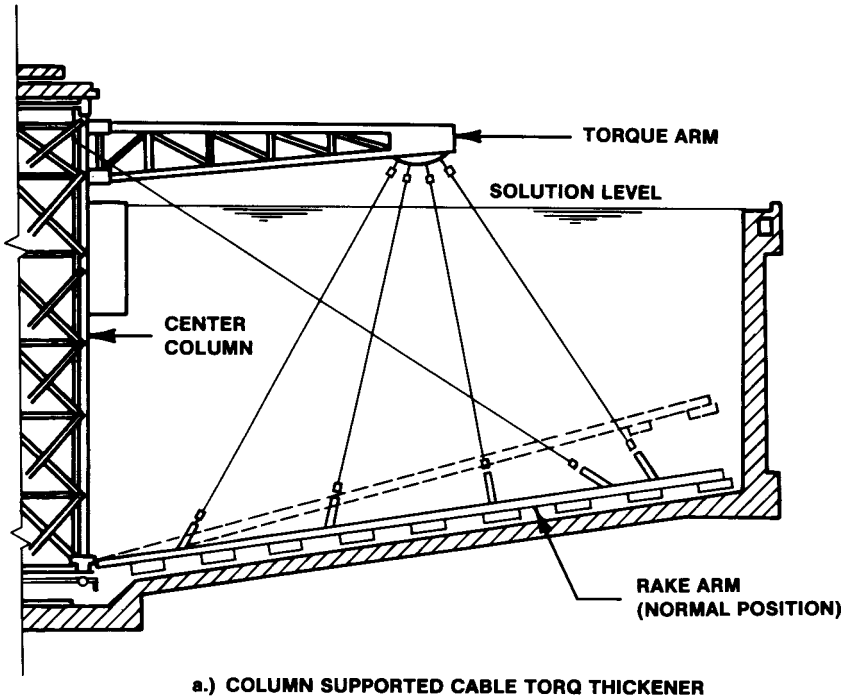


b.) THIXO POST DESIGN

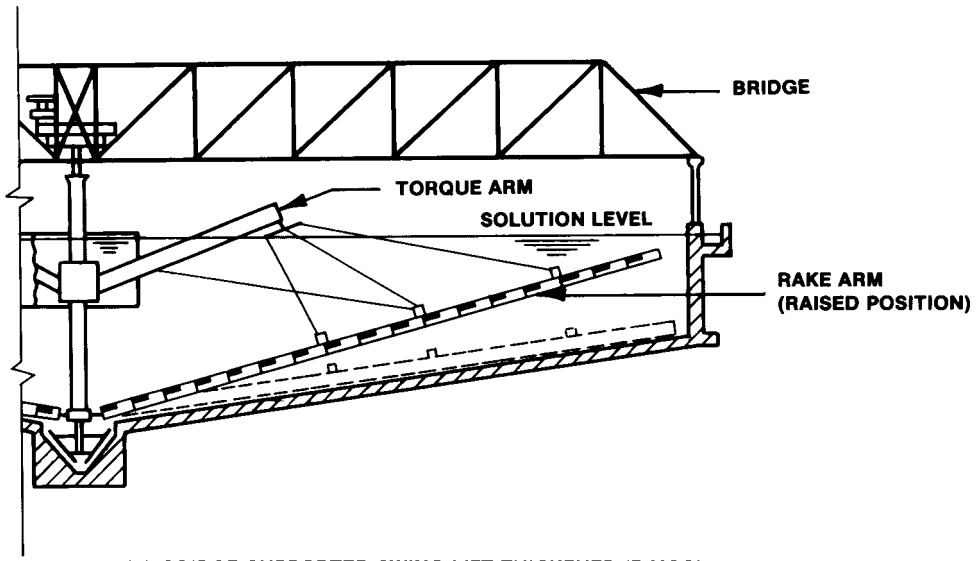


c.) DOUBLE SLOPE DESIGN

Figure 11-8. Thickener Plow Blade Designs.



a.) COLUMN SUPPORTED CABLE TORQ THICKENER
(DORR-OLIVER, INC.)



b.) BRIDGE-SUPPORTED SWING LIFT THICKENER (EIMCO)

Figure 11-9. Hinged Rake Arm Designs for Thickeners.

When more positive lift is desired, a standard lifting device (usually with a drive motor or hydraulic system) is employed. This type of lift can be activated by the torque encountered by the arms, either by means of an ammeter on the mechanism drive motor, or by a mechanical torque indicator. When excessive torque is experienced, the entire mechanism is raised evenly. Lifting devices have been employed with up to five feet of lift, although 1 to 2 ft is more common. Indicators show the degree of arm lifting. Some vendors also offer a lift height sensing device for remote indication of rake arm location.

Flow Arrangements.

Feed. Slurry suspensions are usually fed to the tank through a pipe under the walkway, Figure 11-5. In some designs, the influent pipe runs under the tank and the feed enters through the center column, Figure 11-10.

Overflow. Clarified effluent usually exits via a peripheral launder at the upper tank edge. V-notch overflow weirs help distribute the internal flow patterns evenly within the tank.

Underflow. Buried or inaccessible sludge lines incur the lowest installation cost of all underflow arrangements. Usually, several of these lines are installed (vendors recommend a minimum of two), with one kept as a spare in case of plugging. A high-pressure water or air line should be available to clear the plugging. One underflow design consists of a tunnel to allow complete accessibility to the discharge point, valves, and associated piping, as shown in Figure 11-10. Although the most costly approach, it handles the maximum underflow solids concentrations with minimum maintenance problems.

Center-column pumping lowers installation costs and can be used where ground conditions preclude a tunnel. Outlet pipes from the discharge trench end in one central vertical pipe, which passes up inside the center column, along the walkway, to a pump situated outside the tank perimeter. Another system utilizes a submersible pump near the bottom of the center column. With this arrangement, long suction lines are avoided, and underflow concentrations approaching that of the tunnel system can be handled. Although it is more expensive, the system will pump higher solids concentrations with less probability of plugging or loss of prime. In the column pumping operation, however, spare pumps and a pump hoist are recommended.

Thickener Area and Depth

The basis of gravity thickener design is to identify the concentration of sludge with the lowest capacity for transmitting solids under desired operating conditions

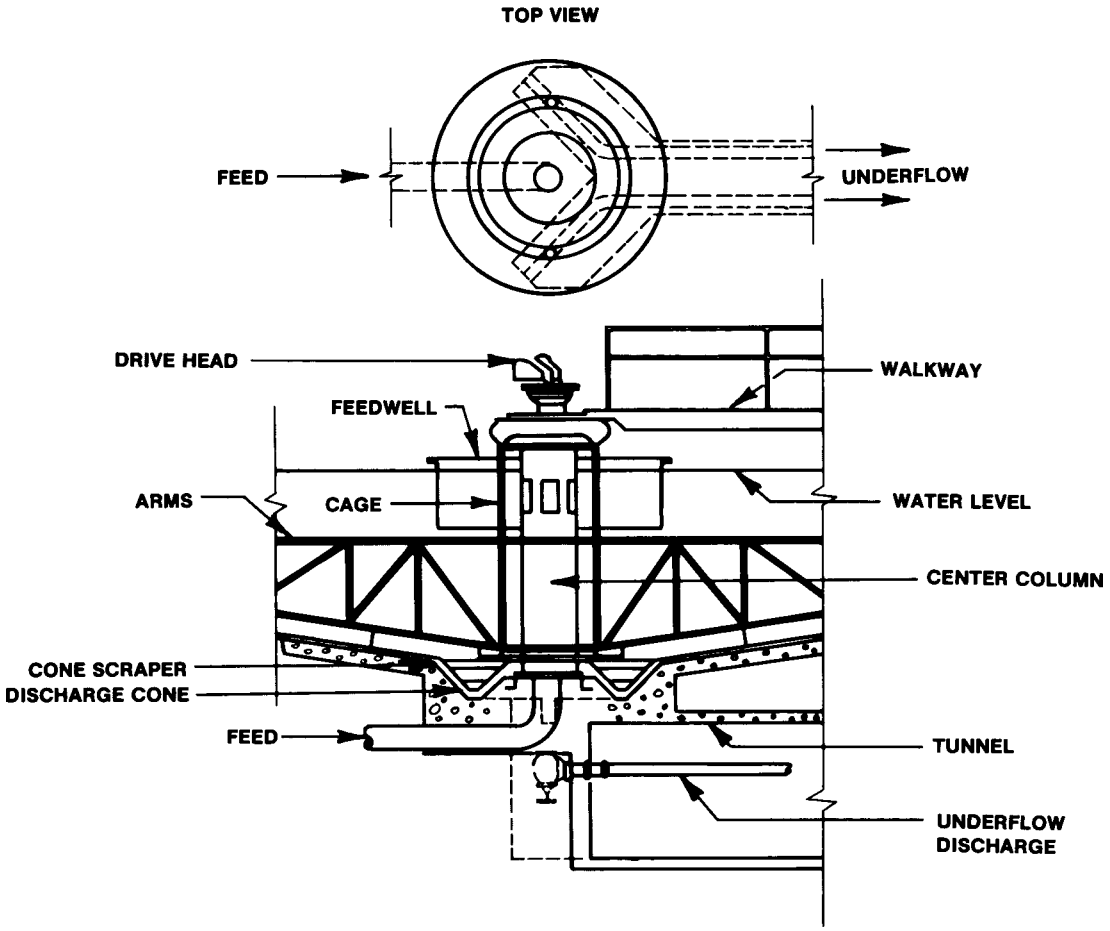


Figure 11-10. Thickener Cross-Section Showing Tunnel.

and to provide sufficient area that the rate of solids application per unit area per unit time does not exceed the capacity of the rate limiting solid layer. Hence, under the operating limitations, most efficient surface area and liquid depth need to be determined.

Thickener sizing is usually based on the mechanical compaction of solids without much concern for the clarity of the overflow. However, in many FGD systems, the sedimentation equipment is required to both thicken and clarify. This is often true when limestone is used as the scrubber absorbent. In this case, the sizing of the unit must be based on whichever process requirement -- clarification or thickening -- demands the greater area. The clarification of the liquid and consolidation of the solids proceed simultaneously but independently in the same tank. Both are dependent on tank surface area, but the clarification also depends on the tank depth. The following design aspects cover mainly the process of thickening. The designer should carefully incorporate clarification needs with the thickener design dimensions if a clarifier/thickener is the principal design intent.

The dimensioning of a thickener in the absence of representative slurry, is very often accomplished by using empirical relations and data based on operating experiences. When representative sludge is available, usually laboratory settling tests are performed to determine important solid settling and thickening characteristics. The observed characteristics are utilized to determine the area of the clarifier/thickener.

Empirical Method of Thickener Sizing. The criteria which are usually used to size a clarifier/thickener unit are solids loading and/or hydraulic surface loading. For thickener and clarifier/thickener, the solid loading factor is more important. Solids loading without polymer may range from 12 to 30 ft^2/ton/day for 25-35 percent solids in the underflow (11). For higher underflow solids concentration within the range of 35 to 45 percent solids, the solids loading without polymer ranges from 8 to 12 ft^2/ton/day. With polymers, the rates are reduced to 3.5 to 11 ft^2/ton/day and 1.7 to 4.5 ft^2/ton/day, respectively, for the two ranges of underflow solid concentrations.

Recommended surface loadings range from 300 to 4,000 gal/ft^2/day for granular solids; 800 to 2,000 gal/ft^2/day for slow-settling solids; and 1,000 to 2,000 gal/ft^2/day for

flocculated particles. The latter range is normal for thickeners utilized in FGD scrubber sludge dewatering.

Tank depth is determined from experience and the necessity for feedwell and raking mechanisms. The most common depths for thickeners of 50 to 100 ft diameter are from 8 to 14 feet (11).

Methods Utilizing Sludge Settling Characteristics.

Method A

In this procedure, a column is filled with a suspension of solids of uniform concentration C_o, to a height H_o. The position of the interface between the solid and clarified liquid is observed as time elapses. The data usually result in a relationship as shown in Figure 11-11. The rate at which the interface is subsiding at any time is then equal to the slope of the curve at that time. Such settling tests are also very important for evaluating the effects of various types and dosages of polymers as flocculation aids.

Two design procedures slightly different from each other utilize Figure 11-11 type curves to determine the thickener sizes.

Method A-1

This method is a direct calculation technique. First a point on the curve is selected considering the desired underflow concentration. The time value of the point is directly utilized in the following equation to determine the design unit area of the thickener.

$$A = \frac{t_u}{C_o H_o} \qquad (2)$$

Where: A = unit area, ft^2/TPD of dry solids

C_o = initial concentration, t dry solids/ft^3

H_o = initial height, ft

t_u = time, days required for the interface to reach the height, H_u under which the average concentration is the same as the desired underflow solids concentration, C_u.

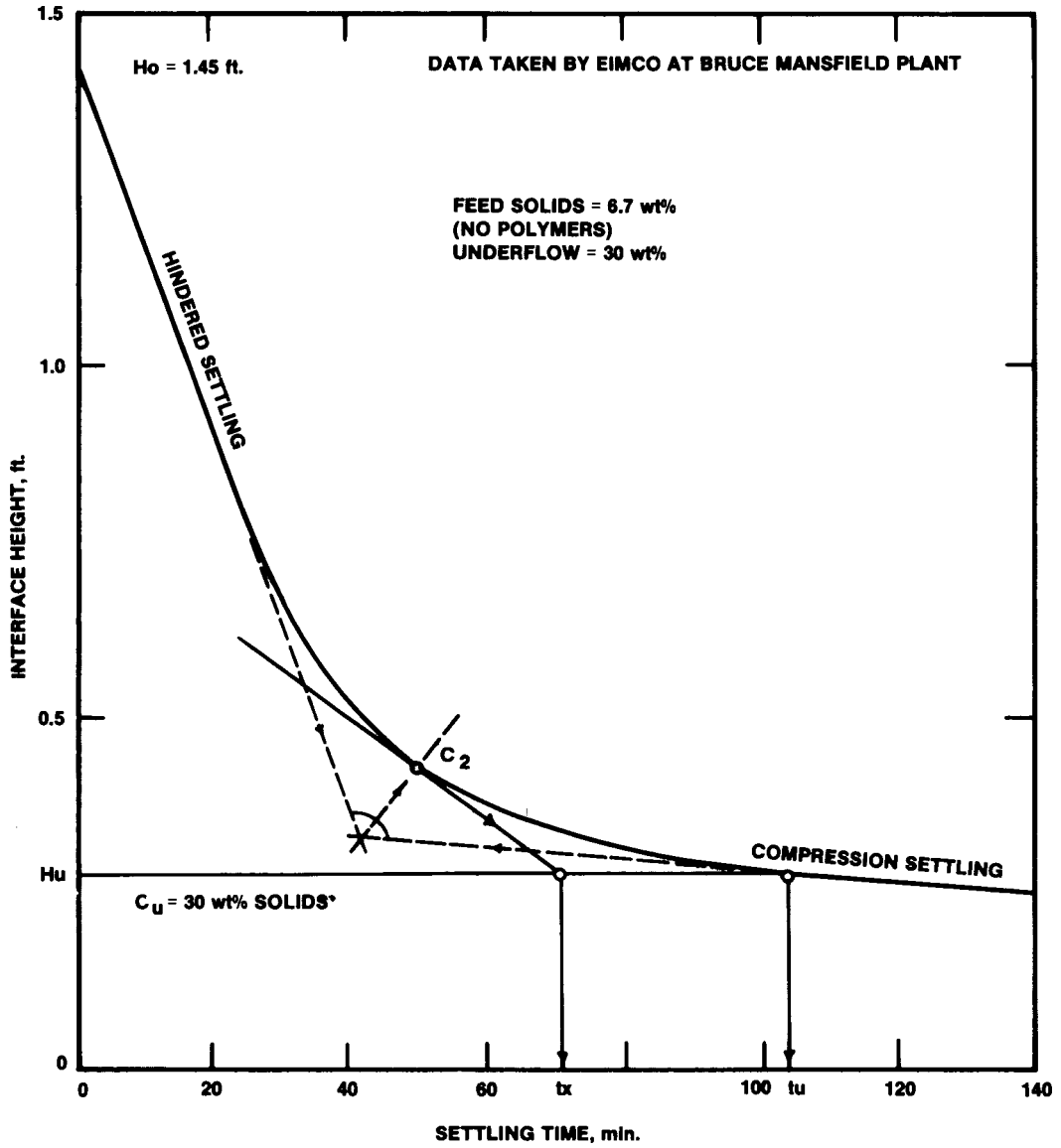


Figure 11-11. Results of a Thickener Settling Test.

Since: $H_u C_u = H_o C'_o$ (3)

t_u is obtained from the settling curve at $H=H_u$. When C is expressed in weight percent, Equation (3) becomes:

$$C'_o H_o \rho_o = C'_u H_u \rho_u \quad (4)$$

where C'_o and C'_u are the weight percent of the initial and underflow solids concentrations, and ρ_o and ρ_u are the specific gravity of feed and underflow respectively. Therefore, Equation (4) becomes:

$$H_u = \frac{C'_o H_o \rho_o}{C'_u \rho_u} \quad (5)$$

Figure 11-11 presents the result of a settling test made by EIMCO on a slurry sample from the Bruce Mansfield plant (3). For this sample,

H_u = 1.45 ft, ρ_o = 1.0386, ρ_u = 1.206, C_o = 6.7 wt %, and C_u = 30 wt %.

Therefore:

$$H_u = \frac{0.067 \times 1.45 \times 1.0386}{0.30 \times 1.206} = 0.2789 \text{ ft}$$

and

$$C_o = \frac{1.0386 \times 0.067 \times 62.4}{2000} = 0.002172 \text{ t/ft}^3$$

Since t_u is 104 min (or 0.0722 day), the thickener area from Equation (2) becomes:

$$A = \frac{t_u}{C_o H_o}$$

$$A = \frac{0.0722}{0.002172 \times 1.45} = 22.93 \text{ ft}^2/\text{t/day of dry solids}$$

The depth of a thickener is best determined from experience with similar units. The sources for this information are equipment vendors or engineering personnel with other utilities that have operating thickeners.

For clarification process, it has been found that solid removal is a function of time, and the following empirical relation exists (3):

$$C = kt^m \quad (6)$$

where:

C = Concentration of solids in supernatant at time t, mg/l.

t = time where t > 5 min, min.

k and m = empirical constants.

From laboratory test results, the relation is established by plotting C vs. t in a logarithmic scale. The relation is then utilized to determine solid retention time for a desired supernatant clarity. The retention time, hydraulic flow and area of the thickener determine the depth of the thickener:

$$D = t \times Q/A \tag{7}$$

Where:

D = depth of thickener, ft.

t = retention time, min.

Q = inflow, ft^3/min.

A = surface area, ft^2.

This depth, however, should be increased with provisions for thickening zone, solid storage and overboard of the thickener.

Method A-2

A variation of the above method has been modeled by Kynch (13) and modified by Talmadge and Fitch (14) for hindered settling condition. The thickener area is expressed as:

$$A_s = \frac{Qt_x}{H_o} \tag{8}$$

Where:

A_s = unit area, ft^2.

Q = hydraulic flow rate, ft^3/day

t_x = time in days required for the interface to reach the height, (H_u), under which the average concentration is the same as the desired underflow solids concentration, (C_u).

The main difference in the methods A-1 and A-2 is in the determination of settling time. The time, t_x of Method A-2 can be determined as follows: Determine the concentration C_2 by extending the tangents to the hindered settling and compression settling regions of the subsidence curve to the point of intersection and bisecting the angle thus formed, as shown in Figure 11-11.

Determination of depth in this method follows the same procedures as discussed in Method A-1.

Method B

In this method, the basic mechanisms of settling are utilized. Two mechanisms are responsible for solid settling in a continuous thickener. The first force is the influence of gravity. The solid flux generated due to this force is:

$$F_b = C_o U_s \tag{9}$$

Where: F_b = batch flux per unit area per unit time when there is no removal of solids from the bottom of the thickener,

C_o = concentration of solids in a layer,

U_s = settling velocity of sludge at that concentration.

The second force acts in a thickener with continuous underflow. The removal of sludge from the bottom causes a downward velocity of solids and the solid flux caused due to the sludge removal is:

$$F_u = C_o U \tag{10}$$

Where:

F_u = Solid flux due to underflow,

U = Subsidence velocity induced by underflow = $\frac{Q_u}{A}$,

Q_u = Underflow rate,

A = Horizontal area of the thickener.

Then, the combined solid flux is:

$$F_s = C_o (U_s + U). \tag{11}$$

A plot of the above flux relation is shown in Figure 11-12.

From the figure, the limiting flux is F_l at concentration C_l. It is less than the solids handling capacity of other concentrations between feed concentration, C_f and underflow concentration C_u. For all solids to reach the bottom of the thickener, sufficient area is needed so that a real solid loading per unit time does not exceed F_l. The required area is:

$$A = \frac{Q_f C_f}{F_l} \tag{12}$$

Where:

Q_f = Influent flow rate,

C_f = Influent solid concentration.

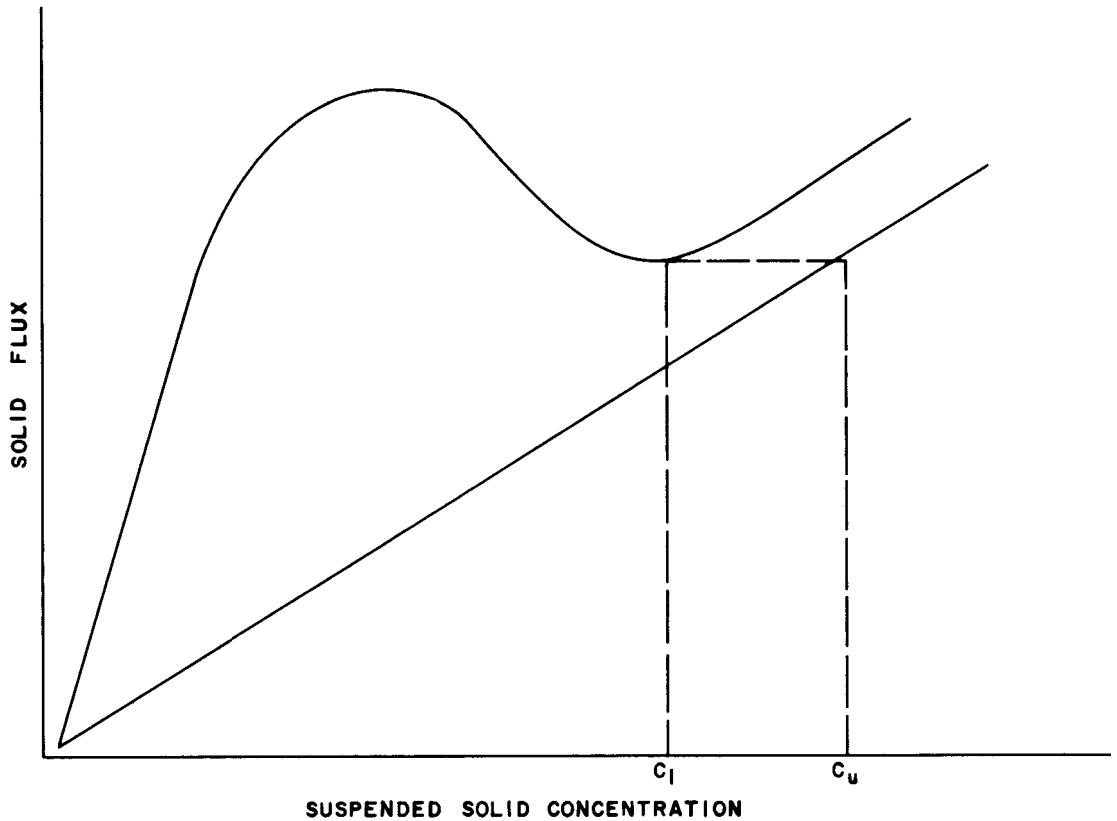


Figure 11-12. Solid Flux Curve for Continuous Gravity Thickener

In the process of determining the thickener area one has to develop the flux curve from laboratory data. The depth of test thickeners is usually the same as the full scale thickener.

For details of the procedure, the reader is referred to the reference (15).

Underflow Pumping Rate

The density of underflow withdrawn from a thickener is heavily dependent upon the pumping rate or rate of sludge withdrawal. Everything entering a thickener may be classified as a solid or a liquid. Assuming that all solids are withdrawn as a sludge constituent, it may be reasoned that withdrawal rates in excess of solids input volumes will contain a fixed solids volume and a volume of water that increases directly with higher pumping rates. Accordingly, the density or solids concentrations of sludges will generally decrease with pumping rate increase.

Another condition that results from high pumping rates is a phenomenon known as "Rat-Holing (16)." If a high rate of withdrawal is continued for an extended period of time, the sludge blanket directly above the discharge portal will be evacuated at a rate that exceeds the ability of the sludge to refill the resulting surface depression. As the depression grows, a piping condition occurs allowing liquid to be drawn through the sludge blanket.

In light of the critical nature of sludge withdrawal rates, it is recommended that positive displacement pumps with metering capabilities be utilized in lieu of centrifugal pumps which are far less sensitive to pumping rate control (16).

Construction Materials

Thickeners used to dewater FGD scrubber sludges usually consist of a lined, mild steel tank with a steel or concrete bottom. The feedwell and launder are also made of mild steel. The gear mechanisms are of heat-treated steel and alloys, such as bronze or alloy steel. To facilitate lubrication, all gear components are normally enclosed in a dust-tight, cast-iron housing.

Since the pH of the solution in the thickener tank may vary and chloride content may be high, most parts submerged below the solution level are protected from corrosion by an epoxy or rubber coating (11).

Recirculation of Underflow

In the event that a thickener is oversized or when low solids loading occurs due to plant load changes, the settled solids may become compacted and cause excessive torque. The proper action in this case is to stimulate a higher feed rate by recycling part of the underflow back to the thickener feedwell. Piping should be provided to facilitate this mode of operation.

Pickets

In conventional thickeners, deep trusses or vertical pickets may be provided in the sludge collection mechanisms of the thickener. A typical gravity thickener with pickets is shown in Figure 11-13.

Benefits from the use of pickets have been reported by Ettelt and Kennedy (17). The role of pickets is believed to be in opening up the channels for water to escape, thus promoting solid densification. However, the mechanism by which the pickets work and their proper design is not well understood. Several investigators have studied the effects of pickets on thickening of domestic sludge and questioned whether they offer any benefit (18,19).

CYCLONE/HYDROCLONE

Description

In some sedimentation systems, the liquid cyclone or hydroclone is replacing the thickener/clarifier as the primary dewatering device. The unit is a free vortex centrifugal separator that removes solids from liquids by combination of centrifugal force and liquid shear.

The pressure energy of the liquid pumped to the cyclone is changed to velocity energy at the inlet, and then into rotation as the liquid travels down through the cyclone. The natural vortex created by this rotation moves the heavier particles to the outside of the cyclone and the lighter ones to the center. The heavier solids are then discharged from the orifice at the cyclone's tip. Figure 11-14 presents a typical hydroclone.

Principal advantage of hydroclones are (20,21):

- less space intensive
- installation cost is less and less time consuming

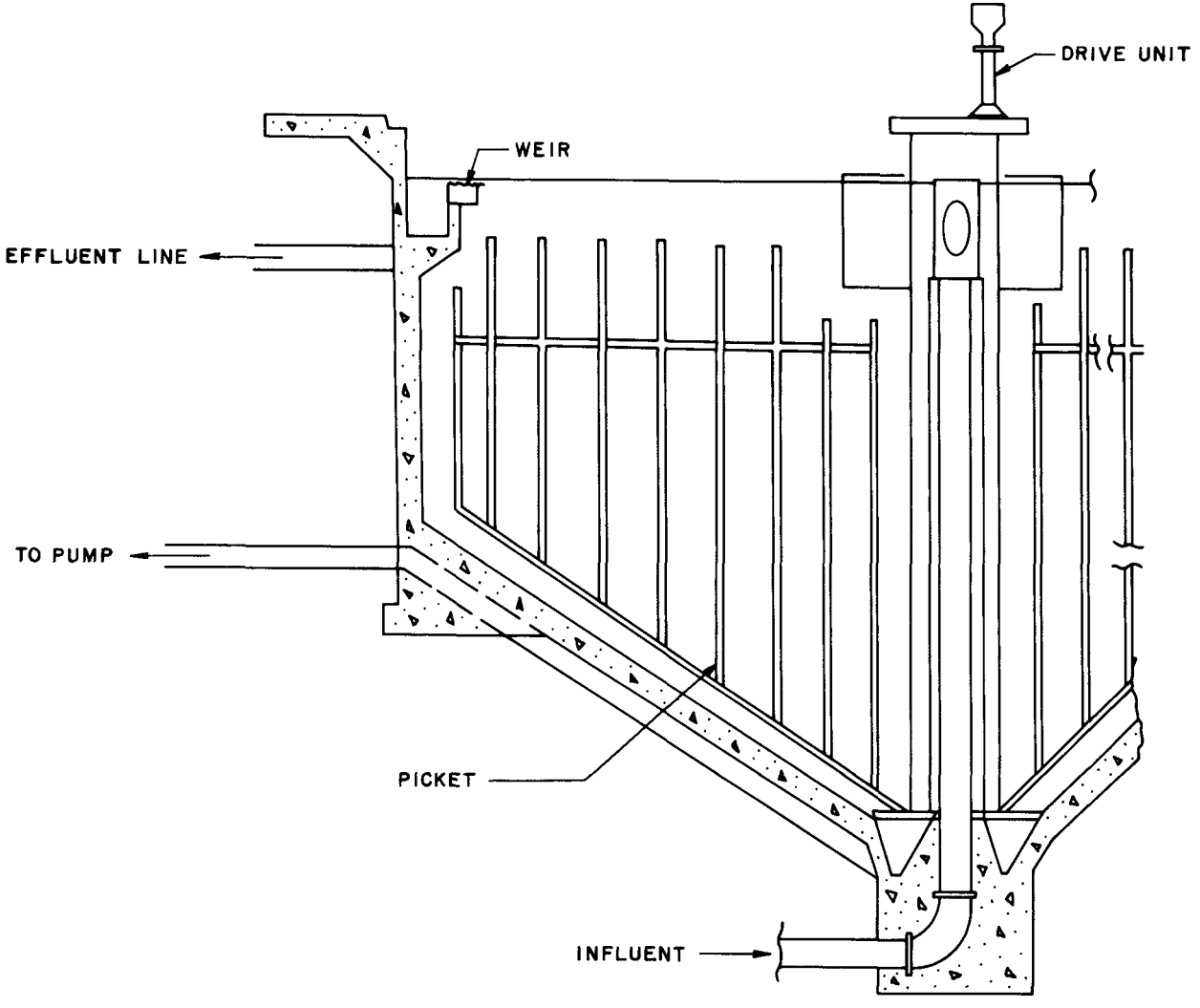


Figure 11-13. A Typical Gravity Thickener Section Showing Pickets.

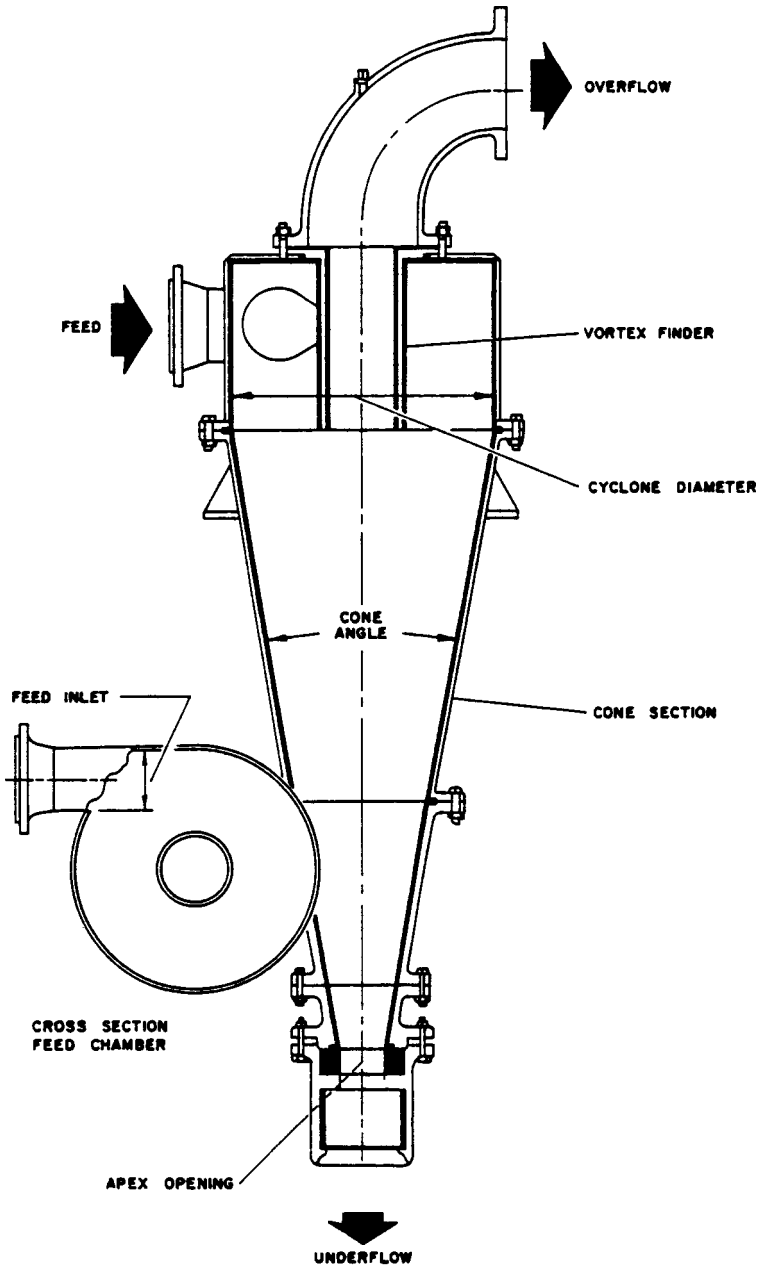


Figure 11-14. Cyclone Cross-Section

Courtesy: Dorr Oliver, Inc.

- small waste detention time
- centrifugal force as high as 7500 g
- as small as five micron particles may be removed

When choosing a cyclone instead of a thickener, it is important to note that a cyclone is a classifier, and therefore deals with particles rather than flocs or agglomerates. A cyclone will predictably separate and collect particles down to a certain size, and reject finer particles which then end up in the cyclone overflow. This separation is a function of particle mass, shape, liquid viscosity, and cyclone feed concentration, among other things. Recirculation of fines to the scrubber system may cause the average particle size in FGD sludge to decrease to a point where the existing sedimentation tank cannot handle it. Generally speaking, collection of finer particles means larger equipment and a higher final moisture in the dewatered sludge. One manufacturer (20) relates particle size removed with flow through the cyclone as follows:

- Up to five micron particles may be removed at a flow rate of 20 gpm.
- Up to 25 micron particles may be removed at a flow rate of 850 gpm.
- Up to 2 inch particles may be removed at a flow rate of 5,700 gpm.

Design variables and the operational factors which affect the liquid cyclone performance are:

- Cone diameter - Generally the smaller the diameter, the finer the separation and the lower the capacity at a given pressure drop.
- Feed inlet size - With certain limits, the larger the inlet, the greater the cyclone capacity and the coarser the separation.
- Dimension of bell overflow.
- Dimension of underflow nozzle - longer cyclones produce finer separation.
- Size, shape and density of suspended solids, and density and viscosity of liquid medium -- the higher liquid viscosity lowers the separation efficiency. Concentration of solids in the feed also has a significant effect upon the size of separation. Higher percentages of solids produce coarser separation and higher throughput.
- Vortex finder diameter - The larger the vortex finder, the larger the cyclone capacity and the coarser the separation.
- Other process variables such as abrasion and corrosion.

Underflow liquid loss is normally 2 to 10% depending on the orifice size and the pressure at the overflow. Increasing inlet pressure creates pressure drop in the cyclone and produces finer separation and higher capacities. One manufacturer of the cyclone claimed that a 30-50 psi pressure drop or pressure differential in the cyclone is sufficient to separate 98% and more of particles in the 10-15 micron range (21). The analysis of design and operating variables of several vendor products helps the designer to choose proper equipment. Once a cyclone is chosen for the purpose, the total process flow determines the number of necessary cyclones.

The main factors limiting the use of cyclones are:

- Cyclones are ineffective in separating particles less than five micron in size.
- Cyclones are inefficient when the feed contains more than 15 percent solid content (20).
- It appears that cyclones are very efficient in high quality solid liquid separation in small flow with the intent of recovering solid materials and/or liquid effluent.

VACUUM FILTERS

Much of the information provided in this subsection has been condensed from the EPRI Lime Data Book (11). A more detailed discussion of vacuum filters may be found in that reference.

Types of Vacuum Filters

Vacuum filters are mechanical processes used for secondary dewatering of sludges. Five types of vacuum filters may be applicable to dewatering sludges from lime/limestone FGD systems: drum, belt, disk, horizontal belt, and pan.

The horizontal belt and pan vacuum filters are designed for dewatering quick-draining, coarse solids that cannot be retained on a vertical filter medium. They are also useful for recovering valuable chemicals by washing. The disk vacuum filter, which provides the highest filtering surface area for the size of the equipment, is normally used to handle large volumes of slurries, as in mineral processing operations. These types have not been used in field applications on FGD sludge and will not be discussed further.

The drum and belt vacuum filters are the types that have been used in FGD applications where filtering has been a part of the process. These types also can be adapted for washing the filter cake.

Description

Rotary-drum vacuum filters (Figures 11-15 and 11-16) are widely used for continuous service. The drum is divided into sections, each of which is connected through ports in the trunnion to the discharge head. The slurry is fed to a tank (or vat) in which the solids are held uniformly in suspension by an agitator. As the drum rotates, the faces of the sections pass successively through the slurry. The vacuum in the sections draws filtrate through the filter medium, depositing the suspended solids on the filter drum as a cake. As the cake leaves the slurry, it becomes completely saturated with filtrate and undergoes dewatering by the simultaneous flow of air and filtrate. The drying is negligible when using air at room temperature. Finally, the cake is removed by a scraper, which may be assisted by a slight air reversal through the filter valve. Continuous rotary-drum vacuum filters of this general type provide high filtering rates and are available in a wide range of sizes, from about 3 to 800 ft^2 of filter area.

The rotary-drum vacuum filter is the most popular design since it is usually the least expensive filter in $/$ft^2$ of filter area for a given application which still permits cake washing to be accomplished. The disadvantage of the unit is that it is susceptible to clogging and wearing of the medium because of the scraper at the discharge point which abrades the filter cloth. Replacement of the medium is time-consuming because it must be caulked and sometimes wirewound. Therefore, the rotary filter can be costly from a maintenance standpoint.

The belt filter, Figure 11-17, is an improved version of the rotary-drum filter. The filter medium is lifted from the drum after the dewatering portion of the cycle is completed and is passed over a small diameter roller to effect cake removal. This rapid change in direction ensures a complete discharge of cake without the need of a scraper. Thus, the filter cloth life is comparatively long. After cake discharge, the medium is subjected to washing on both sides. This arrangement provides a clean medium for each filter cycle and prevents blinding, a particular advantage in filtering of solids which tend to blind the medium. The lifting of the filter medium from the drum usually results in the reduction of sludge drying time (Figure 11-18). In some cases, even a 50% reduction of drying time may result from a belt type arrangement (2). The installed cost of a belt filter is approximately 30% higher than that of the equivalent size drum filter unit.

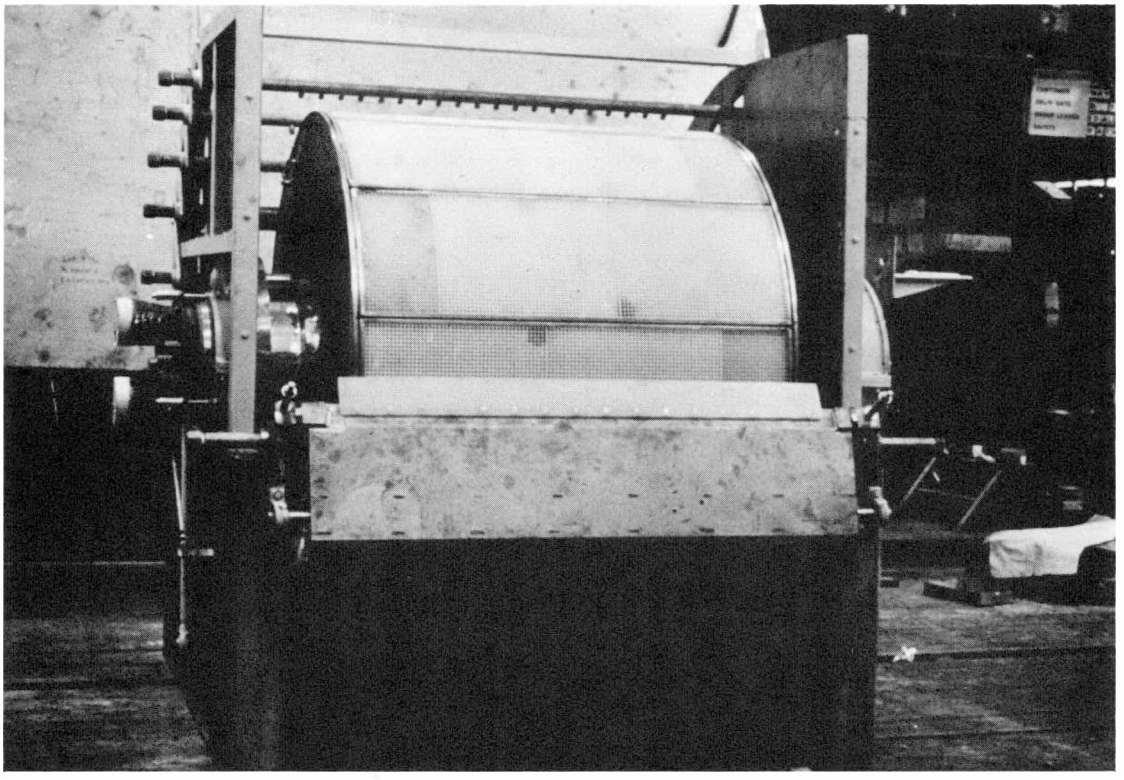


Figure 11-15. Typical Rotary Drum Vacuum Filter.

Courtesy: Komline-Sanderson Engineering Corporation

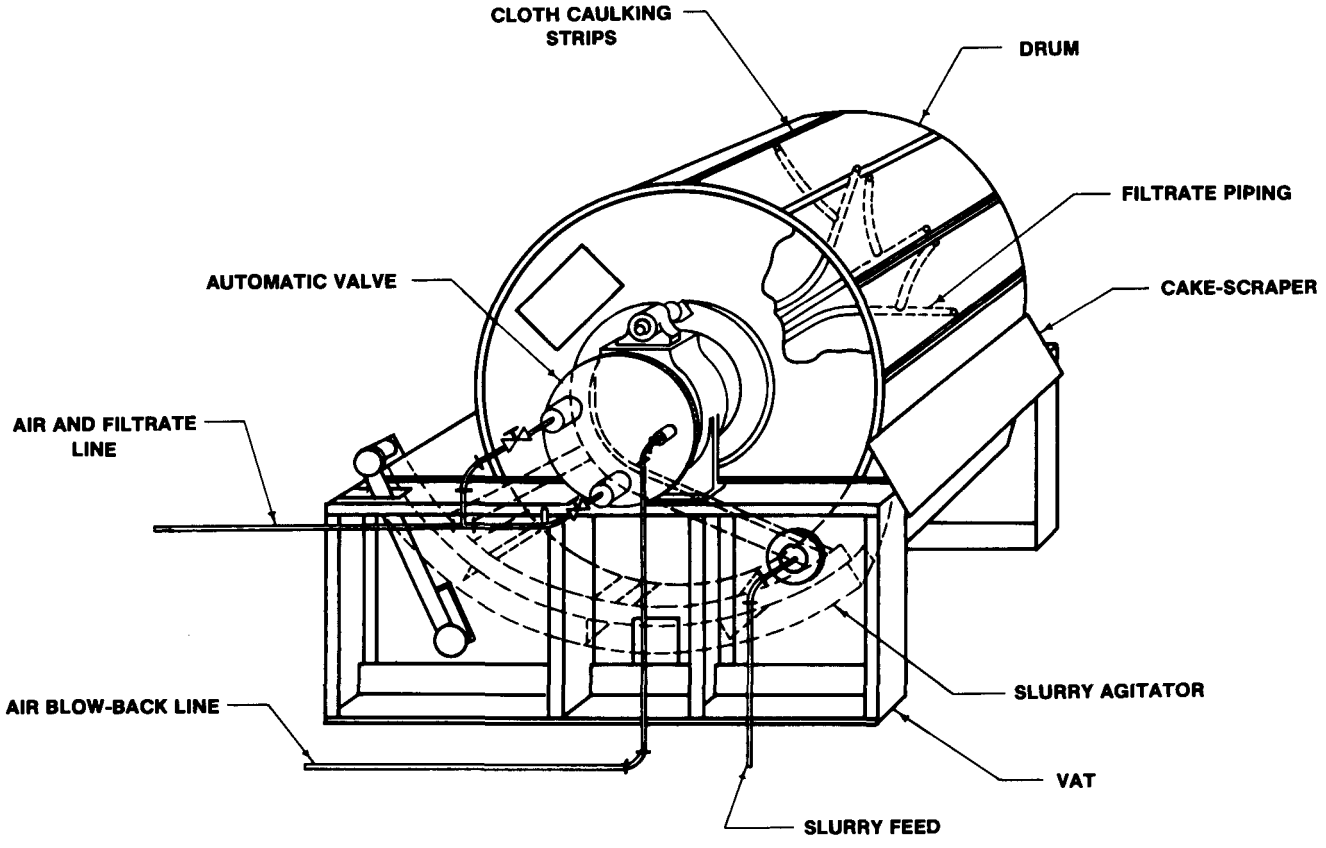


Figure 11-16. Cutaway View of a Rotary Drum Vacuum Filter.

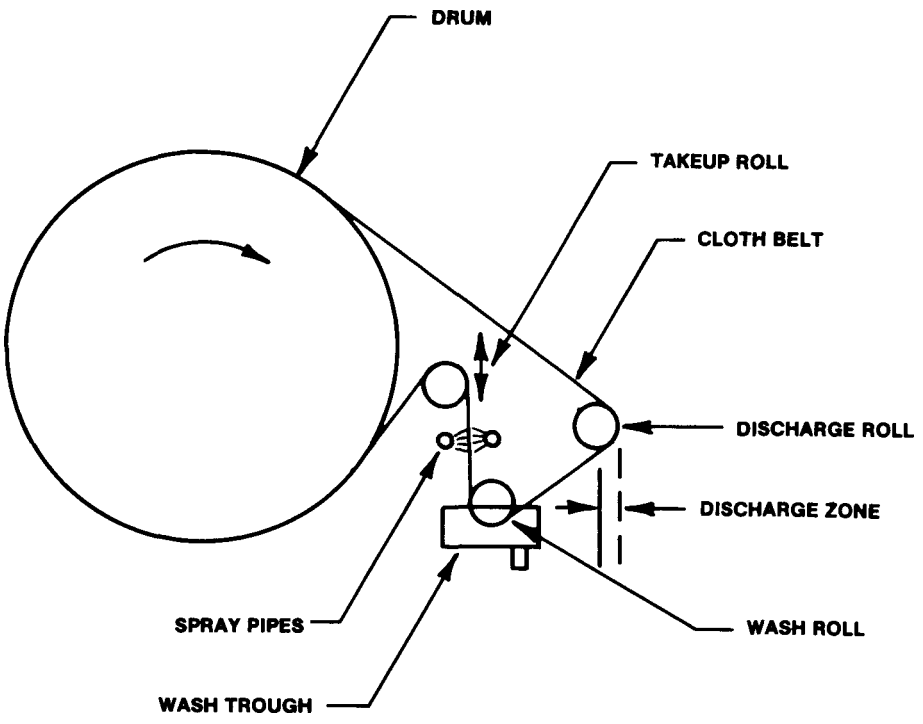


Figure 11-17. Cross-Section of a Belt Filter.

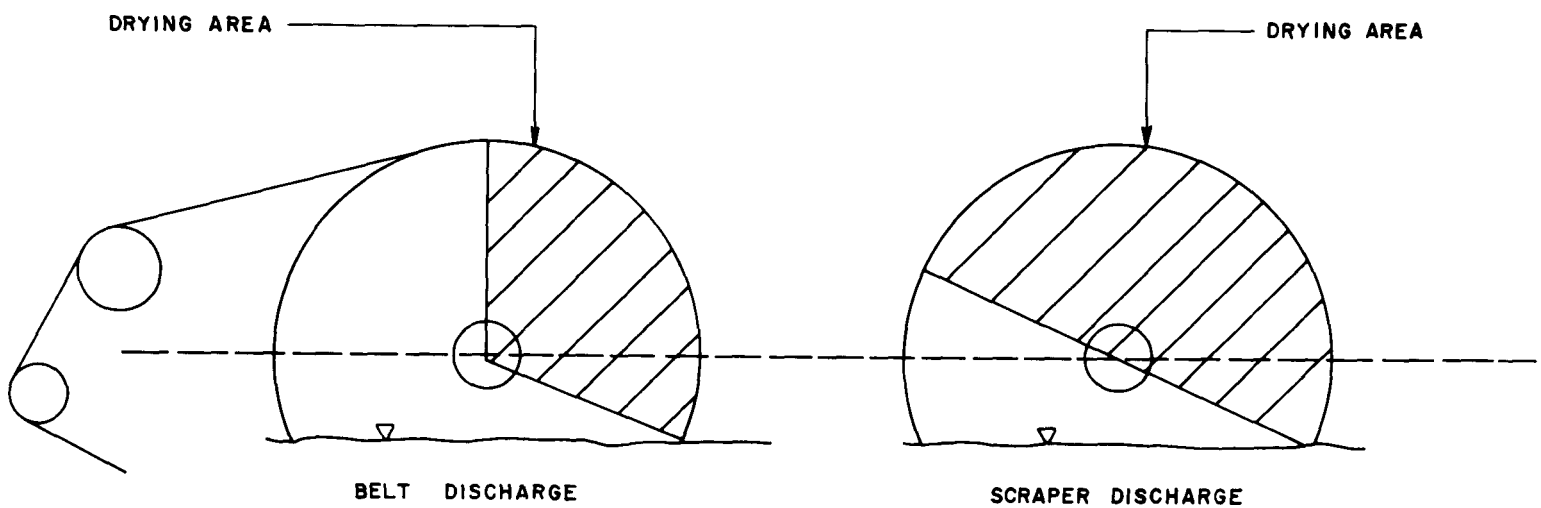


Figure 11-18. Difference in Drying Times of Belt Discharge and Scraper Discharge

A typical filter system is presented in Figure 11-19. The lower pipe connection at the filter valve accommodates the liquid pulled through the sections in the pickup zone. The upper filter valve connection carries the liquid and air pulled through the cake in the dry zone. When a drum section reaches the end of its cycle, vacuum is released and a low pressure air supply discharges the cake through the processing chutes to the conveyor below for final disposal or further processing.

Liquid and air enter the side connection of the filtrate receiver where the liquid drops down to the filtrate pump and the air is pulled through the top connection of the receiver to the moisture trap. Each receiver may be equipped with a vacuum-limiting device to admit air flow if the design vacuum is exceeded, a condition that would cause the pump to overload. The receiver also acts as a reservoir for the filtrate pump suction. The receiver is usually designed to give a maximum air velocity of 2.5 to 5 ft/min and a minimum air detention time of 2 to 3 min. Check valves on the discharge side of the pumps are usually provided to minimize air leakage through the filtrate pump and receiver back to the vacuum pump.

A two-receiver system is employed in those cases where vacuum regulation is considered. This is especially advantageous when the cake solids tend to crack, and regulation is desired to limit air flow or to control cracking in cake washing systems.

The air pulled through the receiver enters a bottom tangential connection at the moisture trap. The spiraling air, upon entering the trap, expands, gives up heat and drops moisture in the form of water vapor and entrained droplets from the receiver through the bottom connection of the moisture trap. The moisture trap has a barometric leg 34 ft long. Since 34 ft water differential pressure is equal to 30-in. mercury vacuum, any water which might enter the trap would drop out the barometric leg by gravity. The trap, therefore, offers protection to the vacuum pump, in the event that the filtrate pump should fail.

The air pulled out of the upper tangential moisture trap connection is carried over to the intake of a vacuum pump and discharged to the atmosphere. A silencer should be placed on the pump discharge to reduce the noise from the pump.

Lime/limestone-generated filter cakes are compressible and appear to be thixotropic, in that subsequent handling via conveyor belt or trucking tends to liquify the sludge, resulting in a difficult-to-handle putty. It is noted that the term "thixotropic" is

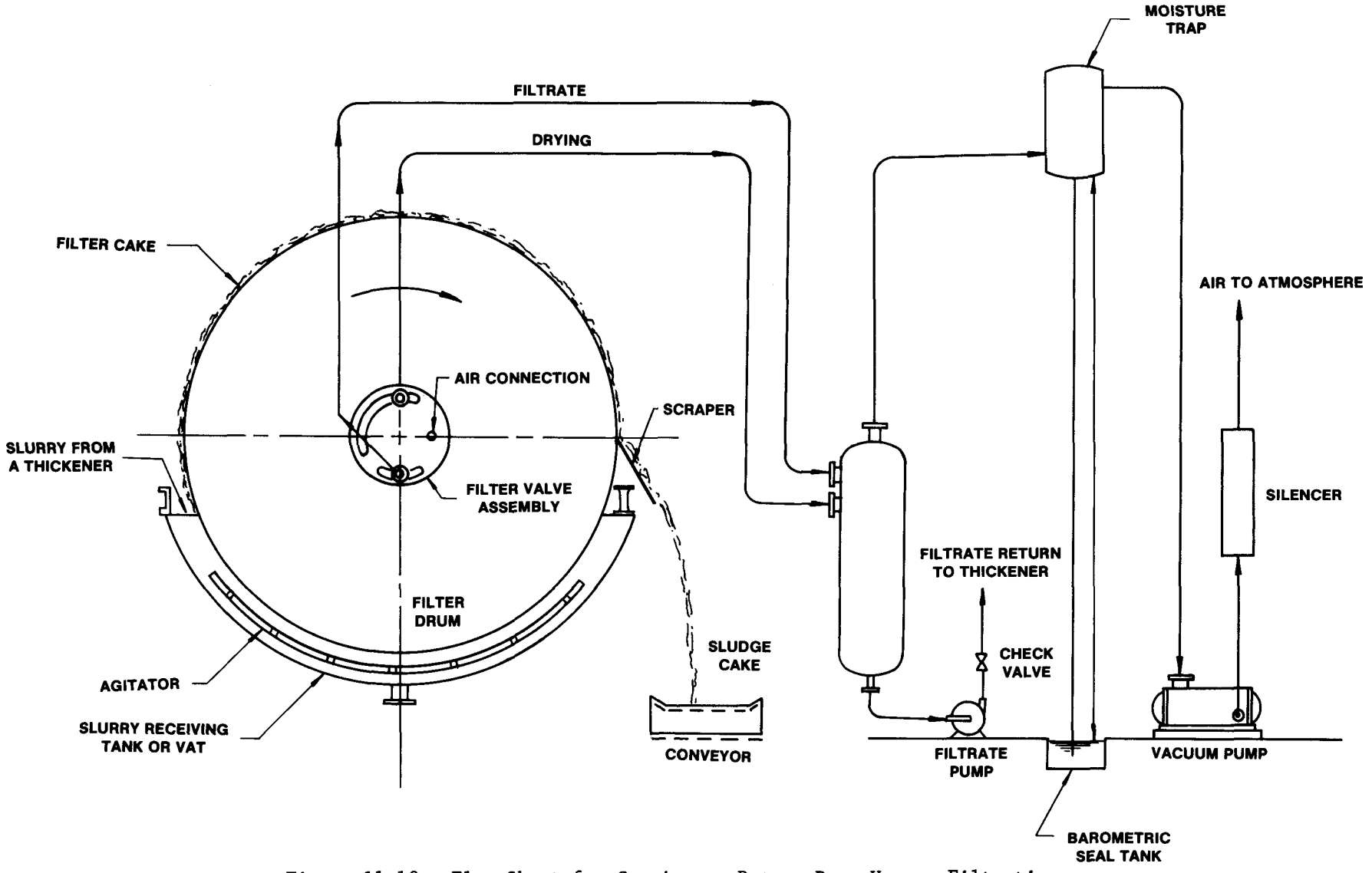


Figure 11-19. Flow Sheet for Continuous Rotary-Drum Vacuum Filtration.

not used in an accurate sense here, since thixotropic materials become stable when the shearing force is removed from them. Flue gas desulfurization sludges tend to remain in the liquid-plastic form and have been termed "pseudo-thixotropic."

Recent filtration testing by EIMCO personnel indicated that lime-generated filter cakes crack easily during the early period of dry cycle; therefore, a short dry time (about 10 sec or less) is desirable to prevent cake cracking.

The plants using vacuum filters dewater slurry from a thickener containing 20 to 45% solids into filter cakes containing 50 to 85% solids for disposal. The filtrate and the overflow return to the thickener for recycle.

Design Parameters

The major components of a rotary-drum vacuum filter consist of a rotary drum, grids, internal piping, receiving tank (or vat), and agitator. The mechanical design of these components is provided by equipment vendors. Corrosion resistance is usually the controlling factor in selection of the filter equipment. Rotary-drum vacuum filters are available in a variety of materials including carbon steel, stainless steel, special alloys, rubber-covered steel, plastic-covered steel, or all plastic. Use of special materials requires higher capital costs. Nevertheless, when moving parts or wear surfaces are exposed to the sludge, they should be properly protected. Specific areas of concern are internal piping, wear plates, filter valves, filter cloths, the filter drum and grid, the filtrate pump, and external piping.

Major Components. The internal drum piping may be made of thin-wall steel tubing, e.g., Schedule 10, 304 stainless steel. The drum heads are usually made of mild steel; the drum face and media are fabricated with 304 stainless steel. Manholes on the drum covers provide access to all internal areas.

The slurry receiving tank and the agitator can be made of carbon steel, rubber-covered for corrosion protection.

Some vendors offer plastic filter equipment made entirely of high-strength FRP. The corrosion resistance of this equipment is excellent. The available filtering area, however, is limited to about 100 ft^2 and costs are high.

Grids that support the filter media are available in wire screen, molded rubber, polypropylene, and other plastics with open areas up to 55%. The snap-in grid design greatly simplifies maintenance.

Auxiliary Equipment. The important units of auxiliary equipment are the vacuum receiver, filtrate pump, and the vacuum pump. Design considerations of the filtrate pump and the vacuum pump will be discussed in this section.

To discharge the filtrate, a filtrate pump is necessary in order to overcome the suction head created by the vacuum. A check valve is placed in the filtrate pump discharge to insure that no air is drawn back into the system. Should this occur, an inoperable system would result. Thought must be given to the application of filtrate pump discharge. The filtrate pump is rated for a given total dynamic head (tdh), gallons per minute (gpm), and net positive suction head (npsh). These factors must be correctly applied for efficient pump operation. The discharge head available will be the sum of tdh minus suction head and friction head. The practical application of npsh is to allow the static head from the bottom of the receiver to the eye of the pump impeller to be equal to or greater than the required pump npsh.

Filtrate pumps should be specifically designed to operate at very low npsh. The design inlet pressure is at least 20 to 22-in Hg vacuum. Centrifugal pumps are common, but they should be protected against loss of prime with a balance or equalizing line connected from a high point of the receiver to the eye of the pump impeller. Nonclogging centrifugal-style pumps are used with coil filters or with coarse metal filter media. They permit a somewhat higher solids concentration in the filtrate. Self-priming centrifugal pumps are used most frequently, since they are relatively maintenance-free.

The filtrate pumps must be sized to accommodate the entire range of filtrate flow rates likely to be encountered. In sizing a filtrate pump, the designer must recognize that the rate of filtrate flow is a function of the mode of chemical conditioning. Generally, polymers allow the sludge to drain much more rapidly than do inorganic conditioners.

The piping from the filter valve must be in a horizontal plane or dropped vertically to the receiver side connection. The moisture trap height above the receiver is inconsequential as long as the bottom connection of the trap is above the top connection of the receiver, and at least a 34 ft tail leg is on the trap. All equipment should be placed as close as possible, and unnecessary pipe turns and bends should be avoided to reduce friction head loss. Pipe connections and auxiliary equipment sizes should be as recommended by the filter manufacturer.

Filtrate may also be discharged from the receiver by use of a barometric leg rather than a filtrate pump. This type of system avoids filtrate pump problems. However, discharging filtrate by a barometric leg is not always possible because of plant elevation limitations. If a barometric leg discharge is used, the leg should be immersed in the cleanest circulating water in the plant to prevent plugging of the leg with solids. It is recommended that an electrode be placed in the line from the receiver to the trap so that the vacuum pump is stopped when water contacts the electrode.

Wet-type vacuum pumps are most popular since they are easily maintained and provide sufficient vacuum. In such a system, the vacuum pump uses water for its sealing medium, and the moisture trap, the barometric leg and the seal tank shown in Figure 11-19 are eliminated. Because wet-type vacuum pumps utilize seal water, the water must be of good quality. If the water is hard or high in total dissolved solids, a sequestering agent may be needed to prevent carbonate buildup on the seals, but no moisture trap protection is required.

Sizing Criteria. Correct sizing, that is the determination of the correct filter area, is important for economical operation, since size usually accounts for an appreciable portion of the capital and operating costs. Sufficient filter area must be provided so that the sludge solids removal can be maintained at a rate necessary to prevent excessive solids accumulation in the scrubber cycle.

The size of a filter for a given application is inversely related to the slurry feed concentration. Thus, if a thickener is installed upstream, it is important to determine the minimum underflow concentration encountered in average operation of the unit. When the filter is sized at this minimum solids concentration, it will have adequate capability to dewater the solids output of the plant.

Unit sizing parameters for vacuum filters include the air removal required in cfm/sq.ft. and the filtration rate in lb/sq.ft./hr. Table 11-3 shows some typical filtration rates (2).

TABLE 11-3

TYPICAL SLUDGE - FILTRATION
RATES FOR VACUUM FILTERS

SO_2 REMOVAL PROCESS	FILTRATION RATE LB/SQ.FT./HR.		VACUUM-FILTER RATING
	FLY ASH	NO FLY ASH	CFM/SQ.FT.
Lime	100	75	3
Limestone	175	175	2
Fly Ash	250	-	2
Dual-Alkali	-	100	4

The filtration rate for sludges containing almost all calcium sulfite appears to range between 50 to 60 lbs/hr/ft^2. On the other hand, filtration rates of the sludges where calcium sulfate crystals predominate appear to range between 150 and 250 lbs/hr/ft^2. In a vacuum filter performance test (3), satisfactory dewatering was possible with the following sludge loading rates:

- Lime scrubbing sludge - 90 to 235 lb/h/ft^2.
- Limestone scrubbing sludge - 40 to 270 lb/h/ft^2.

Because of the wide variation in slurry characteristics, it is advisable to run laboratory vacuum filtration tests on representative samples of the sludges to be dewatered to allow accurate sizing of the filter equipment.

The two test procedures used for determining the filterability of sludges are the Buchner funnel method and the filter leaf technique. The Buchner funnel method enables a determination of the relative effects of various chemical conditioners and the calculation of the specific resistance of the sludge, but it is seldom used for the calculation of required filter area. The filter leaf test is used for that purpose.

Filter Leaf Test. The filter leaf test, Figure 11-20, employs a test leaf, over which is fitted a filtering medium identical to that which will be used on the full-scale filter. The procedure for conducting filter leaf tests is as follows:

- Condition approximately two liters of sludge for filtration. The sludge should be thickened to a concentration anticipated for the full-scale application.
- Apply the desired vacuum to filter leaf and immerse in sample 1-1/2 min (maintain sample agitation). The test leaf normally is inserted

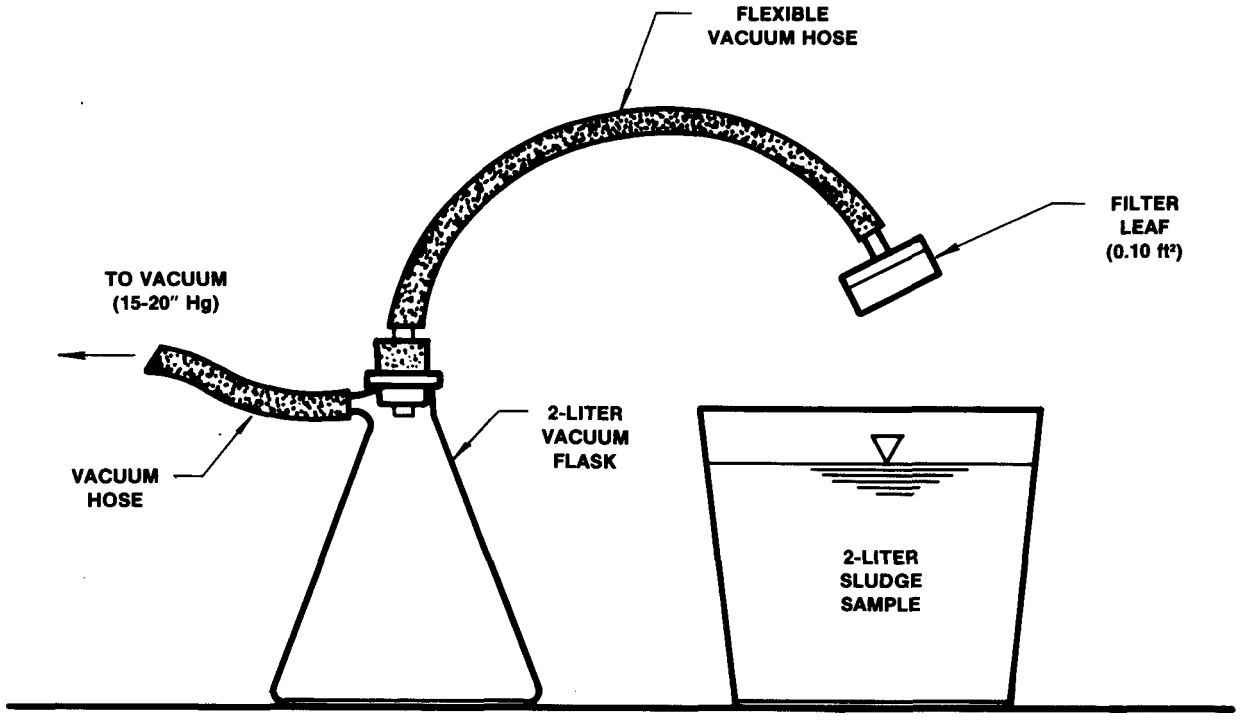


Figure 11-20. Filter Leaf Test Apparatus.

upside down in a representative slurry to simulate the cake formation zone of the drum filter.

- Bring leaf to vertical position and dry under vacuum for three min (or other predetermined time). This is the cake draining and drying part of the cycle.
- Blow off cake for 1-1/2 min (this gives a total drum cycle of six min). To discharge the cake, the leaf is disconnected and air applied (pressure not exceeding two psi).
- Dry and weigh cake to determine percentage moisture. The filter rate (Y) in lb/ft^2 is computed:

$$Y = \frac{\text{dry weight sludge (lb) x cycles/hr}}{\text{test leaf area}(ft^2)}$$

The test can easily be modified for other cycle times and discharge mechanisms. Filter leaves are readily available from filter manufacturers and include instructions. It may be necessary to adjust the above result by a factor to compensate for partial medium blinding and for scaling over a long period of operation. The test results will provide filtration parameters for the form, dry, and wash portions (if necessary) of the filtration cycle. Although the filter leaf test is a simple one, there are some precautions which should be observed to insure accurate results:

- Representative sludge samples must be used.
- Several (five to 10) tests should be run to monitor filter medium blinding.
- The test sample must be agitated to insure that it is homogeneous.
- The test filter vacuum must be regulated so that it does not vary during the test and so that it is the same as proposed for use in full-scale operation.

Normally, the moisture content of the filter leaf test cakes is plotted as a function of a correlating factor on rectangular coordinates. The equation for the correlating factor is:

$$F = \frac{cfm}{ft^2} \times t_d \times \frac{P}{W'} \qquad (13)$$

where:

cfm/ft^2 = Air flow through the cake per unit area of filtering surface

t_d = Dry time, usually expressed in minutes

P = The vacuum differential, psig

W' = Weight of the dry cake solids in lb/ft^2 for a given cake thickness

A decreasing moisture correlation indicates that, as the air rate through the cake per unit of filtering area is increased, or as the vacuum differential or length of the drying time is increased, the moisture content decreases. Conversely, if the cake thickness and subsequently the cake weight (W') is increased, the moisture content increases. Knowing the percentage of available drying time of the filter cycle and using the design information (the proper cake thickness for a given type of filter, the vacuum level, and air rate through the cake), it is possible to predict for each cycle time the discharged filter cake moisture contents expected from the full-scale filter.

The filter leaf tests have been conducted for numerous industrial and waste treatment applications, and the scale-up techniques are well established. The filter area provided in the design should be for the peak sludge removal rate required plus a 5 to 15% area allowance.

If large variations in solids handling capability are encountered, it is oftentimes desirable to install two smaller filters rather than one large filter. In this way, when the solids amount decreases substantially for a long period of time, one of the units may be shut down, which will allow the other to operate at the proper submergence level and optimize performance.

Operational Criteria

Most filters will achieve the highest filtration rate at cake thickness ranging between 1/4 to 3/4 inch. The usual minimum for good cake discharge is 1/4 inch and cake thickness in excess of 1 inch may be difficult to retain on the filter surface.

The maximum feed slurry level in a vacuum filter vat is normally adjustable between 25-35% of the drum diameter. Automatic filters may be adjusted even for a slurry level below 25%. Due to this adjustable property, the filter operation may be set to respond to pulsating flows from the thickener underflow pump. The increase of drum submergence time increases cake formation time, but reduces the cake drying time. Consequently a wetter cake results. A minimum drum submergence is also necessary for maintaining a continuous vacuum. Solid concentration in the feed affects the filter yield and chemical requirements. The rotational speed of the drum affects both cake formation and cake drying operation.

As the vacuum increases, the filter yield will increase. Higher vacuum accounts for a thicker cake during the formation process. The practical vacuum limit for filters has been experienced to be 15 inch-Hg (22).

CENTRIFUGES

Introduction

Centrifuges are widely used for separating solids from liquids. Normally they are used as a secondary dewatering process which requires an upstream thickener. However, with recent improvements, the centrifuge has been claimed to be effective in reaching a dry cake of 60-70% solids with 9 to 15% solids slurry directly fed from the FGD scrubbers (1).

Centrifuges are compact high-intensity settling basins. Whereas the subsidence rate of sludge in normal settling basins is limited by the value of the acceleration of gravity, g, acceleration in centrifuges is rw^2 where r is the distance of a particle from the axis of rotation and w is the rotational speed. In modern centrifuges, rw^2 may be 1500 to 4000 times g (15). A direct analogy between settling basins and centrifuges may help in a theoretical evaluation of processes; however, there are several factors which prevent centrifuge theory from describing operational performance. The theory is for discrete particles and does not consider hindered settling of sludge, and it fails to account for the effect of scrolling.

Modern centrifuges are developed to be reliable and efficient. Their products are consistent and uniform; however, they are not effective in producing clarified overflow and, because of high rates of wear, erosion and corrosion, they require special construction materials and frequent maintenance.

While there are several types of centrifuges available, FGD sludge dewatering usually uses a horizontal, cylindrical, or conical solid-bowl machine.

Description

The solid bowl centrifuge, Figures 11-21 and 11-22, consists primarily of a combination cylindrical/conical rotating element or bowl, which is partially closed at each end by bowl heads. Slurry is piped into the bowl and forms a peripheral ring due to the centrifugal force of the rotating bowl. In this ring of slurry, solid particles (which are denser) are forced to the outside of the ring, leaving a clear liquor toward the inside. As more slurry is added to the bowl, clear liquor fills the bowl to a preset level and begins to overflow through ports in the bowl.

Obviously the tendency of this operation is to fill the machine with solids as more and more are settled out against the bowl wall. To remove these solids, the bowl is

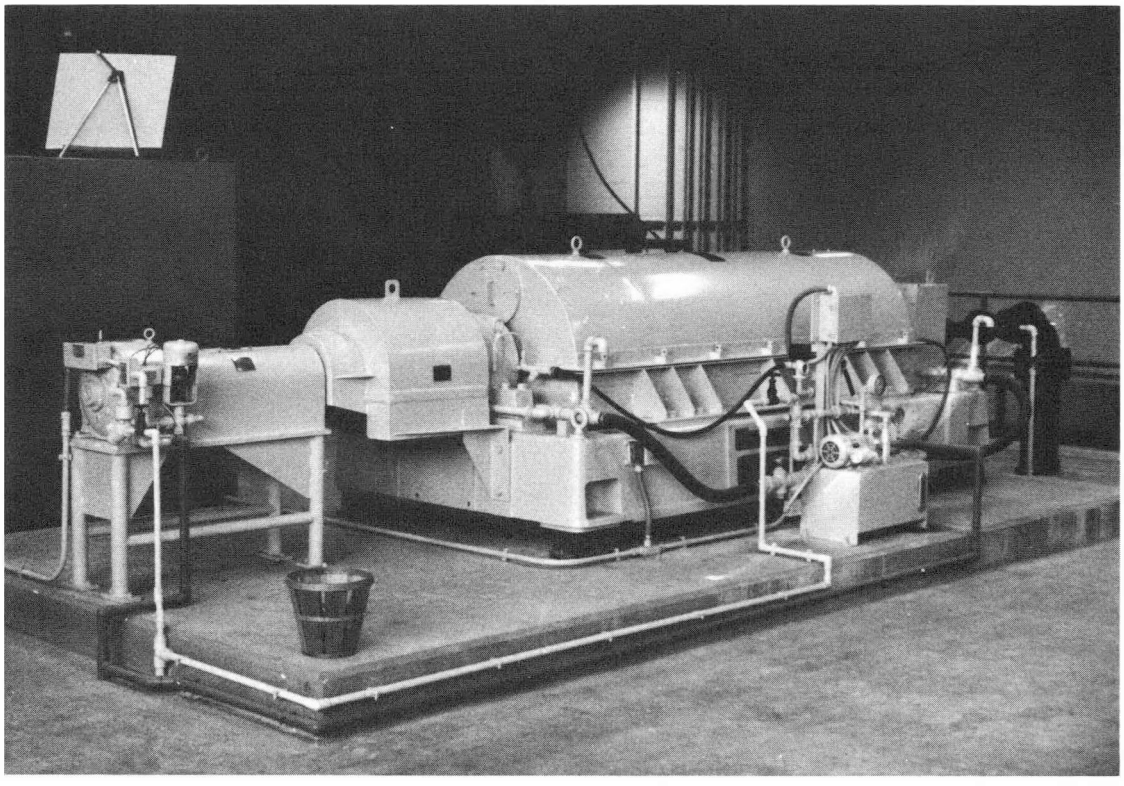


Figure 11-21. Typical Solid Bowl Centrifuge.

Courtesy: Sharples-Stokes Division, Pennwalt Corporation

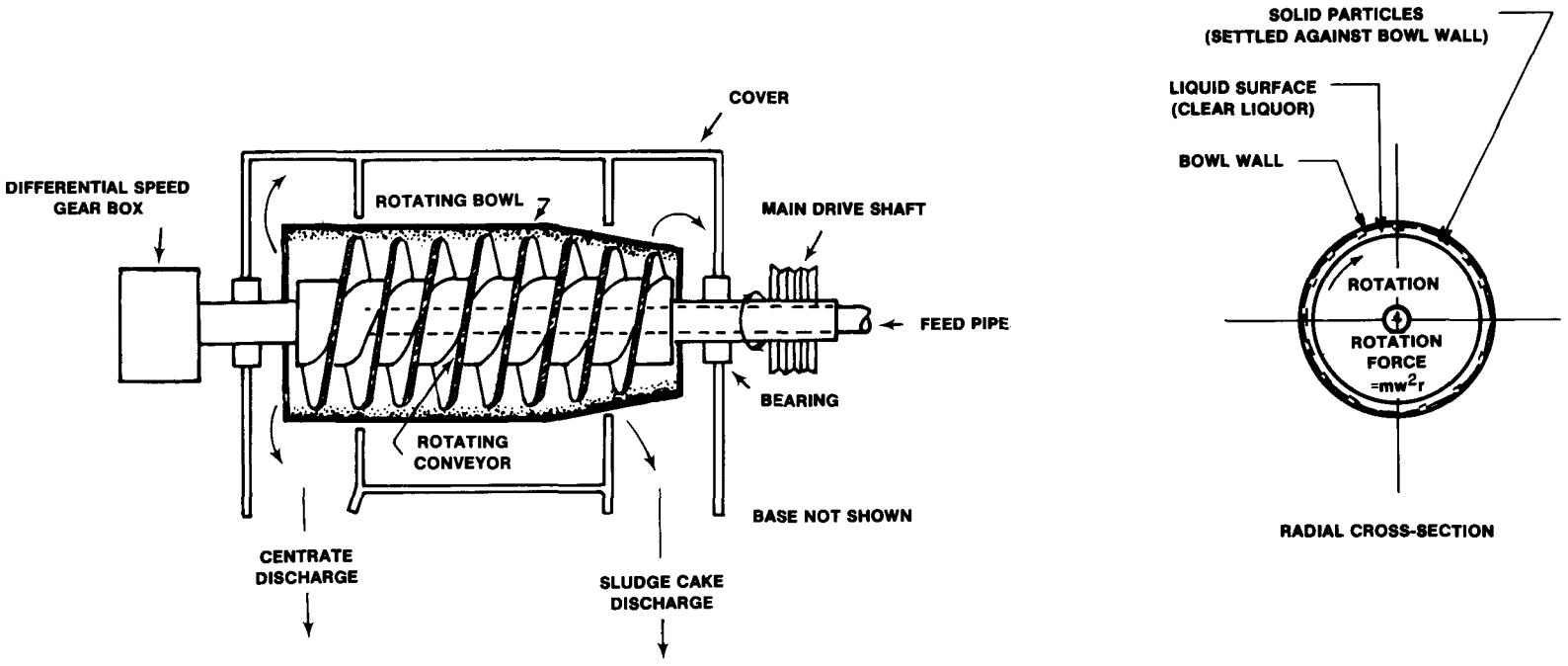


Figure 11-22. Cross-Section of Solid-Bowl Centrifuge.

fitted with a concentrically-mounted screw conveyor which rotates at a speed different from that of the bowl and pushes the solids toward the conical end of the bowl and out the discharge ports in the bowl head. The liquid does not discharge from the solids ports since they are nearer the machine centerline than the liquor discharge ports. The machine receives slurry and discharges both liquor and solids continuously.

For FGD sludges, centrifuges are generally constructed of carbon steel, although various alloys are available for handling severely corrosive materials. The areas subject to high abrasion are the feed ports, discharge ports and screw conveyor flight tips. These areas are normally protected by wear plates made of metal alloys or ceramic materials. Wetted surfaces may be protected with corrosion resistant materials such as epoxy or polyester coatings.

A major consideration in selecting machines for this service is operating speed. In general, the power required is proportional to the square of the operating speed, and maintenance costs are proportional to the cube of the operating speed. Therefore, it is significant in terms of operating cost to select a large machine to operate at a low speed rather than a smaller machine to operate at a significantly higher speed. For example, a machine of one design may need the hard-surfaced elements replaced once every two years when it is run at 1600 rpm. The same machine would need to be serviced each year if it were operated at 2000 rpm or twice a year if it were operated at 2600 rpm. Performance would change very slightly over a wide speed range, for most sludges. The purpose of "startup" service provided by supplier personnel is to select the operating point which is the lowest efficient speed for the machine selected. Conveyor speed and discharge weir position would be selected to complement the selected operating speed (23).

Machine and Operating Variables

All machine variables have either a direct or an inverse effect on the length of time a slurry is retained within a machine. Slurry retention time affects solids recovery and cake dryness. In general, longer retention times produce high solids recovery but result in a wetter cake. Conversely, shorter retention times result in a dryer cake at the expense of solids recovery. This is due to the smaller solids particles escaping in the centrate (10).

Two types of machine variables affect the operation of a centrifuge. The first and more important type are the design variables which the engineer must select

prior to specifying a centrifuge. The design variables which must be considered are as follows:

- Bowl Diameter - Large bowl diameters and low speeds (rpm) may produce the same particle settling velocity as a high speed machine with a small bowl diameter. A larger machine operating at the same centrifugal force as a small machine will have a longer retention time.
- Bowl Length - Increasing the length of a bowl will result in a proportional increase in retention time. For example, doubling the bowl length will double the residence time when all other variables are held constant.
- Bowl Speed - Bowl speed controls the centrifugal force that will be produced in a machine with a fixed bowl diameter. The general trend is to select machines that operate at low speeds to decrease operating costs and increase machine life. However, recent application of special wear resisting materials such as tungsten carbide and ceramic tiles with long-life bearings have reduced the maintenance problem significantly (1).

  From the relationship of bowl speed to process performance, it would seem that the bowl speed need only be increased to improve the quality of cake and centrate. There is a practical limit to this relationship that is dictated by the difficulty in removing the solids from the centrifuge, as well as by the increased maintenance problems of high bowl speeds. The slope of the conical section has a significant effect on the passage of the cake from the bowl. As the bowl rotates, a force on the sludge is developed, that tends to push the solids back down the beach into the pool. This force varies with the square of the bowl speed.
- Conveyor Speed - Increasing conveyor speeds results in moving solids through the machine in a shorter period of time. With most sludges, higher conveyor speeds will produce a dryer cake by causing the wetter solids to be left behind.
- Conveyor Pitch - In fluid-like and sulfite-rich FGD sludge, increasing the scroll pitch will produce results similar to those encountered with increased conveyor speeds.

The second set of variables which affect centrifuge operation are operating variables. It should be noted that operating variables may be changed by making adjustments in the equipment and are, therefore, of a less critical nature than the machine variables which were previously discussed. Operating variables which should be considered are as follows:

- Pool Depth - Increasing pool depth will result in an increased retention time.

  The influence of pool depth on cake dryness is easily visualized because the pool depth determines the amount of beach that is available for drainage. Reducing the pool depth exposes more drainage area, thereby producing a dryer cake. Ideally, shallow depths are advantageous because the distance of travel for a particle to be captured is small.

- Sludge Feed Point - Varying the sludge feed point will change the retention time.
- Sludge Characteristics - Ideal characteristics include discrete, spherical particles, high particle density relative to liquid and low compressibility.
- Polymer Addition - The use of chemicals, usually polymers, signifiantly improves solid characteristics thus improving the solid recovery and centrate clarification.
- Sludge Feed Rate - The sludge feed rate in a solid bowl centrifuge affects the resident period of slurry. As the feed rate increases, the resident period decreases and the solid recovery decreases.

Table 11-4 summarizes the effects of variables on the performance of a centrifuge (22).

Table 11-4

EFFECTS OF CENTRIFUGE VARIABLES ON ITS PERFORMANCES

	CAKE MOISTURE	SOLID RECOVERY
Bowl speed increases	Decreases	Increases
Pool depth increases	Increases	Increases
Conveyor speed increases	Increases	Decreases
Feed rate increases	Decreases	Decreases
Feed solid concentration increases	Decreases	Decreases
Temperature increases	Decreases	Increases

The major difficulty encountered in the operation of centrifuges has been the disposal of the centrate which is relatively high in suspended, nonsettling solids. The return of these solids to the scrubber system could result in a large load of fine solids in the recirculating liquid flow. Such solid build-up may be unacceptable to the operation of the scrubber as well as the centrifuge. Two methods can be used to control the fine solids. Increasing the liquid residence time and/or particle size with polymers can improve the solid recovery.

Design

When choosing a centrifuge, the engineer should carefully weigh the following factors:

- Process Rate (gpm)
- Bowl Speed
- Horsepower
- Solids Recovery
- Cake Solids (% by weight)
- Polymer Dosage
- Physical Size
- Machine Weight
- Energy Consumption
- Noise Level
- Wear Rate
- Turn Down Rate
- Maintenance Requirements
- Abrasion Resistance
- Capital Costs
- Operating Costs

Many factors contribute to the wide variation in the physical and chemical properties of sludge produced by FGD scrubbers. Therefore, it is not possible to accurately predict the dewatering characteristics of sludge that will be generated by any planned pollution abatement facility. It follows then, that prudent selection or design of centrifuges by the application of fundamental principles is not possible. The best available method of designing a centrifuge is to operate a small bench scale machine on actual sludge samples. The empirical results obtained from the bench scale tests will then serve as a basis for scale-up to a full-size installation. Scale-up computations are usually made by vendor-employed mechanical engineers. However, the utility engineer should become familiar with the concepts utilized in scale-up to larger, geometrically similar centrifuges.

The centrifuge is subject to two major physical capacity limitations--liquid limits and solids limits. The liquid limiting capacity is usually calculated by the Sigma method, a variation of Stoke's law. When employed in conjunction with the Beta Concept, which describes limitations imposed by solids throughput capability, the Sigma Concept is quite useful. The utility engineer, however, should be aware that some process engineers rely solely on the Sigma Concept to predict scale-up relationships,

and that this practice may lead to serious error. All scale-up design efforts should evaluate both solids and liquid limits of machines being considered. The following formulas are utilized in determining essential scale-up ratios:

- Sigma Concept - Prototype scale-up of geometrically similar machines on the basis of liquid limitations can be undertaken utilizing the Sigma Concept which is described in the following:

$$\underline{\text{Sigma Formula}}$$

$$\Sigma = \frac{2\pi L\omega^2}{g}\left(\frac{3R_1^2}{4} + \frac{R_2^2}{4}\right) \qquad (14)$$

Σ = Sigma Value, ft^2 (equivalent area of a gravity settling tank)

L = Effective clarifying length, ft

ω = Angular velocity, radians/sec

R_1 = Inside radius of bowl, ft

R_2 = Inside radius of liquid surface, ft

g = Gravitational constant, 32 ft/sec^2

Note: Based on Stoke's law - assumes ideal shaped particle settling under "terminal" velocity conditions under free settling conditions without turbulent effects.

A more detailed discussion of the Sigma Theory may be found in Reference 11.

- Beta Concept--Prototype scale-up of geometrically similar machines on the basis of solids throughput, can be undertaken utilizing the Beta Concept which is as follows:

$$\underline{\text{Beta Formula}}$$

$$\frac{Q_s/\gamma_c}{b_1} = \frac{Q_s/\gamma_c}{b_2} \qquad (15)$$

$$(b = \Delta\omega\ SN\pi DP \text{ in } ft^3/hr)$$

Q_s = Solids throughput in pounds per hr

γ_c = Specific weight of wet cake in lb/ft^3

$\Delta\omega$ = Bowl/Conveyor differential speed

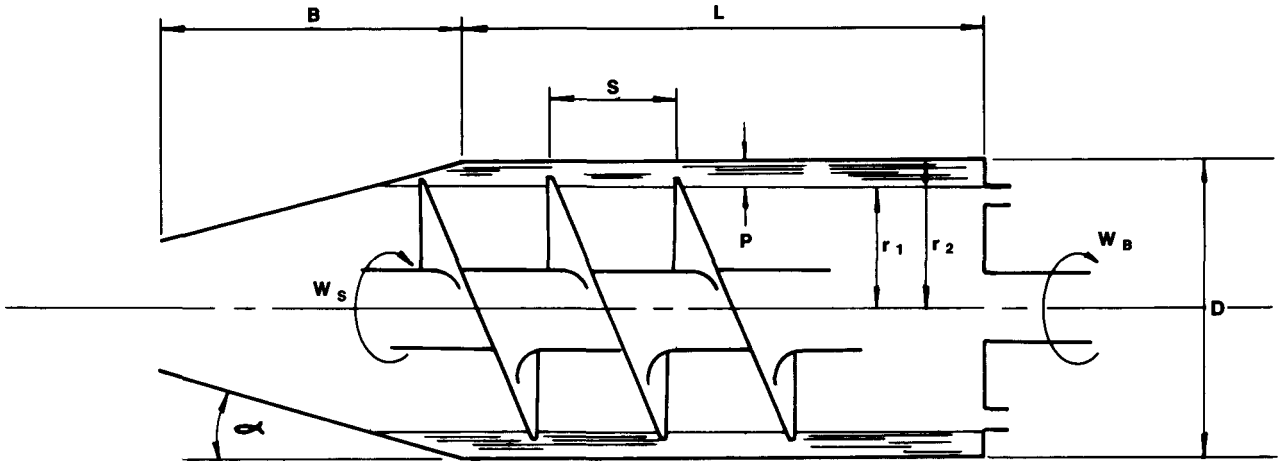
S = Pitch of blades in ft

N = Number of leads

D = Bowl diameter in ft

P = Pool depth in ft

Note: See Figure 11-23 for relationship of terms. A more detailed discussion of the Beta Theory may be found in Reference 5.



L - BOWL LENGTH
B - BEACH LENGTH
D - BOWL DIAMETER
P - POOL DEPTH

S - SCROLL PITCH
α - BEACH ANGLE
W_B - BOWL SPEED
W_S - SCROLL SPEED

Figure 11-23. Beta Concept for Sizing Centrifuges - Definition of Terms.

DEWATERING AIDS

Very often chemicals are used to enhance 'floc' formation in sludge. The larger and heavier flocs improve the sludge thickening and dewatering process. Such chemical aids are used in the feed to gravity thickeners, centrifuges, cyclones, and filters irrespective of primary or secondary stage of dewatering.

Chemicals used to promote sedimentation are generally known as 'flocculants.' Because they are long chained organic compounds, they are often referred to as 'polymers.' A recent study evaluated several polymers used in the gravity thickening of FGD sludge (11). The results indicated that polymer addition may reduce thickener surface area requirement by 63 to 79 percent. The dosages tested ranged from 0.001 to 0.03 pounds per ton of dry solids.

Depending on the charge condition, a polymer may be in one of the three classes: anionic, cationic and nonionic. Anionic polymers were found to be more effective in FGD sludge (3). The effective rate of application is reported to vary from 0.001 to 0.02 pound/ton of dry solid (4).

Polymers can be obtained in one of the three forms: dry, solid and emulsion. Dry polymers should be carefully dispersed in water before use, otherwise, large masses of dry polymers will form and cause polymer waste. In order to eliminate some of the problems of site mixing, many vendors supply polymers in liquid forms. While shipping cost is a little bit higher, it eliminates mixing problems and usually results in higher utilization of the solution.

Emulsion polymers are encapsulated in an organic base. The polymers can be easily mixed with water before use.

Most polymers are purchased in powder form and are generally used at strengths of 0.5 to 1%. Stock solutions may be prepared as infrequently as twice a week, but they are usually made fresh every day or, in some cases, as often as once per shift. The solution preparation system includes a manual or automatic blending system in which polymer is dispensed by hand or by a dry feeder. A schematic of a typical automatic dry-feed system is presented in Figure 11-24.

The addition of polyelectrolytes to sludge as a dewatering aid has proved to be successful in all types of dewatering operations. It should be noted that an extensive variety of different polymers are currently in use, and that the effectiveness of polyelectrolyte conditioning is highly sensitive to the point of

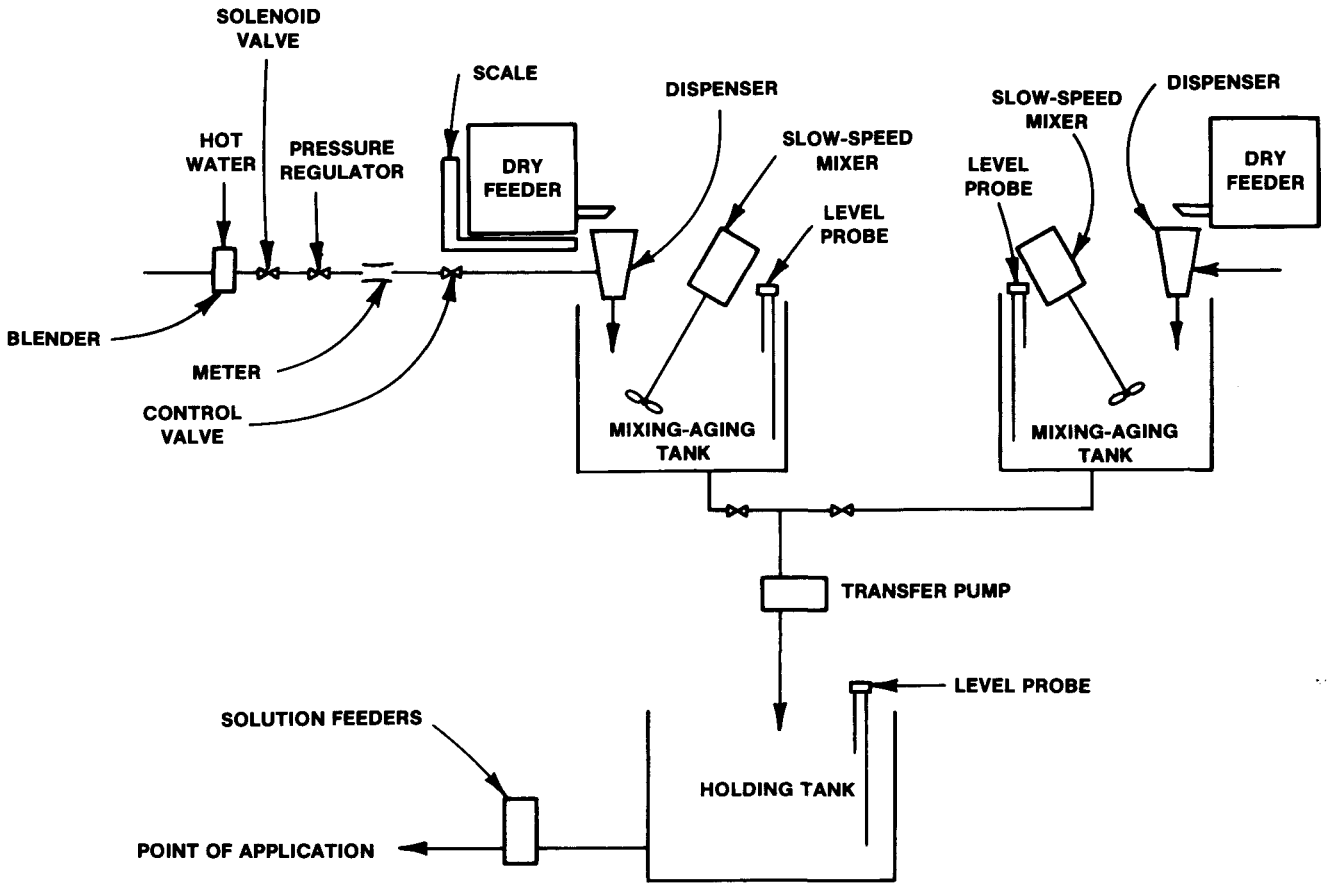


Figure 11-24. System for Preparation and Feed of Dry Polymer.

application. Therefore, laboratory and/or pilot scale evaluations are always essential to selecting the correct polymer.

The price of dry polymer as of 1979 ranged between $1.45 to 2.78 per pound. Reference (3) contains a detail cost evaluation of several polymers tested on FGD sludge.

PROCESS COST

Reliable cost data which may be used to compare the economic aspect of various thickening and dewatering processes are not usually available. An EPRI study presented a cost estimate for three processes: gravity thickener, vacuum filter and centrifuge (3). Much of the information provided in this sub-section has been condensed from the above reference. For details on approach and data, the reader is referred to that publication.

Capital Cost

Capital costs were shown as the functions of primary capacity factors of the dewatering processes. The capacity factors for thickeners, filter and centrifuge were selected to be thickener area, filter area and centrifuge sigma (Σ) factor respectively. Capital cost estimates for these three processes appear in Figures 11-25, 11-26, 11-27. The costs represent 1979 material and installation prices. Thickener cost represents a conventional gravity thickener with a 24 inch lift. The unit prices include a rubber covered rake mechanism, mild steel tank, walkway, handrail, superstructure, concrete tank, epoxy coated and erection at site. It does not include piping, foundation, engineering and facility costs and other associated installation costs.

The drum filter was assumed to be constructed of rubber-coated mild steel in all wet parts and of 316 stainless steel in all dry parts. The cost includes vacuum regulation, vacuum receivers (two), filtrate pump (two), platform, control panel and starter and vacuum pump.

Basic assumption involved in centrifuge capital cost is the 95 percent solid recovery at 1400 g's. The cost includes bowl, scroll and all wetted parts made of stainless steel, tungsten carbide tile on scrolls, drive, motor, starter, control panel and safety system. Installation costs such as piping, foundations, building space, erection, facilities, solids conveyor, overhead crane and shipping were not included.

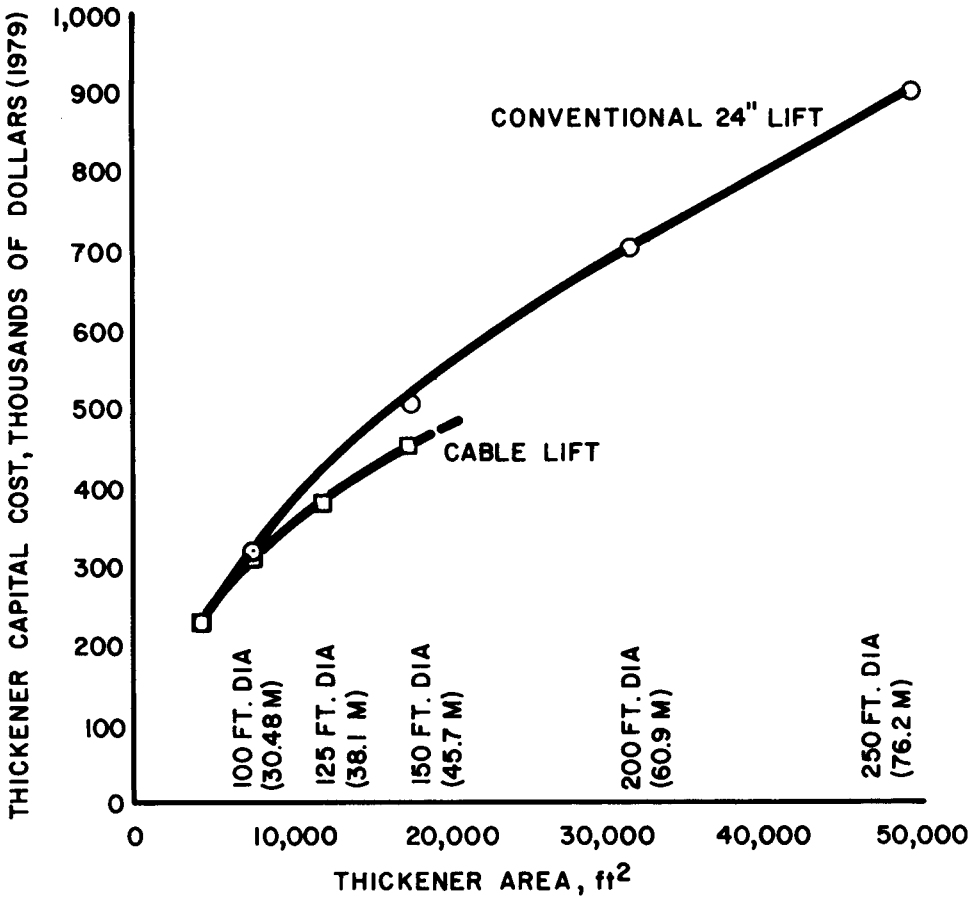


Figure 11-25. Thickener Area and Capital Cost

Source: Sludge Dewatering for FGD Products, EPRI FP-937.

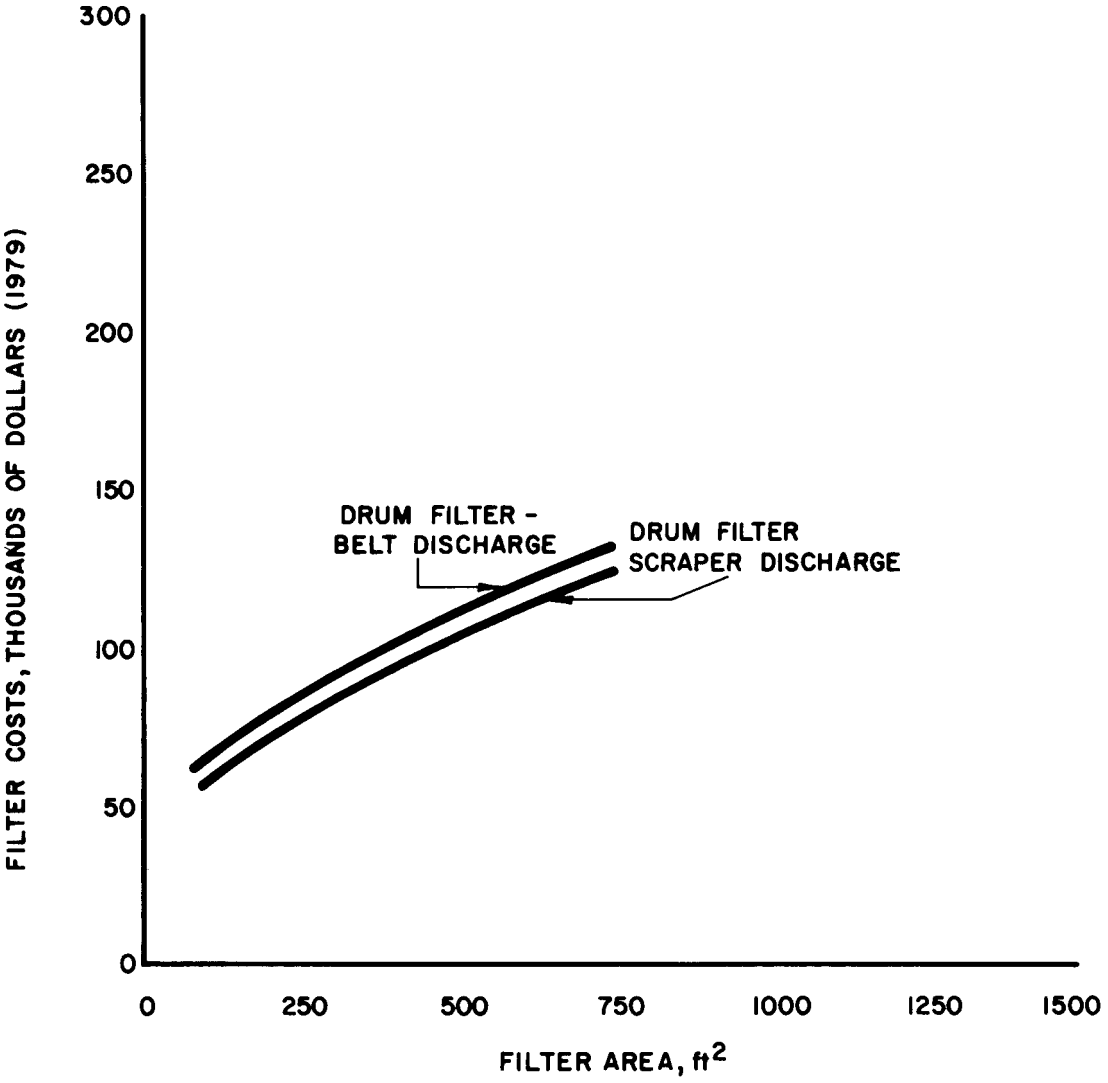


Figure 11-26. Capital Costs for Vacuum Filters

Source: Sludge Dewatering for FGD Products, EPRI FP-937.

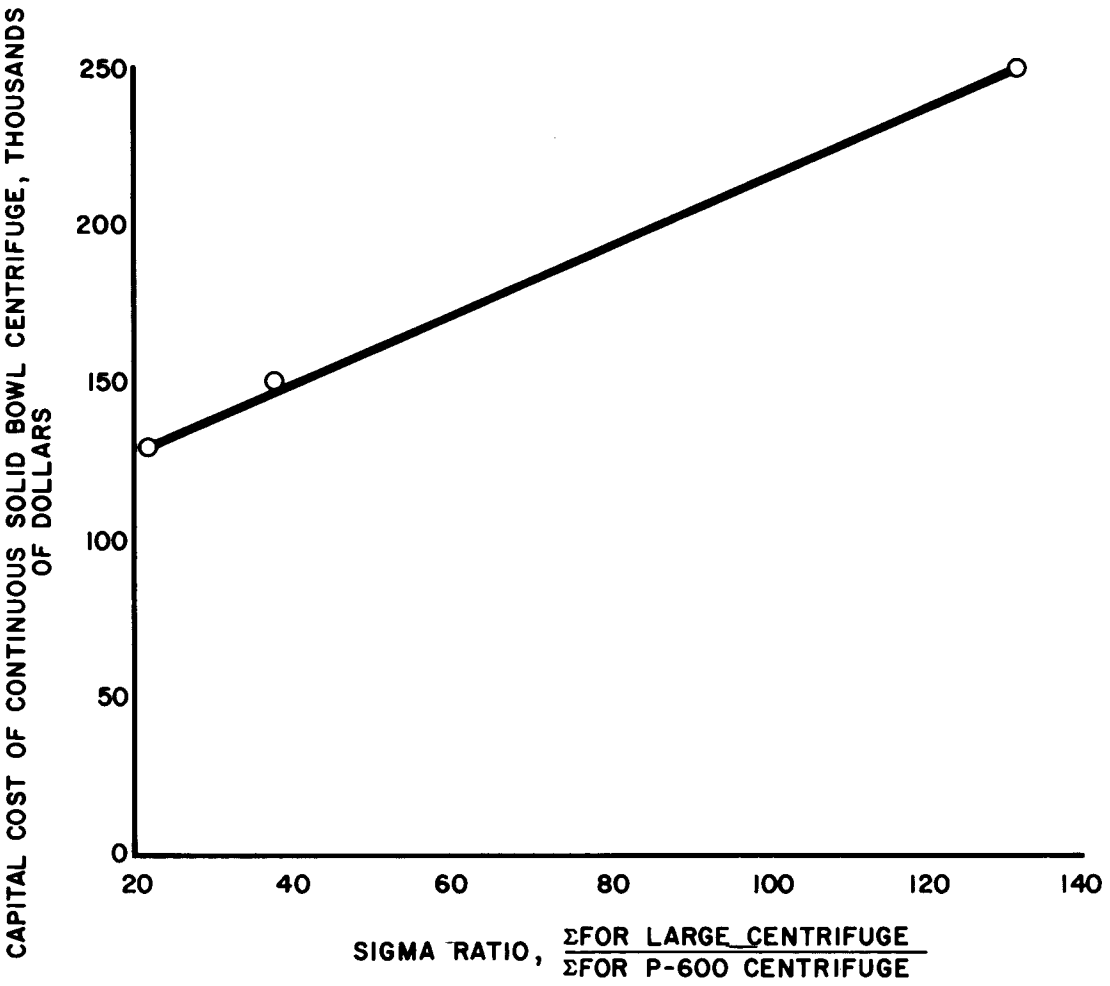


Figure 11-27. Centrifuge Capital Cost as a Function of Centrifuge Capacity

Source: Sludge Dewatering for FGD Products, EPRI FP-937.

Operating and Maintenance Costs

The following is a summary of base costs related to the operation and maintenance of thickener, filter, and centrifuge processes (3).

Thickener:

- Electricity cost/yr. (includes drive and pump motor) - 0.55% of thickener capital cost (assumes operation 100% of time and power cost 4¢/kwh).
- Manpower cost - Rate $23.75/day. Assume manhour requirements as:

  3 manhour/day for operation
  3 manhour/day for monitoring underflow etc.
  3 manhour/day for maintaining polymer system
  3 manhour/day for each additional thickener.

- Maintenance cost - 1% per year of the initial capital cost.

Vacuum Filter:

- Electricity cost (Thousands of Dollars/yr.) $\simeq$ 0.02 x (Air Rate cfm @ 20 inch Hg.)
- Manpower cost - Rate $23.75/day. Assume 12 manhour/day required to operate a vacuum filter facility.
- Maintenance - 4.5% per year of the initial capital cost.

Centrifuge:

- Electricity cost (Thousands of Dollars/yr.) $\simeq$ 1.5 x (Tons of dry solids loading/hr.)
- Manpower cost - Rate $23.75/day. Assume 3 manhour/day/centrifuge.
- 4.5% per year of initial purchase price.

The summary of costs presented above are estimates, and the actual cost may vary significantly depending on the particulars of the process and installation.

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Section 12

FIXATION/STABILIZATION

PURPOSE

This section provides information on the fundamentals of stabilization/fixation, alternative stabilization/fixation technologies, and an outline for design procedures to utilize for implementing stabilization/fixation processing.

DEFINITIONS

The terms stabilization and fixation are often used interchangeably in the technical literature and there is, in fact, no generally accepted, clear differentiation between these terms. In this manual, a distinction is made for the sake of clarity and is based primarily on the mechanisms involved. Stabilization is used in a broad sense to mean any chemical and/or physical treatment designed to improve chemical and/or physical properties. However, in this manual the term will mean the addition of flyash, soil or other similar material to the sludge to induce only physical changes without chemical interaction between the additive and the sludge. Fixation (sometimes termed chemical treatment) on the other hand, is a type of stabilization which involves the addition of reagents causing chemical reactions with the sludge. The better known processes employ lime and other alkaline materials such as blast furnace slag or alkaline flyash which result in cementitious-type reactions in the sludge. Less-developed processes use other mechanisms. Regardless of the mechanism, the reactions with the sludge bond the solids together to reduce the permeability and increase the shear strength, thereby enhancing the physical stability and environmental acceptability. This manual focuses on the better known processes most of which have been implemented at full-scale scrubbing operations.

IS STABILIZATION/FIXATION NECESSARY?

Legal Framework

Fixation/stabilization is not presently mandated directly or indirectly under any Federal or state regulations. The EPA has been leaning in that direction but no specific regulations have been promulgated. The question of whether fixation/stabilization is required became of significant interest with the action of the U.S.

Appeals Court in remanding certain new-source performance standards promulgated under the Clean Air Act to the EPA (1). One of the items of consideration in the remand was the requirement that power plants use lime slurry scrubbing systems with the attendant problems of scrubber sludge. In a draft statement, the EPA responded to that portion of the remand on September 10, 1975, saying that the permanent land disposal of raw (unfixated) sludge was considered environmentally unsound and that the "adverse environmental impact of sludge disposal can be avoided at reasonable cost by fixating the sludge, or by using alternative control systems that do not generate sludge" (2).

The most recent, pertinent court action was in the U.S. District Court, Southern District of Indiana, Indianapolis Division. The case (No. IP 76-657-C) was brought by the United States of America against the Public Service Company of Indiana, Inc. The judgment of September 30, 1977, included the statement "No final response (from the EPA) has been submitted . . . and Environmental Protection Agency has taken no final position on what, if any, methods are available to dispose of the sludge resulting from lime or limestone slurry scrubbing systems without being exorbitantly costly in an economic environmental way . . ." In the December 5, 1977, Federal Register the "final EPA response to remand" stated that none of the comments received by the Agency had persuaded it to change the policy expressed in the September 1975, draft response (3). These decisions indicate that the question of fixation/stabilization has not yet been resolved.

There are no regulations under the Resource Conservation and Recovery Act (RCRA) which specifically require fixation/stabilization. RCRA does require protection of ground and surface waters around a disposal site and in some situations, the most practical means of reducing leachate and runoff quantities and contamination may be fixation of the sludge (4). Also fixation/stabilization may be of value in developing a waste disposal plan which complies with other regulations.

The regulatory situation regarding FGD sludges, flyash, and RCRA may not finally be defined for several years. The Final Regulations for Subtitle C - Hazardous Wastes were published on May 19, 1980 and these regulations specifically exempt large volume utility wastes from consideration under the hazardous category. Therefore these wastes are regulated under the non-hazardous category and disposal plans must comply with those portions of the RCRA Regulations. The EPA has commissioned a detailed study of the environmental impacts of utility waste disposal and may use the results of this study to modify the current categorization of these wastes. The EPA study and a number of others are currently underway and useful reports

should be published soon by several investigators. It should be recognized that utility solid waste management plans which are now acceptable may require significant revisions to maintain their acceptability as RCRA evolves. Refer to Appendix B for more details on RCRA.

To further complicate current decision making, several states have or are considering regulations identifying flyash as a resource and encouraging its utilization. The state of Maryland identifies flyash and bottom ash as hazardous substances only when they are placed in a permanent disposal site. If ash is stored for eventual utilization, its placement is subject to much less stringent controls. The Commonwealth of Massachusetts may, if flyash and bottom ash are categorized by the EPA as non-hazardous material, identify the ash as a recoverable resource. In this event utilization of the ash in construction might take precedence over its value as a stabilizing or fixation agent for FGD sludges. In both cases, combined disposal of the ash and the sludge, arising from use of the ash to stabilize the sludge, will impose additional costs on the disposal operations. In Maryland use of the ash to stabilize the sludge is recognized as permanent disposal of both materials, thus placing the whole volume of the combined disposal area under the stricter controls governing hazardous waste disposal in that state. In Massachusetts, the impact of using flyash to stabilize FGD sludge will not be clear until the utilities test their wastes using the EP test as given in Section 7, LEACHATE. The designer confronted with regulations of these types must evaluate the costs of disposing of the combined material under prevailing state regulations versus the costs of alternative methods of fixing and disposing of the FGD sludge and the flyash as separate items.

Technical Framework

Another important question is, "Is fixation/stabilization necessary from an environmental and structural stability viewpoint?" The answer to this question is that it depends on the situation. Sometimes fixation/stabilization is necessary, and sometimes it is not. If dry disposal is to be utilized, stabilization by the mixing of dewatered sludge with dry flyash or other sorbent is usually required to reach sufficient dryness to insure physical stability. Fixation may be required from an environmental standpoint and will impart greater stability. If wet disposal is utilized, neither stabilization nor fixation will be required to obtain structural stability as long as the retaining dikes or dam are sufficient for retention purposes. Environmental aspects will be governed by regulatory requirements.

PRIMARY ALTERNATIVES

There are a number of alternatives available for stabilization/fixation methods from which to choose. These include:

Stabilization (physical treatment)

- mixing with non-alkaline flyash
- mixing with soil, such as strip mine overburden

Fixation (chemical treatment)

- mixing with alkaline flyash
- mixing with lime and flyash
- mixing with Calcilox^{R} and (sometimes) flyash

Other alkaline materials such as portland cement or limestone could also be utilized, but have not been economically or technologically demonstrated at the present time.

Recent literature has shown that from a theoretical standpoint lime addition to FGD wastes may reduce the soluble levels of certain constituents such as arsenic and manganese. More importantly, however, the total soluble levels of several other trace metals, such as cadmium, chromium, copper, lead, mercury, selenium and zinc increase in aged FGD wastes following lime addition (47). Therefore, the benefits obtained from permeability reduction may be outweighed by the potential environmental damage from increased toxic metals solubilities.

Laboratory work conducted by Radian Corporation under EPRI RP1260-1 has indicated the addition of hydrated lime to sludge/fly ash mixtures containing high calcium fly ash hindered long term strength development in several cases (48). Radian also observed that in the sludge/ash/lime columns having permeability coefficients in the range of 10^{-4} to 10^{-6} cm/sec, the final pore volume was always greater than the original pore volume. This behavior indicates the possibility of physical instability and deterioration with time in the FGD mixtures.

It should be noted that wet disposal of fixed sludge is currently used only in the Dravo impoundment system with their proprietary material, Calcilox. The other systems now in use, whether proprietary or non-proprietary, all employ dry disposal.

PROPRIETARY PROCESSES

There has been a somewhat general misconception that all stabilization/fixation processes are proprietary and require the services of such companies as IU Conversion Systems (IUCS) and Dravo Lime Company. Fixation processes are not, as a group, proprietary. However, both Dravo and IUCS regard their respective processes as proprietary.

It should be recognized, however, that these and other companies have valuable experience with handling and processing FGD sludges, and it may be worthwhile to retain the services of these firms. The range of service varies considerably including: problem identification, design only, design/construct, or design/construct/operate. The two firms with commercial fixation processes have taken a flexible approach and provide the level of services desired by the utility.

A recent EPRI report shows that there are only two companies providing fixation processes for utility applications on a full scale multiple user basis -- Dravo Lime Company and IU Conversion Systems, Inc. (5). Two other firms - Research Cottrell, Inc. (6) and American Admixtures, Inc. (7) - have designed and/or operated FGD sludge disposal systems. However, these services are similar to those provided by other utility contractors and A/E firms and they do not involve proprietary products or processes. Several other firms have done pilot scale or laboratory testing work in FGD sludge fixation but none of these firms claims a full-scale, market-ready system. Most appear to have halted any work on FGD sludge fixation and redirected their efforts toward management of hazardous and toxic wastes (8,9,10). In addition, one utility - Minnkota Power Cooperative - uses highly alkaline flyash as the SO_2 sorbent to result in some fixation before the mixture is placed back in the mine for disposal.

Both Dravo Lime Company and IU Conversion Systems, Inc. hold patents on their respective processes. The IUCS patent (No. 3,785,840) covers the use of lime and flyash to fixate FGD sludges and form Poz-O-Tec^R material, the IUCS registered trademark for the material produced by its process. The Dravo patent (No. 3,920,795) covers the use of a granulated blast furnace slag derivative with the registered trademark of Calcilox to fixate the FGD sludge with or without flyash. Both firms market the services and/or products under a pricing structure which includes a royalty for the use of their process.

At this time there is some doubt over whether or not fixation by lime addition is truly a proprietary process. Research Cottrell constructed an alkaline flyash and FGD sludge blending and disposal facility at the Martin Lake Plant of Texas Utilities Generating Company. Because the sludge-flyash mixture forms a cementitious material similar in many ways to IUCS's Poz-O-Tec, IUCS brought suit for infringement of their patent. After a jury trial and a review by the trial judge, a final judgement was entered on November 18, 1978, by the Federal District Court that the IU patent was, in part, invalid (11). IU has appealed this judgment to higher Federal Courts but expects no further judicial action until late 1980. They regard themselves primarily as a utility service contractor and do not believe the patent is essential to their business success (12). Except for appealing the Texas judgment, they are not currently engaged in activity defending their patent.

A number of utilities, or their service contractors, are employing non-proprietary methods for FGD sludge fixation. In practically all cases, the methods consist of some form of sludge dewatering followed by blending with alkaline flyash. In a few cases, where alkaline flyash is used as a scrubbing agent or where the scrubber is used primarily for particulate removal, some degree of fixation of the scrubber sludge fixation may result simply from the residual alkalinity in the flyash.

FIXATION/STABILIZATION MECHANISMS

Stabilization

Physical stabilization is accomplished primarily by reducing the moisture content of the sludge or admixture to the point where structural properties are optimized when the material is disposed of in a landfill. At the optimum moisture content (discussed in Section 8 - DISPOSAL AREA DESIGN), maximum density is obtained. This enables placement of the maximum quantity of material in a given disposal area, improves shear strength and reduces permeability. However, material physically stabilized in this manner is subject to erosion, rapid saturation and leachability potential when exposed to rainfall.

The dewatering methods, such as thickening, centrifugation, and vacuum filtration, all extract water physically or mechanically from the sludge. However, the particle size and crystal structure are such as to limit the extent to which mechanical dewatering can be effective. The addition of dry flyash or other dry material, such as soil, accomplishes two things. It dries out the mixture by spreading the entrained water through a larger weight of solids while improving the particle size distribution so that closer packing can be accomplished. The additional drying and

closer packing result in increased shear strength, lower permeability and lower combined volume. There are no chemical reactions involved in the changes, so the stabilization process is reversible. If the mixture is re-wetted or allowed to saturate, the material will fluidize causing a rapid decrease in shear strength and possible structural failure. Precautions must, therefore, be taken at an actual facility to minimize water contact with a stabilized fill.

Fixation

Fixation processes employ the same mechanisms described above (at least for dry disposal), while at the same time taking advantage of chemical interactions between different components or additives in the sludge. Presently available processes stabilize FGD wastes with chemical reactions similar to those involved in cement chemistry, i.e., the hardening of concrete. Some of the principal reaction mechanisms are described below.

Portland Cement Chemistry. The setting or hardening of portland cement is a hydration reaction. When portland cement is mixed with water, the water chemically combines with the cement during the reaction process to become part of the final solid product. The solid products form a matrix which physically encapsulates and sometimes chemically bonds any filler which may be present. The following description is a simplified version of very complex chemistry, and there are a number of side reactions which can occur to affect the final material properties.

Portland cement contains three compounds of principal interest: tricalcium silicate ($3CaO \cdot SiO_2$), dicalcium silicate ($2CaO \cdot SiO_2$), and tricalcium aluminate ($3CaO \cdot Al_2O_3$). These hydrate more or less in the following fashion:

$$2(3CaO \cdot SiO_2) + 6H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2$$
$$2(2CaO \cdot SiO_2) + 4H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + Ca(OH)_2$$
$$3CaO \cdot Al_2O_3 + 6H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 6H_2O$$

These compounds comprise the primary cementitious agents which bind concrete aggregates together into a monolithic mass. They are responsible for the dense, insoluble and impermeable nature of concrete. In a similar way, portland cement may be utilized to bind FGD sludge solids particles together to fix the material.

Although portland cement is quite effective as a stabilizing agent, it is relatively expensive in methods presently proposed. Blast furnace slag and flyash, being waste products themselves, contribute to lowering costs below those for any system utilizing portland cement as the cementitious stabilizing agent.

Blast Furnace Slag. Blast furnace slag is the material which rises to the top of the blast furnace charge during pig iron production. It is composed of clayey impurities inherently present in iron ore together with limestone which is added as a fluxing agent. The molten state of these materials in the furnace allows them to mix thoroughly so that they are tapped off as a nearly homogeneous blend of lime, silica, and alumina. The compositional ranges for blast furnace slags are shown in Table 12-1.

Table 12-1

COMPOSITION OF BLAST FURNACE SLAG

SiO_2	28 to 38%
Al_2O_3	8 to 18%
CaO	35 to 45%

In order to be suitable for use as a cementitious agent, slag must be rapidly cooled or quenched so that a glass is formed. When finely ground, quenched slag becomes a slow setting cement. However, it is so slow setting that a small amount of activator must be added to accelerate this reaction into the range of practical usefulness. The activator may be lime, soda ash, gypsum, potash or portland cement itself.

Blast furnace slag hydrates more slowly than portland cement but final strengths are nearly the same. The reactants and products involved are presented in Table 12-2.

Table 12-2

BLAST FURNACE SLAG REACTIONS

REACTANTS	PRODUCTS
$2CaO \cdot SiO_2$	
$2CaO \cdot Al_2O_3 \cdot SiO_2$	$3CaO \cdot 2SiO_2 \cdot 3H_2O$
$CaO \cdot Al_2O_3 \cdot 2SiO_2$	$3CaO \cdot Al_2O_3 \cdot 6H_2O$

It should be noted that the blast furnace slag reaction products are practically identical to those of portland cement.

Lime/Flyash. The lime/flyash reaction is very similar to the blast furnace slag reaction, only slower, and it does not yield as high a strength if the materials are of the same density. The composition of flyash is quite variable, as shown in Section 3 - WASTE COMPOSITION.

Flyash is formed in a boiler in a molten state and rapidly cools so that it too is a glass. Much of this glass is in the form of mullite, $3Al_2O_3 \cdot 2SiO_2$. When mixed with lime and water, the glass experiences alkali attack resulting in the products:

$$3CaO \cdot 2SiO_2 \cdot 3H_2O$$
$$3CaO \cdot Al_2O_3 \cdot 6H_2O$$

It should again be noted that these products are basically the same as those of portland cement. Alkaline flyashes are, in effect, self-cementing because they contain free alkaline materials available to react with the mullite.

Additional Reactions. Scrubber sludge stabilized by the reaction products presented in the foregoing does not behave in a manner precisely identical to concrete for a number of reasons. One of the most important differences is the quantity of gypsum and calcium sulfite present in the sludge. These two compounds can take part chemically in both the lime/flyash and blast furnace slag reactions. The reactants and products are shown in Table 12-3.

Table 12-3

SULFATE AND SULFITE REACTIONS

REACTANTS	PRODUCTS
$3CaO \cdot Al_2O_3 \cdot 6H_2O$	
$CaSO_4 \cdot 2H_2O$	$3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$
$CaSO_3 \cdot \frac{1}{2}H_2O$	$3CaO \cdot Al_2O_3 \cdot CaSO_3 \cdot 7H_2O$

The sulfate product shown in Table 12-3 is always present in concrete to a small degree because gypsum is added to portland cement as a set-retarding agent, and its influence on engineering properties is well understood. The sulfite product is not normally present in concrete, but studies indicate that its influence on the behavior in cement chemistry systems is similar to that of the sulfate compound (47).

MIXING WITH NON-ALKALINE FLYASH OR SOIL

Description

Conceptual systems for mixing of sludge with non-alkaline flyash are shown in Figure 12-1. The scrubber bleed is brought to a thickener for concentration, then put through a vacuum filter or centrifuge for further dewatering. Dry flyash can be mixed in at this point with a shaft or muller mixer to provide the desired mix consistency. The dry mix is then transported to the landfill for placement and compaction.

A variation on this is to mix the flyash or other dry material with earthmoving equipment at the landfill rather than at the plant. This may be practical where the sludge is to be mixed with strip mine spoil or other material already at the disposal site. However, landfill mixing may be difficult or impossible in those situations where the dewatered sludge is still fluid, because the sludge is difficult to transport. In addition, uniform or homogeneous mixtures seldom result from such on-site mixing.

Properties

There is little published information available about the physical, chemical, and engineering properties of FGD sludges stabilized by mixing with non-alkaline flyash.

Range of Applicability

Physical stabilization is generally applicable where dry disposal is advantageous (see Section 5 - DISPOSAL ALTERNATIVES and Section 9 - PROCESSING). The critical factors are the optimum moisture content and availability of dry material for blending with the sludge. The computations shown in Section 9 - PROCESSING illustrate how to determine these critical factors. Some careful test work will be needed to determine whether the sludge can be sufficiently dewatered.

Also, since dry flyash is necessary, this system is only applicable to those situations where it is available in sufficient quantity. Mixing with strip mine spoil is generally applicable only for mine-mouth plants, because transport costs would be excessive for most other facilities.

The processing/disposal method is not particularly affected by geographic location or disposal site topography. Drier climates and dry disposal sites are preferred because of lessening the opportunity for re-fluidizing the sludge. The most signi-

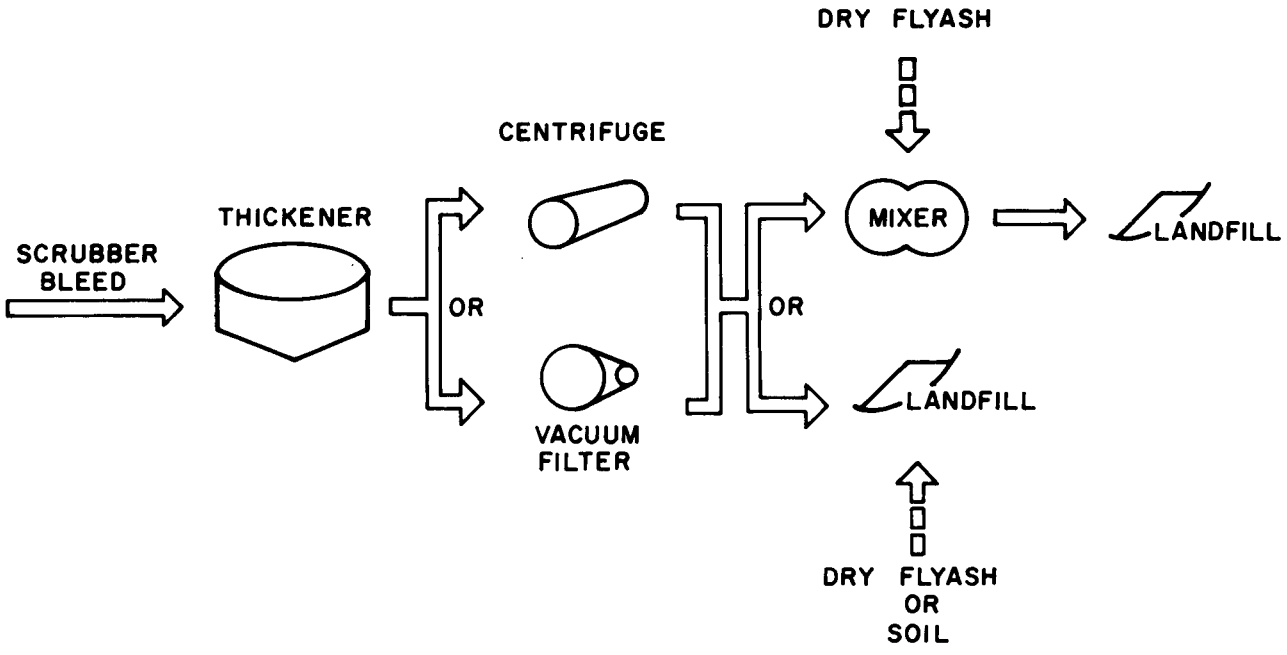


Figure 12-1. Alternatives for Blending Non-Alkaline Flyash.

ficant constraints are the ability to dewater sludge to the desired solids content and to have sufficient dry flyash available for blending to the proper consistency.

Environmental Considerations

There are no data available to substantiate claims for significantly improved environmental acceptability. Most of the environmental advantages come about because this is a dry disposal method. The potential for leachate generation is reduced because the material is dry, and there is no constant head of water causing leachate generation. The permeability is somewhat lower than untreated sludge due to compaction, but not sufficient to prevent fairly rapid permeation.

Since the mixture will refluidize and erode, precautions should be taken to prevent contact of placed and compacted sludge with groundwater, surface water, and precipitation. This can usually be accomplished by careful site selection, diverting ground and surface water, and covering exposed material so that it is protected from the elements.

The stability of landfills created by mixing of sludge and dry flyash has not been tested. Because of the potential for re-fluidizing the placed material, there is some doubt about the long-term structural integrity of a landfill composed of the mixture. A fill could be safely constructed, covered with soil and revegetated, but it is not known whether future site development would be safe. Also the landfill permeability may exceed allowable limits, and a liner might be required. These factors need to be investigated.

Mixing of FGD sludge with strip mine spoil or other similar materials has not been thoroughly evaluated. Obviously a whole new set of environmental concerns enters the picture when this alternative is considered, and a utility should proceed carefully when evaluating this possibility. Work conducted by A.D. Little, Inc., discusses some of the potential problems in more detail (13).

Dravo Lime Company has completed an experimental program determining the fertility of synthetic soils manufactured by blending FGD sludge fixed by their proprietary process and municipal sewage treatment plant waste filter cake (14). Proportions up to 20% municipal waste were mixed for potting soil for test plantings of several field crops. The test results demonstrate that plants will grow in this type of synthetic soil but that only certain plant types are really successful. The synthetic soils exhibited very high pH levels, a feature which affects the growth and chemical content of the plant materials. Certain elements, notably iron and alumi-

num, tend to be drawn into the plants by the high pH of the synthetic soils. The researchers indicated that additional work should be done, but there is currently no known activity in this area.

Implementation Status

One plant which has utilized the concepts described here is the Southwest Station of Springfield (MO) City Utilities. FGD sludge is processed by thickening, followed by vacuum belt filtration. As described in Section 5, the filter cake is then blended with flyash, and the mixture is trucked to an on-site landfill.

MIXING WITH ALKALINE FLYASH

Description

There are a number of possible alternative concepts for stabilizing the sludge with alkaline flyash. The primary alternatives are shown in Figure 12-2.

The simplest case is where the alkaline flyash is used primarily as the scrubbing reagent or where the scrubber is designed primarily for particulate removal. In these cases, the scrubber bleed can usually be ponded, the solids allowed to settle, and the sludge excavated and landfilled.

In other situations, the scrubber bleed is routed to a thickener, and the thickener underflow is sent to a centrifuge or vacuum filter. The dewatered sludge is then mixed with alkaline flyash and the mix transported to a landfill. A variation is to bring the sludge to the landfill and mix it with flyash on site. Another possibility is to omit secondary dewatering and blend thickener underflow directly with alkaline flyash.

Properties

Little data are available on the physical properties of sludges disposed of by mixing with alkaline flyash. Radian Corporation included tests involving such ash their work on EPRI RP 786-2 as reported in FP-671, Volumes 1 and 2. Their tests involved alkaline ash from lignite and subbituminous coal. They report a compressive strength approximating that of concrete for one sluge-flyash mix. Data show a direct relationship between CaO content of the flyash and the unconfined compressive strength (15).

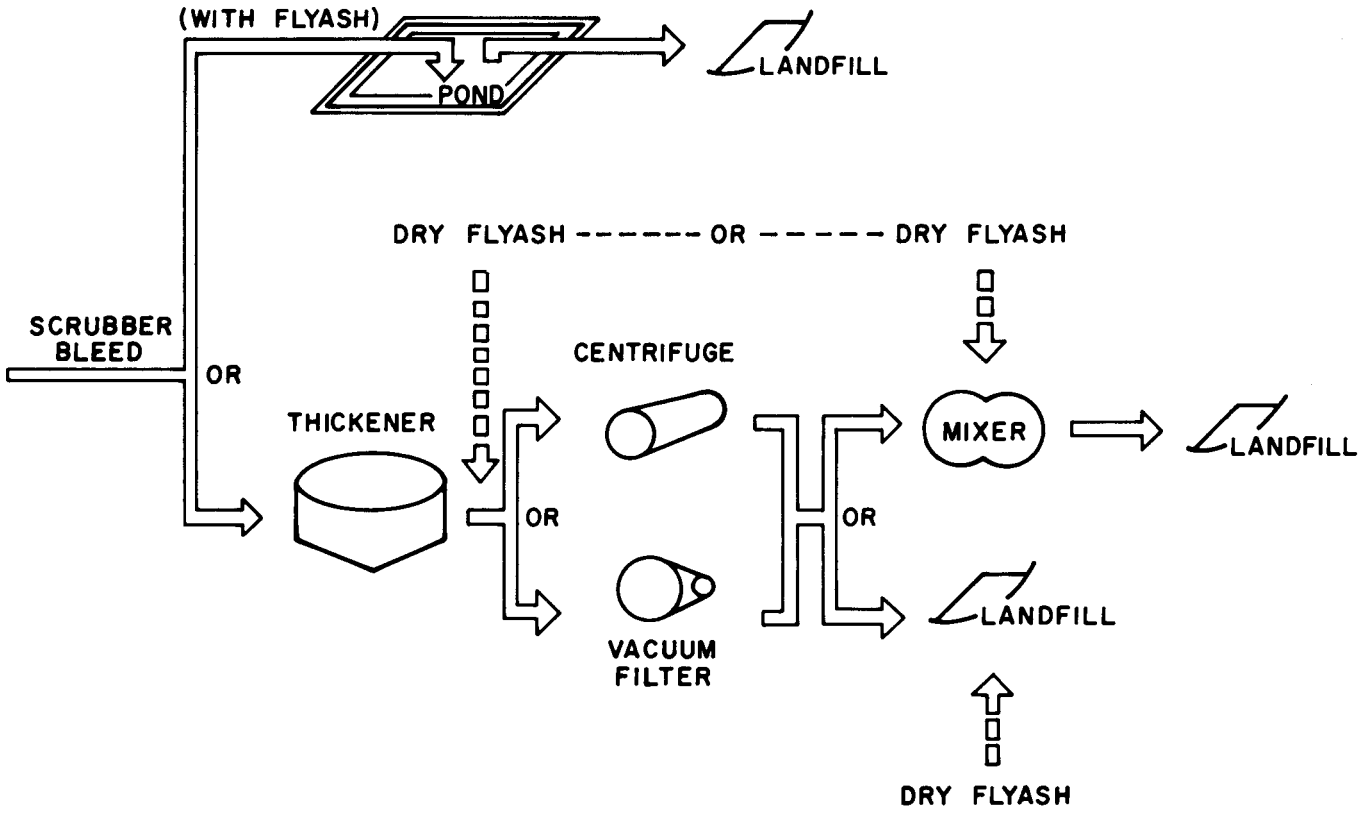


Figure 12-2. Alternatives for Blending Alkaline Flyash.

Range of Applicability

In general, blending with alkaline flyash appears to have particular advantage for the western states, as well as at other locations using western coal. Alkaline flyash is relatively common with western coals and lignite. Also, high evaportation rates contribute markedly to dewatering of sludges in ponds, so simple ponding followed by landfilling is favored in arid regions.

Environmental Considerations

The available data indicate environmental concerns are minimized utilizing this technique. Water-related problems are minimal because the significantly reduced permeability and dry placement reduce the opportunity for leachate and runoff to occur. Land reclamation is greatly facilitated because of the physical stability of the final material. The primary environmental concern relates to fugitive dust from handling, transport, and working of the dry sludge/flyash mix. The active area of the disposal area should be minimized and the inactive area covered to prevent excessive dusting.

Implementation Status

A number of western-coaled power plants are combining sludge with alkaline flyash. The Public Service of Colorado scrubber units (primarily used for particulate scrubbing) use interim ponding, excavating from the ponds for landfill placement. Similar procedures have been used at the Four Corners Station of Arizona Public Service and the Dave Johnston Plant of Pacific Power and Light.

Alkaline flyash is used as the scrubbing reagent in the scrubbers for the Unit No. 2, Milton R. Young Station, Minnkota Power Cooperative. The sludge in the bleed stream from the scrubber is partially dewatered in a thickener, then sent to a vacuum filter for final dewatering. The filter cake is transported to strip mine pits for disposal and to aid in the land reclamation.

The largest installation of this type is at Texas Utilities' Martin Lake Plant. Here, thickener underflow is dewatered by centrifugation, then mechanically mixed with dry flyash to give a soil-like material for landfilling. There is sufficient dry flyash available so that the company is exploring the use of eliminating the use of the centrifuges and simply mixing thickener underflow with the flyash.

MIXING WITH LIME AND FLYASH

Most of the full-scale work relating to the addition of lime and flyash to FGD sludge to accomplish fixation has been conducted by IUCS. Other researchers have found similar results in laboratory studies (16,17,18). Most of the information presented here, therefore, relates to Poz-O-Tec^{R}, the name of the product derived from the IUCS lime/flyash addition process.

Description

A simple process flow diagram is shown in Figure 12-3. The process is similar to that described for non-alkaline flyash except that lime is added. Typically, the scrubber bleed is thickened and vacuum filtered. Centrifuges can be used, but up to this time drum vacuum filters have been preferred. The filter cake is then mixed with dry flyash and lime in an appropriate mixer and transported to a landfill.

While mix proportions will vary depending upon availability of material, a mixture of 0.5 to 1 part or more of flyash to 1 part sludge, dry weight basis, is typical. Lime is added at up to 3% of the dry weight of the mixture. Preferred moisture content of the mixture is the minimum which will allow ease of handling and efficient compaction in a landfill. If the mixture has high initial moisture content, due to low flyash to sludge ratio, stockpiling at the processing plant discharge for up to three days will allow the material to develop the physical characteristics necessary for final disposal. Proper placement and compaction in a landfill are also necessary to obtain maximum advantage of the fixation process.

Properties

Dewatering the sludge and further reducing the moisture content by the addition of dry flyash results in a mixture suitable for placement in a landfill. As the material cures, cementitious reactions occur which provide the necessary physical properties with regard to disposal or utilization.

Moisture Content. The goal in processing the FGD sludge is to obtain a mixture suitable for landfill disposal. Although not necessary, a mixture at or near the optimum moisture content for placement is preferred, if only to minimize disposal volume. The optimum moisture content will vary depending upon ash and sludge characteristics but is generally in the range of 35 to 65% (19).

Bulk Density. The reduction in moisture content and increased density resulting from compaction results in bulk and dry bulk densities considerably greater than

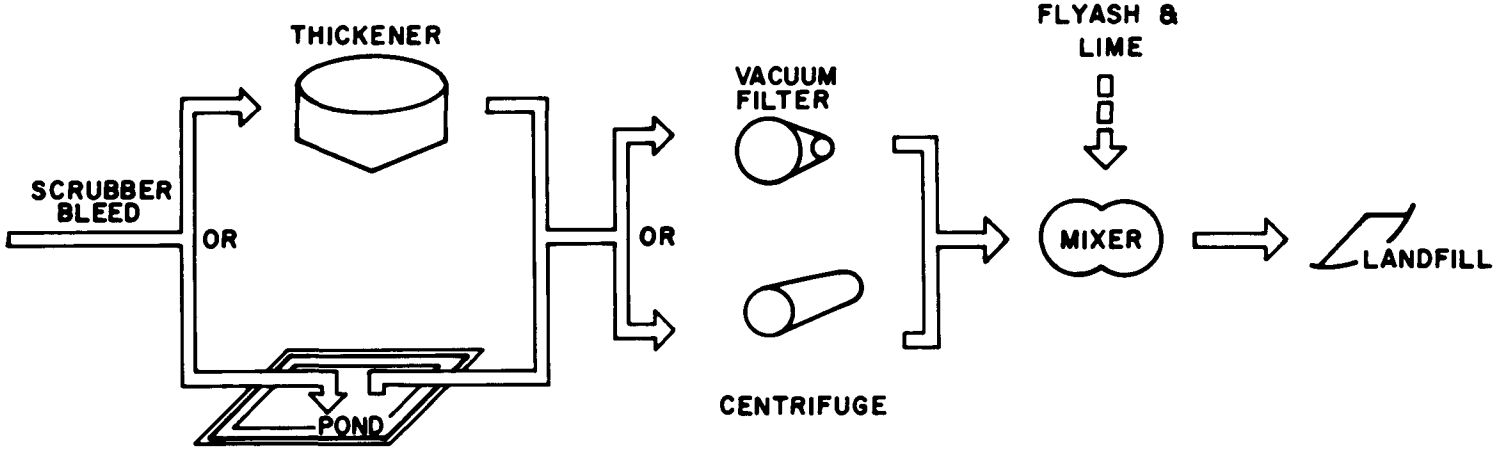


Figure 12-3. Alternatives for Blending Flyash and Lime.

with untreated FGD sludges. Typical ranges for Poz-O-Tec materials are 95 to 100 lb/ft^3 bulk density and 65 to 75 lb/ft^3 dry bulk density (18,19).

Permeability. Freshly placed mixtures have permeabilities on the order of 10^{-5} cm/sec. As the material cures, the permeability is reduced, reaching values of 10^{-7} cm/sec after 60 to 90 days according to reports from IUCS (18,19). An ongoing program of sampling and testing at a full scale landfill is obtaining higher permeabilities (10^{-4} to 10^{-6} cm/sec) but the analysis is not yet complete and the differences may be attributable to other factors (49). In comparison, untreated FGD sludges and flyashes typically have permeabilities in the range of 10^{-4} to 10^{-5} cm/sec. Lime/flyash/sludge mixes are, therefore, about 100 to 1000 times less permeable than both untreated FGD sludge and flyash (20).

Strength. Poz-O-Tec mixes tested in unconfined compression exhibit strengths of several thousand pounds per square foot (21). The material is suitable for supporting normal foundation loads.

Other test results indicate angles of internal friction of 40° and cohesion values of 1500 to 50,000 lb/ft^2 (22). Therefore, the material can be placed on normal landfill slopes of 2 horizontal to 1 vertical without concern about stability of the fill with regard to itself. In contrast, test results with unfixed sludges indicate friction angles of 20° to 30° and little or no cohesion (23).

Environmental Considerations

The physical properties of the mixtures improve with curing since the cementitious compounds form in the void spaces between the individual particles, thus bonding the particles together and reducing the size of the pore spaces. The resulting material is stronger and less permeable.

Leachate quality is improved since some of the sludge constituents are chemically combined into less soluble species. Additionally, some of the pore water and sludge solids are physically encapsulated in the matrix of cementitious compounds. Contact with water permeating through the fixed material is, thereby, prevented. Test results by the Aerospace Corporation at the TVA Shawnee Steam Plant indicate that total dissolved solids in the leachate will be reduced to about 1/2 that of raw sludge (24). Runoff tests conducted by IUCS show reductions in total dissolved solids (TDS) of 1/2 or more after 14 days curing time.

More significant in reducing adverse impacts of leachate from the disposal site is the decrease in permeability achieved. As previously indicated the permeability may be reduced by a factor of 100 to 1000 times less than untreated sludge or flyash (21,25). Therefore, the mass of material leached per unit of time would be 1/200 to 1/2000 that of untreated sludge. Further reduction in leachate quantity are gained by landfill design and construction methods made possible by a dry disposal system.

Sludge fixed with lime and flyash behaves much the same as a silty clay when initially produced and placed in a landfill. The appearance and behavior is very similar to compacted flyash or clayey soil. Upon curing, the material gains strength and develops the properties of a low-strength, concrete-like material.

In contrast to untreated sludge, the fixed sludge will support loads without shear failure. As a result, landfills constructed of fixed sludge are suitable for future development. Based on available data concerning the physical properties, landfills, constructed of the material would be suitable for any type of development which could be constructed on a compacted earth or flyash embankment.

A properly fixed sludge shows no tendency to re-slurry when exposed to water or when compacted. In fact, no special precautions are necessary to protect stockpiled, uncured material from exposure to rainfall prior to placement in a landfill. Fugitive dust and noise are no more of a problem than encountered with any dry disposal method.

Range of Applicability

Fixation with lime and flyash is applicable to all types of calcium-based scrubbing system sludges and sludges from calcium-regenerated, double-alkali systems. Since the process is partially based on a pozzolanic reaction, flyash or some other pozzolan is necessary for its use (26). Therefore, the most significant constraint is the requirement that adequate quantities of dry flyash or some substitute pozzolan be available for blending with the sludge.

The process is not particularly sensitive to variations in sulfite/sulfate ratio except as these influence the dewatering properties of the sludge. The system works best above a pH of 6.5, before lime addition.

The fixation process is not particularly sensitive to varying conditions at the disposal site. Subfreezing temperatures will affect placement and compaction operations in much the same manner as at any landfilling operation. Precautions to avoid freezing of the material, to avoid inclusion of ice and snow, and to insure adequate placement and compaction are required but these concerns are not substantial problems.

The lime/flyash fixation process is not particularly affected by geographic location or disposal site topography. Landfills can be constructed in any location with modification of construction procedures to account for local climatic and topographic conditions, as is done with flyash landfills and earth embankments.

Impermeable liners have not been required for landfills of fixed sludges since the material has a permeability of 10^{-6} to 10^{-7} cm/sec, equal to or less permeable than standard requirements for landfill liners. However, liners might be required if power plant wastes are defined as "hazardous" under RCRA. Possibly the liner could be made from the fixated waste materials if adequate quantities having permeabilities less than 10^{-7} cm/sec could be produced by properly modifying the treatment procedures.

By-Product Utilization

One of the potentially significant advantages of lime/flyash fixation is the possibility of by-product utilization rather than disposal. IUCS performed most of the developmental work on this and has shown that, besides being used as a landfill material, the mix can be used as a road base, as pond, landfill and reservoir liners, as a lightweight aggregate and in artificial reefs. To date, it has been used in a number of projects to demonstrate its potential for by-product utilization. Some of these projects are described in the following paragraphs. When prepared for by-product utilization schemes, the mixture may be modified by the use of other additives and changes in the mix proportions to increase the physical stability of the material.

IUCS used processed sludge from the Mohave Generating Station of Southern California Edison Company as a road base for a parking lot and for sections of public roadway in Arizona. Also at the Mohave Station, IUCS manufactured synthetic aggregate which was used as concrete block filler. The blocks are reported to conform to ASTM specifications (27).

At other locations where they are operating FGD sludge fixation facilities, IUCS has used some of their Poz-O-Tec product as subbase material for roads in a residential area, for an ash haul road, for a municipal parking lot and for a commercial warehouse foundation. Some work has also been done in using the Poz-O-Tec product to construct liners for general runoff ponds at two power plants. Any plan to utilize this material requires extra care and vigilance in proportioning and blending the materials in the product and in placement of the product at the area of use. The IUCS instructions should be followed as closely as possible on all points to obtain the intended results (19).

Implementation Status

IUCS Experience. At the present time, IUCS has a total of 16 systems either in operation or under contract. These are shown in Table 12-4.

The largest installation in operation is at Columbus and Southern Ohio Electric Company's (C&SOE) Conesville Station and is designed to treat FGD sludge and flyash from Units 5 and 6. Total rated capacity of these two units is 830 MW. The plant burns Ohio coal with 4.5% sulfur and 14.9% ash. IUCS designed, constructed and owns a processing plant adjacent to the station. The facility is managed by IUCS with operating personnel provided by C&SOE. Disposal is managed and performed by C&SOE.

Flyash is collected by high-efficiency (99.6%) electrostatic precipitators and conveyed pneumatically to the IUCS facility. The bleed stream from the scrubbers is thickened to a 30% solids slurry by C&SOE and pumped to the IUCS facility. The sludge is then pumped to a battery of three vacuum filters where the solids content is increased to about 45 to 50%. Two filters can handle the total two-boiler output of 170 t/hr of sludge with the third filter as a spare. The filter cake is sent to one of two mixers where it is mixed with flyash and quicklime. From the mixers, the material is conveyed outside the building to a radial conveyor which stacks the material for later spreading and compacting. The Poz-O-Tec is wetter than the optimum moisture content for compaction, so it is allowed to stand for two to four days before placement. Ultimate disposal is an adjacent landfill, which has an estimated life of 30 yr (28). The system is further described and pictured in Section 5.

Other Experience. Only two other facilities have used lime/flyash addition for processing their scrubber sludge: Will County Station of Commonwealth Edison Company and Cane Run Station of Louisville Gas & Electric Company (later transferred to IUCS operation).

Table 12-4

PRESENT AND PLANNED IUCS INSTALLATIONS AS OF
November 1, 1979

Company	Station/Unit(s)	MW
Big Rivers Electric	Green 1, 2	480
Central Illinois Public Service	Newton 1	615
Cincinnati Gas & Electric	East Bend 2	600
Columbus & Southern Ohio	Conesville 5, 6	800
Commonwealth Edison	Powerton 51	450
Duquesne Light	Elrama	500
Duquesne Light	Phillips	400
East Kentucky Power Coop	Spurlock 2	500
Hoosier Energy	Merom 1, 2	980
Indianapolis Power & Light	Petersburg 3, 4	1060
Lakeland Utilities	McIntosh 3	350
Louisville Gas & Electric	Cane Run 4, 5, 6	670
Louisville Gas & Electric	Mill Creek 1, 2, 3, 4	1580
Public Service of Indiana	Gibson 5	650
Southwestern Electric Power	H. W. Pirkey 1	720
Texas Municipal Power	Gibbons Creek 1	410

At Will County, the scrubber bleeder was sent to a thickener and the underflow drained to one of two settling ponds. A front-end loader excavated sludge from the idle pond and transported it to the fixation plant. Here, about 20% dry flyash and 10% hydrated lime (dry weight basis) were added with the sludge to a redi-mix concrete truck. The materials were mixed in transit to an adjacent disposal area. The material was discharged from the trucks and, after several weeks of curing, was spread and compacted. The scrubber is now being used for particulate removal.

MIXING WITH CALCILOX^{R}

Process Description

The Dravo Lime Company, Pittsburgh, PA, has patented a method of fixing FGD sludges through the addition of a material termed Calcilox^{R}, which is a cementitious product derived from basic, glassy blast furnace slag (29). Dravo offers three distinct variations of its process for FGD sludge fixation (30). These variations are:

Full Impoundment. As shown in Figure 12-4, FGD sludge (with or without flyash), Calcilox and hydrated or quicklime are mixed together. The lime is added in sufficient quantity to raise the pH of the mixture to 10.5 to 11.0. Calcilox, the hardening agent, is normally added at the rate of 5 to 10% by dry weight of sludge solids. Addition of lime and Calcilox may be dry or in slurry form.

After mixing, the sludge/additive slurry is pumped directly to a disposal pond where the material is deposited and allowed to cure. Pond supernatant may be returned to the scrubbing system or discharged to local surface water streams with an NPDES permit. A Calcilox addition rate, determined through testing, is selected so that the deposited sludge will attain an unconfined compressive strength of 4.5 t/ft^2 within 30 days. This is the system used at the Bruce Mansfield Plant of the Pennsylvania Power Company, described in Section 5, and at Allegheny Power System's Pleasants Power Station.

Interim Ponding. As an alternative, where dry handling of the sludge is preferred, the sludge/additive slurry can be pumped to a series of small curing ponds, see Figure 12-4. The material after curing for a period of 15 to 30 days is excavated and transported to a landfill. A series of ponds are sequentially filled, cured and excavated to allow for continuous operation. The supernatant from the settling slurry is recirculated to the plant for re-use or discharged under an NPDES permit to local streams. This is the system which was used for test purposes at the Duquesne Light Company Phillips Station for approximately 2-1/2 years.

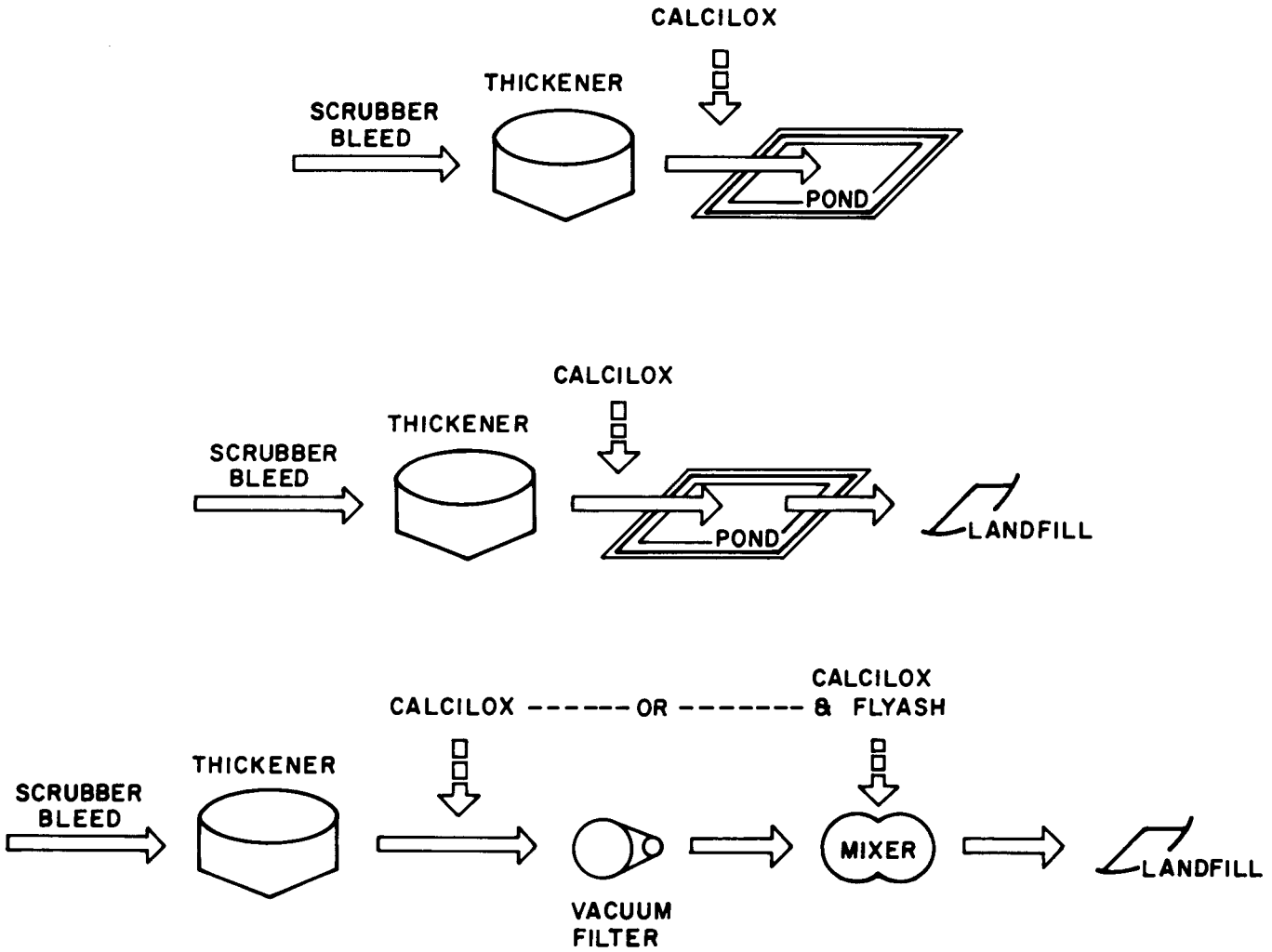


Figure 12-4. Dravo Treatment Processes.

Mechanical Dewatering. For situations where dry flyash is available, the sludge could be partially dewatered by vacuum filtration, mixed with flyash and Calcilox and transported directly to a landfill as shown in Figure 12-4. At the landfill, the material would be allowed to cure for five to six days prior to spreading on the landfill. Calcilox and lime for pH adjustment could be added before or after vacuum filtration. This system has not been used on a full-scale basis.

Product Properties

The addition of Calcilox to FGD sludges cements the solid particles in the slurry together, resulting in a solid material after curing for a few weeks or less. Typical changes in physical properties of sludges after curing are reported by Dravo to be:

Moisture Content. Untreated FGD sludges have moisture contents varying from 150 to 250% of dry weight (40 to 29% solids), with 160% (39% solids) being a typical value (31). Calcilox addition tends to reduce the moisture content of the sludges. Tests on the treated sludges show a range of moisture contents from 106 to 140% (48 to 42% solids)(32).

Bulk Density. The reduced moisture content of treated FGD sludge, results in a corresponding increase in solids content and bulk density, thereby reducing the size of the disposal area required. Dry bulk densities of the treated sludges are reported to vary from a low of 33.1 lb/ft^3 up to 43.7 lb/ft^3 (32).

Permeability. Fixation of FGD sludge with Calcilox, added at a rate of 10% of the dry weight of sludge solids, typically reduces the permeability by one order of magnitude. Permeability values for the treated sludges are in the range of 10^{-5} to 10^{-6} cm/sec.

Compressibility. Calcilox treatment of FGD sludges reduces the compressibility of the material for loading below a certain maximum value. The range over which the compressibility is reduced depends upon the amount of additive used, curing time and other variables. Typically, Calcilox addition reduces compressibility for loads less than 4 to 10 t/ft^2 to the point where settlement is insignificant. Compression indexes are reported as 1.2 to 1.35 for undisturbed material and 0.69 to 1.15 for remolded material.

Strength. Calcilox-treated sludges are routinely tested by Dravo using a pocket penetrometer, an instrument for measuring the strength of soil which gives qualitative results for treated sludges (33). The sludges after 30 days curing typically have unconfined compressive strength in excess of 9000 lbs/ft^2, the upper limit of the calibrated penetrometer scale.

The strength of the fixed sludges has also been determined by direct shear and consolidated, undrained triaxial tests. These tests more accurately define the strength properties of the material. Test results indicate angles of internal friction of 38° to 51° and cohesion varying from 0 to about 10 lb/in.^{2}. These values indicate that the sludge has strength parameters equal to or exceeding those of dense sands. In contrast, test results on untreated sludge indicate an angle of internal friction of about 20° to 30° and little or no cohesion (32).

Environmental Considerations

Calcilox treatment of FGD sludge improves leachate quality and reduces leachate quantity. Test results by Aerospace at Shawnee indicate that total dissolved solids in the leachate will be reduced to about 1/2 that of untreated sludge (34). Since testing by Dravo and others indicates a reduction in permeability by a factor of 10 or more, it is predicted that the TDS leached per unit of time would be 1/20 that of untreated sludge, or less.

Without dewatering, Calcilox treatment does little to increase the density of the FGD sludge. Therefore, the volume of the sludge and the disposal space required are essentially the same before and after processing if the Interim Ponding or Full Impoundment disposal methods are used. Some reduction in surface area required for a disposal area can be attained by the Interim Ponding method as compared to simple ponding of untreated sludge. The reduction in surface area results from the treated sludge having improved handling characteristics, allowing better landfill management and steeper slopes without dikes or dams. Based on bulk density test data, approximately one ac-ft of disposal volume would be required for each 1000 t of sludge solids (32).

In contrast to raw untreated sludge, Calcilox-treated material will support loads without appreciable settlement or shear failure. As a result, landfills constructed of the treated sludge are suitable for future development. For disposal areas developed using the Full Impoundment method, the possible ultimate use of the disposal site can be either a lake or landfill, depending upon final drainage provisions.

However, if used as a lake, the extent to which the sludge would affect water quality and recreational use has not been determined.

After curing, sludge fixed with Calcilox does not tend to reliquify when exposed to excess water. However, severe remolding of sludge samples treated with 10% Calcilox and cured for 30 days will reslurry the material. This tendancy to reslurry is reduced with increased percentages of additives, longer curing periods and higher solids content (35).

In order for the Calcilox additive to be effective, the treated slurry must have a pH of at least 10.5. After the solids have settled, in the Full Impoundment or Interim Ponding methods, the supernatant normally has a pH exceeding 9 due to the dissolved solids (36). Water with a pH that high is not acceptable for discharge into surface streams and the supernatant must be treated with small quantities of acid before entering the stream. Provision must be made at the point of acid addition to allow the dissolved solids to form a precipitate and settle out onto the bottom of a sedimentation basin before the treated supernatant enters the stream. Similarly, if the supernatant is returned to the power plant, either the intended uses must tolerate the high pH or provision must be made to reduce the supernatant pH before it is re-used. If the pH is reduced, caution must be exercised to allow the precipate to settle at a place which does not foul the piping systems. The control of supernatant pH prior to use or discharge is an item which should be provided in the basic system design of the treatment system if the Dravo process is selected.

Range of Applicability

Dravo claims that the process is applicable to all types of calcium-based scrubber sludges. Test data have shown the ability of Calcilox to fix sludges with and without flyash and with varying sulfite/sulfate ratios (29).

Two sludge properties which do affect the process are pH and solids content of the sludge. A pH of about 11.0 is preferred and, if necessary, adjustment of the pH by lime addition to the sludge is recommended. Solids content of the sludge influences the percentage of Calcilox addition required. Laboratory tests have shown that less additive is required for sludges with higher solids content sludges. Calcilox is claimed to be applicable for calcium-based scrubber sludges with solids content ranging from 25% to 60% (29). However, experience has indicated a range of 5 to 75% (37).

The process is not particularly sensitive to varying conditions at the disposal site. Subfreezing temperatures will retard the hardening process; however, laboratory studies indicate that the hardening process will resume once the temperature rises above freezing. Dravo claims that their experience has shown that subfreezing ambient temperatures will not adversely affect the hardening process. In full-scale field operations, the sludge tends to be self-insulating, retaining sufficient heat to allow the hardening process to proceed. Some additional heat is also generated by the hardening reactions which are exothermic.

The required curing period, that is the time required between initial Calcilox addition and final disposal, will vary depending upon which variation of the fixation process is used. With Full Impoundment option, the sludge is transported directly to the disposal site after treatment. No interim curing step is necessary and, presumably, the curing time to attain design strength is not critical. However, in design of Full Impoundment disposal systems, Dravo recommends using sufficient Calcilox additive to attain a penetrometer reading of 4000 lbs/ft^2 after 30 days curing time.

With the Interim Ponding option, curing time is critical because it determines the number and size of the interim curing ponds. As with the Full Impoundment option, a penetrometer reading of 9000 lbs/ft^2 after 30 days curing is the target strength recommended to attain a workable product. Because the interim curing ponds are used in a sequential fill-cure-excavate rotation, strength gain within the design curing time is critical to uninterrupted continuous operation. Dravo recommends the use of four or five ponds in situations where continuous operation is mandatory. The additional ponds allow some system redundancy and greater flexibility with regard to curing time. For greater system reliability, one pond should be reserved, if feasible, for emergencies to permit power plant and scrubber operation to continue if pond excavation is interrupted for any reason.

With the Mechanical Dewatering option, the treated sludge can be transported directly to the disposal site. Laboratory tests indicate that the material should be allowed an initial curing period of three to five days prior to spreading and compaction. Final curing will then proceed after placement in the landfill.

Calcilox treatment is not particularly affected by site topography. The disposal method can be either wet, as in Full Impoundment, or dry, as in Mechanical Dewatering. In areas where liners are required to protect groundwater aquifers or to meet regulatory standards, Dravo advocates using treated sludge as a liner. In this

case, additional Calcilox would be added to the bottom few feet of the landfill to further reduce the permeability to as low as 10^{-8} cm/sec, which was obtained in laboratory tests. Preliminary approval for lining a disposal site with treated sludge was obtained from the State of Ohio by Dravo (38).

Handling and transportation methods for treated sludge depend on which disposal method is used. In the Full Impoundment system, the Calcilox is added to the sludge and the material is then pumped to the disposal site. Precautions to prevent setting of the material in the pipeline are crucial, and Dravo recommends that piping should be designed so that the system can be flushed with water and drained into one or more external sumps. It is also recommended that "dead spots" where the material can set-up be avoided and the piping arrangements and fittings (especially valves) be selected to minimize the void spaces in which sludge can accumulate. For the same reason the operators must be diligent in cleaning, flushing, lubricating, and maintaining the treated slurry mixing, pumping, and piping facilities to prevent build-ups of hardened treated sludge.

Implementation Status

At the present time, the full-scale operating system using Calcilox with the most service is at the Bruce Mansfield Plant in Shippingport, Pennsylvania, operated by the Pennsylvania Power Company. The FGD wastes from Unit Nos. 1 and 2, each 917 MW, are being processed. Both flyash and sulfur oxides are collected in the scrubbing system, about 7,500 t/day of sludge on a wet basis being produced (39). Current additive usage is about 46,000 t/year, reflecting lower than expected power production and coal sulfur contents (40).

The sludge disposal pumps receive the thickener underflow at 20 to 30% solids. In the treatment facility which adjoins the plant, sludge and additive are mixed in two 176,000 gal tanks. Dravo has recommended that 7% by weight of solids in the sludge be added. The slurry is agitated continuously and the tanks are sized for 40 min retention time to insure thorough mixing.

The mixed slurry is pumped through various combinations of four pipelines, a distance of about seven miles to the disposal site. Two 12-in. diameter and two 8-in. diameter pipes are provided for sludge transport and supernatant return, respectively. A flushing system to purge the lines in case of shutdown is provided (41). While Dravo does not advocate 100% redundancy for reliability, the Bruce Mansfield sludge treatment and transport system was designed in this manner (42).

The disposal site is a valley impoundment covering more than 1300 ac. The sludge and supernatant are retained behind a 420 ft high earth and rock-fill dam. The dam has an impervious core, is 2200 ft long at the crest, 1550 ft wide at the base, and is designed to retain the sludge even if it were not stabilized (43). Clearing of the reservoir area is being done as the supernatant water level rises, to reduce erosion, minimize environmental impact and for overall appearance of the area.

The sludge-Calcilox slurry is discharged to the reservoir below the water surface by means of a flexible pipeline. The discharge point is beneath a raft which can be moved from place to place to distribute the material throughout the reservoir. Return water intakes, also on rafts, are provided for supernatant return to the plant or discharge to the Ohio River, if necessary for water balance (44). Acid treatment is normally required to lower the pH of the supernatant to values which are acceptable for discharge or reuse (36).

Dravo has recently completed a system for the Pleasants Station of Allegheny Power System, where the FGD sludge from two 600 MW units will be treated with Calcilox additive and disposed of in a full impoundment. This system will treat 4500 wet t/day of 30% solids sludge from a 1236 MW power plant when in normal commercial operation. Flyash, to be collected separately, will be used for construction of the dam. This system started operation in 1979, but full scale operations have not yet been achieved due to start-up problems with Unit No. 1 and construction delays with Unit No. 2.

Dravo Lime Company currently indicates that they are restricting their marketing target area for FGD waste treatment to the upper Ohio Valley due to limitations on the availability of the raw material and rapidly rising transportation costs for bulk commodities (36).

DESIGN PROCEDURES

There is insufficient experience at the present time to provide detailed design procedures for developing a stabilization/fixation process. The design process is highly variable, depending largely on the type of system desired. In most cases, there is no rigorous design procedure; however, some general guidelines can be offered which may prove useful.

Step 1. Determine Sludge and Ash Volumes and Characteristics

As a first step, use the procedures outlined in Section 3 - WASTE COMPOSITION and Section 4 - WASTE QUANTITIES to determine the quantities and characteristics of the

sludge and ash to be produced. Critical factors relating to sludge properties are: pH, percent solids, amount of flyash captured with the sludge, quantity of dry flyash available, and free calcium oxide available in the dry ash. Free calcium oxide can be measured by ASTM C114-69.

Step 2. Determine Theoretical Processing Requirements

The next step in the design process is to determine the level of processing required. It is of critical importance to know whether stabilization is adequate or whether fixation is necessary, either for technological, environmental, or regulatory reasons. Section 9 - PROCESSING describes a general methodology for determining the level of processing required.

Step 3. Determine Theoretical Requirement for Flyash

Following the line of reasoning shown in Section 9 - PROCESSING, determine the approximate amount of flyash or other material necessary to adjust the sludge to the optimum moisture content. This procedure gives the approximate relative proportions of sludge to flyash necessary to achieve fixation/stabilization. A check of the flyash quantities available at the disposal area will guide the decision on mechanical dewatering requirements.

Step 4. Determine Process Additives Required

If alkaline flyash is being used, determine whether there is sufficient free alkalinity available in the ash to adequately fix the sludge. If there is insufficient alkalinity, determine the lime requirement necessary to accomplish fixation. In the absence of data to the contrary, assume approximately 4% lime by dry weight will be adequate.

Step 5. Combine Steps 1 through 4

The previous steps will indicate the approximate quantities of sludge, flyash, and lime or other materials which will be needed. From this information, storage, handling, and transport equipment can be rough-sized and preliminary cost estimates developed. Provision should be made for peak operating periods as well as normal operating periods.

Step 6. Confirm Design Details

The calculations shown above will not match actual operating conditions. In order to better estimate a full-scale situation prior to purchase and installation of

equipment, it is advisable to run a pilot plant operation to confirm the design details.

The pilot plant program should be designed to match as closely as possible the operating conditions expected at the new scrubber facility. The purpose is to obtain a sludge at the pilot scale that matches as closely as possible the sludge expected from the full-scale facility. While this is seldom possible, it is important to use coal, scrubbing reagent, particulate removal, scrubber operating conditions, and flow conditions nearly identical to those anticipated at the full-scale installation. Worst-case and average conditions should be considered. Baseline pilot plant studies should be run to characterize the waste, as follows:

1. For FGD sludge, determine the effect of variations in:

   quantity
   % solids
   sulfite/sulfate ratio
   excess reagent
   pH
   flyash content

2. For dry flyash, determine the effect of variations in:

   quantity
   free alkalinity as calcium oxide

If thickening and vacuum filter or centrifugation are to be considered in the processing, then these should be piloted at the same time.

As sludge and flyash become available for use in the pilot studies, verify the earlier calculations by mixing appropriate proportions of sludge, flyash, and lime or other materials. The method of mixing and other physical factors will be a function of the size of the pilot plant and the funds available for research. Set up a series of experiments which allows separate testing of different mix proportions and length of curing time. Thirty days is the normal curing time for maximum strength development.

After the samples have cured for the desired length of time, test them for moisture content, solids content, optimum moisture content, dry bulk density, permeability, compression index, angle of internal friction, cohesion and unconfined compressive strength. (See Section 3 - WASTE COMPOSITION and Section 4 - WASTE QUANTITIES for methods of testing.) Other special tests may be required if unusual placement is required.

Based on these tests, it should be possible to confirm the primary design variables of volume and weight which were estimated earlier.

Step 7. Select Appropriate Equipment

Selection of primary equipment necessary for fixation/stabilization is described in other sections and includes:

- Ponds--Section 8 - DESIGN OF DISPOSAL AREAS
- Dewatering Equipment--Section 11 - THICKENING/DEWATERING
- Earth-Moving--Section 13 - TRANSPORTATION

Mixers or blenders have not been discussed previously. At present, there are two types of mixers in service in FGD sludge processing systems, and experience is limited.

Double-Shaft Mixer. This mixer has two counter-rotating horizontal shafts on which are fastened corrugated-face paddles cast of Ni-Hard (chromium-nickel alloy iron) which are mounted in a "tub". The latter is of sufficient length to provide thorough mixing and has removable cover plates. The cover plates are gasketed and dust takeoffs are provided. Capacities range from 150 to 1200 t/hr. Feed is from the top at one end; discharge is from the bottom at the opposite end. An adjustable dam controls the residence time and degree of mixing (45). A top view of the mixer is shown in Figure 12-5. This type is used by IUCS.

Muller. A typical continuous muller has two connected mixing "pans". Inlet is to one pan; outlet is from the other. Each pan has a vertical rotating shaft, to which is fastened a carriage carrying two muller wheels and two plows. Mixing is said to consist of a kneading/smearing/rubbing action. Mullers with mixing capacities from 7 to 500 t/hr are available (46). A top view of the muller is shown in Figure 12-6. This type mixer was installed at the Martin Lake Plant.

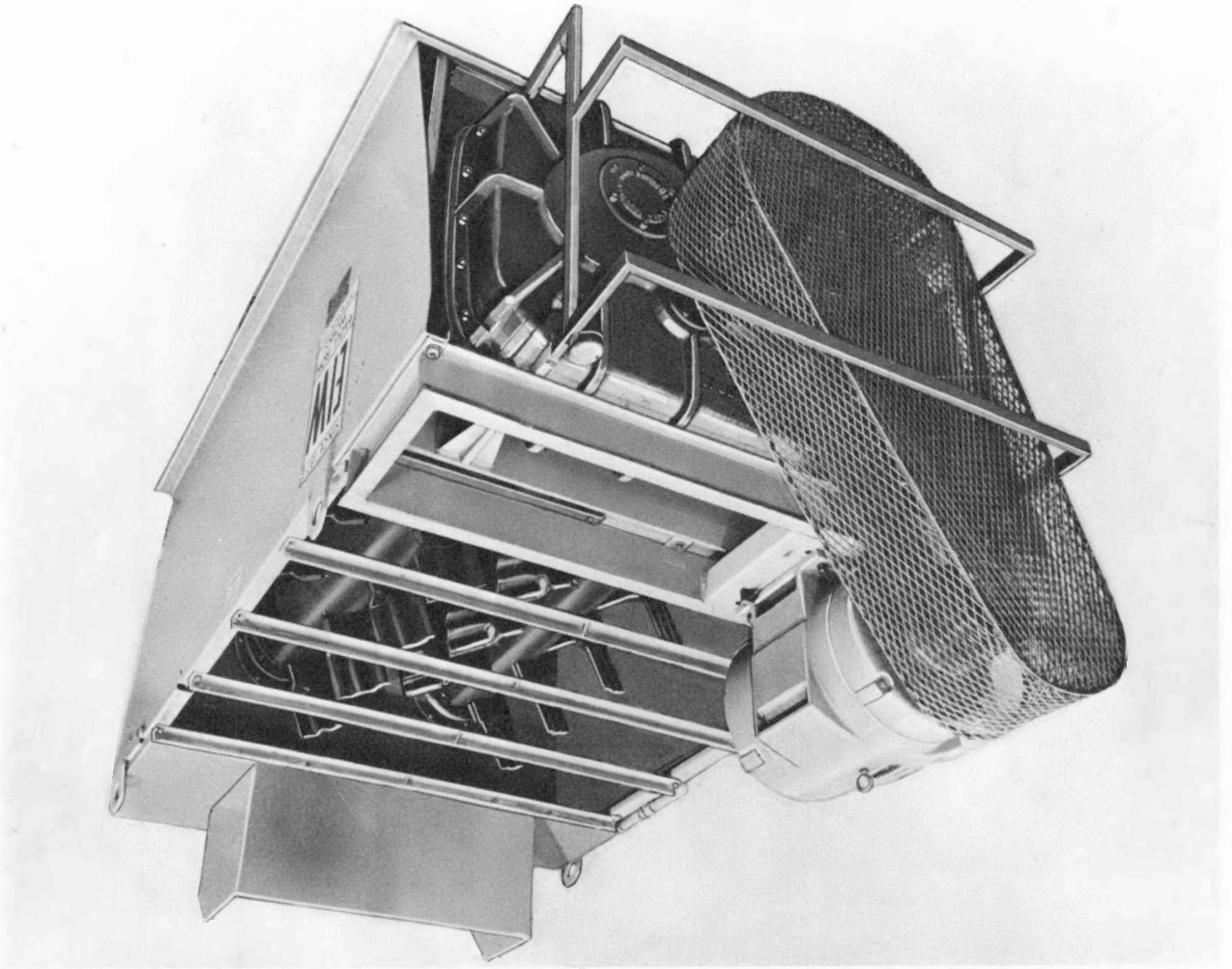


Figure 12-5. Top View of Double Shaft Paddle Mixer.

Courtesy: Eagle Iron Works.

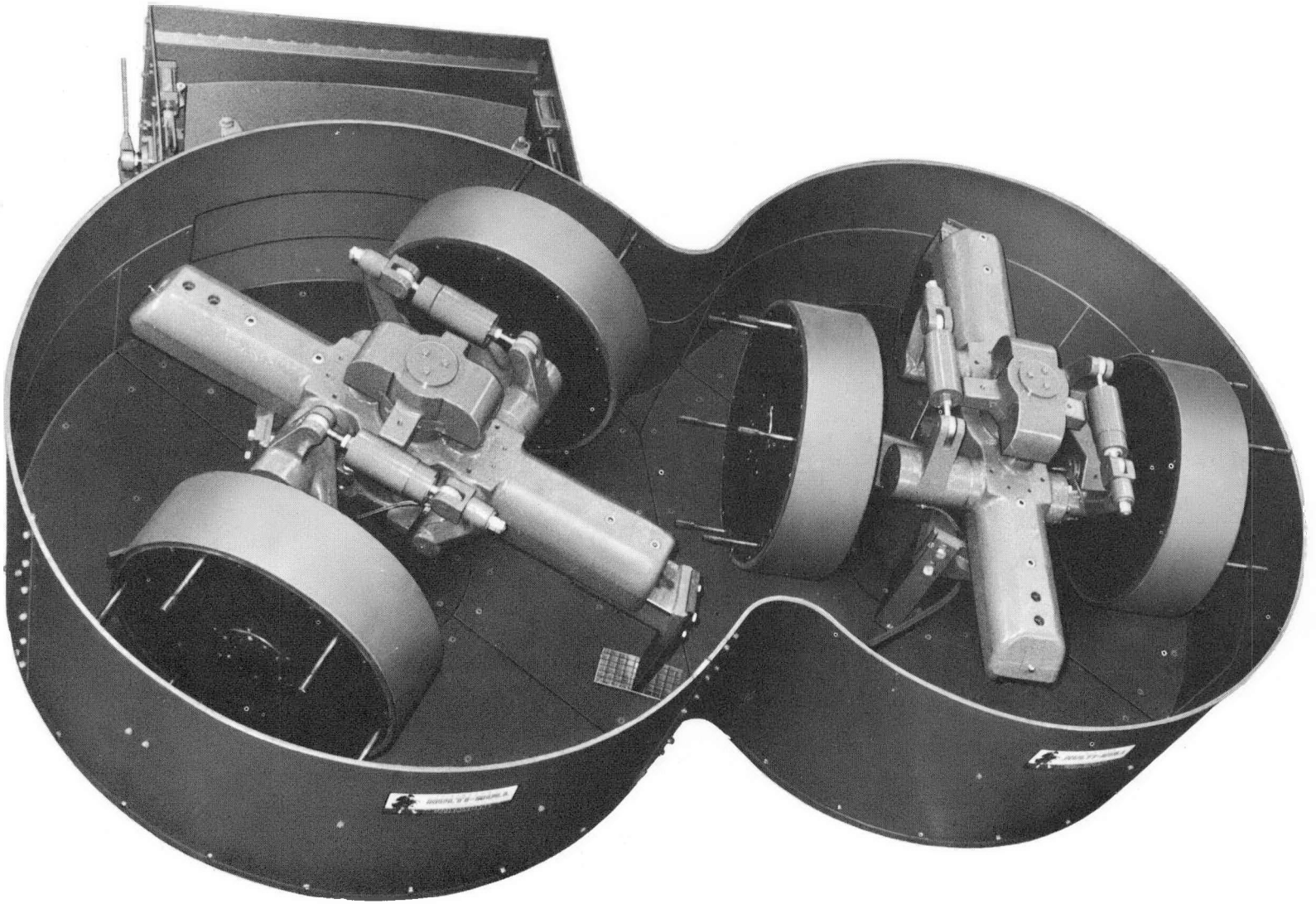


Figure 12-6. Top View of Muller Mixer.

Courtesy: National Engineering Company

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Section 13

TRANSPORTATION

PURPOSE

This section provides information relative to the selection and design of transport methods and facilities for FGD sludge. Both wet and dry disposal methods are discussed along with the waste characteristics pertinent to each method. Surge or temporary storage facilities are a necessary part of a transport system and will also be discussed, along with short-distance transfer equipment.

INTRODUCTION

The sludge transport system is an essential component of the FGD system. It is necessary that the sludge be transported from the scrubber, either to processing steps or directly to the ultimate disposal site, in as continuous a flow as possible. Recognizing that the flow can be interrupted by equipment outages, the inclusion of surge or temporary storage capacity is necessary.

Because transport systems perform a major support function to FGD sludge disposal, and because their costs may exceed 50% of the total capital and operating costs for FGD sludge disposal, considerable attention must be given to the design, layout, and engineering of these systems. The systems are interrelated as an integral part of FGD sludge processing, and it is necessary to determine the best combination of FGD sludge processing, transport, and ultimate disposal. Thus, transport system selection and design depends primarily on whether the FGD sludge will be transported dry or wet, which in turn depends on the selection of the FGD sludge processing and ultimate disposal methods.

OVERVIEW OF ALTERNATIVES

Conceptually there are five transport methods which can be used for FGD sludges.

- Belt conveyors
- Trucks
- Rail
- Barge
- Pipeline

Belt Conveyors

Belt conveyors are popular FGD sludge transport systems, but are limited to dry disposal systems. Conveyor equipment, similar to that used in coal handling, is suitable.

The capital costs for conveyor systems are relatively high. However, short conveyors, especially those mounted on wheels or skids, have a great deal of flexibility and can be moved to different locations. Longer conveyors of several hundred feet or more are usually permanent installations which have economic advantages when the material flow is relatively constant and both loading and discharge points are fixed. Aboveground conveyors are relatively unobtrusive (depending upon the route). The cost of conveyor systems is higher than that of trucks, but they have longer lives and lower depreciation rates.

Trucks

Trucking probably offers the most flexible and, therefore, the most widely used mode of dry sludge transportation. All but two of the 13 utilities using dry FGD sludge disposal, employ truck transport. The availability of trucks, in varied numbers from private contractors for varying time periods, provides the utility with the option of contracting all hauling or supplementing the use of a captive fleet as the need arises.

Truck transport may be utilized for wet (liquid) and dry sludge hauling, but dry hauling is preferred. Dry materials may be handled with equipment such as dozers, scrapers, or front-end loaders, designed for common earthwork or coal-hauling activities, and no special equipment is required. Wet materials would be more difficult to haul, requiring special enclosed vehicles. Hauling of liquid sludge in open vehicles is not feasible because of leakage and spillage.

The primary advantage of truck transportation for FGD sludge is the flexibility offered. Such a method can accommodate changes in the quantity of sludge produced fairly easily, and routes can be changed conveniently in response to relocation of the disposal site. System reliability is inherent, with stand-by provided by additional vehicles. Furthermore, idle vehicles owned by the utility may be used for other hauling purposes at the station on an interim basis. Contract hauling is cost-accountable as an operating expenditure, and requires little or no capital investment. Except for a basic charge which may be part of the contract, costs are incurred

only when sludge is being hauled. On the other hand, trucking is reasonably labor-intensive, and operating costs can be expected to increase appreciably over the life of a scrubber facilty.

A principal disadvantage of truck transport is the high public visibility. The quantity of sludge produced at a fully-operational station requires a nearly continuous flow of truck traffic in and out of the station site. For example, a 1000 MW plant burning a typical eastern coal would require about 110 30-ton trucks per day to haul sludge and flyash from the plant. Hauling over public roads may meet with opposition from affected citizens due to the increased truck traffic and related dust and noise.

Rail

Theoretically, rail cars may be used to transport both wet and dry sludge. However, wet sludge rail transport has not been demonstrated and may prove difficult. Open cars are not suitable for liquid sludges, being subject to leaks and spills during transit, and freezing on prolonged exposure to cold. Enclosed cars containing wet sludge could prove difficult to empty due to settling of the sludge during transit. An alternative would be to maintain mixing in the cars enroute to the disposal site, but this would take specially designed cars which are not presently available.

Dry disposal using conventional side-dumping cars has been shown to be effective at the Martin Lake Plant of the Texas Utilities Generating Company. Bottom dumping from hopper cars and rotary dumping are possible but unproven. There has been speculation that bridging of the waste might make it difficult to unload bottom-dump hopper cars. No specially designed sludge cars have been developed.

It is possible to use existing commercial rail-haul routes or captive private haulways (hauling on track and right-of-way owned or controlled by the utility). The choice depends on the economics of the situation and existing trackage. In general, hauling by commercial routes is not economically competitive at distances less than 50 miles. Hauling by captive private line is viable at lesser distances if the right-of-way exists or can be obtained. Under such conditions, it may be competitive with and preferred to truck transport.

Like other transport modes, there are both advantages and disadvantages to rail transport. System reliability is easily attainable with rail transport because of

the surge capacity available from stand-by rail cars. However, rail cars are not as readily available on a contract basis with short notice as trucks. Also, rail cars are not as versatile as trucks. For instance, an unscheduled shutdown of a scrubber will result in having idle rail cars waiting for sludge to be hauled with subsequent demurrage charges. On the other hand, because they haul bigger loads, rail traffic is not as continuous as truck traffic. As a result, they are less obtrusive than trucks to the general public and may be less of a problem in sensitive areas. Fugitive dust in transit may be a problem and require control by covering the cars or using dust-suppressant sprays.

Barge

Barge transport of FGD sludge may be practical for a few cases, but it does not show the possibility of wide applicability. At the present time, no utilities use barging for FGD waste. Barging will be limited to stations located on or very close to navigable waterways, stations which can consider ocean disposal, and/or stations requiring a long transport distance (greater than about 100 mi).

Theoretically, barging provides the advantages of accommodating wet or dry sludges, having high system reliability and very low unit costs. However, the limited transport routes and the special loading and unloading facilites make the overall economics unfavorable for all but a few selected cases. Except for ocean disposal, barging alone will not get the waste to the disposal site. The off-loading of a barge carrying FGD sludge would require additional transport by pipeline, truck, or conveyor to get the sludge to the actual disposal area. Barging is not, therefore, a practical alternative for most cases.

Pipelines

Pipelines are the most-used FGD sludge transport system because of the predominance of wet disposal. Out of 31 currently operating utility scrubber systems, 18 employ wet handling of the waste, and all of these use pipeline transport of sludge.

A typical pipeline transport facility consists of a single pumping station. More than one might be required for long distances and/or up-hill traverses. For redundancy, two full-size pipelines will be required. This redundancy can be obviated by providing emergency storage capacity in the event the pipeline must be shut down. If supernatant is to be returned to the station, then supernatant return lines will also be needed. If the sludge pipeline is in use only part of the time, it may be available for returning supernatant to the station. Provision should be included for flushing

and cleaning of the lines periodically, and for automatic draining following shutdown. Conventional pumping and piping materials are generally suitable if the pH is near neutral, but the abrasive character of the sludge and flyash, if present, may lead to failure from erosion, especially at bends.

Pipelines are applicable to a wide range of systems, but are limited to wet disposal concepts. Pumpable FGD sludges are reported to vary from 30 to 70% in solids content. (13-1) The reasons for this wide variation are not clear, although the sludge viscosity is believed to be affected by both the particle size distribution and type of crystals/particles present. Pumping and deposition velocity tests are desirable in the design of a system. (13-2)

DESIGN FACTORS FOR TRANSPORTATION SYSTEMS

To supplement the information provided in the Manual, the design engineer should consult with equipment manufacturers, suppliers, engineering firms and plant operators with specialized experience in handling similar materials to assist in the design of transport system and surge storage, including selection and sizing of equipment. When unusual conditions are encountered, which often is the case, actual pilot or full-scale testing may be required to insure adequate design. Overall design factors are discussed in following sub-sections. Specific factors will then be covered under the headings of dry and wet disposal.

Flowsheet

The first step in developing the materials handling system is the preparation of a detailed flowsheet to provide the basic information necessary for adequate design and to assure that no facet of the system has been omitted from consideration. The flowsheet should indicate sludge production rates at various loads and provide material balances. Other factors that could affect design include: solids content and abrasive characteristics of various liquid streams, specific gravity of slurries and solids, particle size analysis of sludge and chemical analyses of liquids and solids.

These data will probably not be available for a new system and must be estimated from pilot studies or obtained from a comparison with similar systems in service elsewhere. The flowsheet provides information for facilities layout, surge storage requirements, and selection and sizing of transport equipment. Transport systems often function improperly because of inadequate flowsheet data or from process revisions, which result in improper equipment selection and sizing.

Production Rates

Average production rates for FGD sludge disposal facilities are based on the estimated capacity factor for the power plant and the sulfur and flyash removal capabilities of the scrubber plant. Factors affecting sludge quantities and the procedure for calculating the amount to be handled are discussed in Section 3 - WASTE COMPOSITION and Section 4 - WASTE QUANTITIES.

Average hourly production is determined by:

$$\text{Avg t/hr} = \frac{\text{Annual FGD Sludge Produced, t/yr}}{\text{Availability x Scheduled Disposal System Operating Hr}}$$

Consider the following example of a large power plant producing 350,000 t/yr of dry FGD sludge, 80% availability for the FGD sludge disposal facilities, and scheduled operation of two shifts per day. The scheduled operating hours would be:

$$2 \text{ shifts/day} \times 8 \text{ hr/shift} \times 7 \text{ days/wk} \times 52 \text{ wk/yr} = 5{,}824 \text{ hr/yr}$$

The avg t/hr would be calculated as:

$$\frac{350{,}000 \text{ t/yr}}{0.80 \times 5{,}824 \text{ hr/yr}} = 75 \text{ t/hr}$$

After surge capacities and locations and average hourly production rates have been established, it is necessary to determine instantaneous production rates and the fluctuations in various physical and chemical characteristics of the flow stream. When flow data cannot be determined, it is recommended that the instantaneous production rate for material transport be established at 100% capacity of the scrubber plant under worst-case (coal sulfur and ash content) conditions.

Constraints

Next, it is necessary to establish any physical, environmental or public relation constraints on route selection. The distances and elevations that the sludge must traverse from origin to destination must be carefully considered and options evaluated. An efficient materials transport system requires that transport distances and vertical transport be minimized so that materials can be transported with a minimum of equipment, energy, and manpower. Environmental and public-relation aspects are discussed in Section 6 - SITE SELECTION.

Availability

Availability of the FGD sludge disposal facilities is affected by (1) reliability of the process and transport equipment essential to sludge disposal; (2) availability of surge capacity so that most equipment can continue to operate during nonscheduled shutdowns due to failure, breakdown, or preventive maintenance of critical equipment; (3) provision of bypass piping to permit short-term outage of equipment; (4) built-in flexibility to enable the modification of sludge processing methods; and (5) availability of maintenance personnel, repair parts and facilities so that nonscheduled or emergency maintenance can be completed with a minimum of downtime.

Redundancy. When the power plant has multiple generating units and/or scrubbers, it is advisable to have sufficient redundancy in the transport system so that shutdown of a critical piece of equipment does not result in shutdown of all scrubbers or the entire power plant.

Surge/Storage Capacity. Surge capacity is necessary for leveling production rate fluctuations due to variations in sludge characteristics, production scheduling, equipment mismatching, failure or breakdown, and scheduled maintenance downtime. Surge capacity often is placed ahead and behind of process equipment so that the power plant and scrubbers can continue to operate during routine maintenance.

Costs

An economic assessment should be made of several feasible FGD transport systems to determine the most economical system for a specific sludge disposal facility. The economic comparison of various transport systems should be based on the cost per unit volume or weight as related to expected FGD sludge production and the distance transported. A more detailed discussion of economic factors and methods of cost estimating are given in Section 14 - COSTS.

The economics of FGD sludge transport system selection also depend on technical considerations. Economics dictate that the most reliable equipment be selected. Where new types of transport system components must be used, these should be engineered, tested, and proven reliable for the specific application before being installed.

Effect of Design Factors on Operation

FGD sludge transport systems must be operated by qualified and experienced personnel. It is important that sludge flows on demand and at predictable rates. Storage and

transport problems are some of the most difficult problems faced by the plant operator. Sludge not flowing in chutes, or sticking to or overflowing conveyor belts, pipeline plugging, and distributors malfunctioning are a few examples of the many problems presenting major operating problems and often requiring equipment shutdown. Storage and transport systems that do not function properly can cause costly delays and lost station capacity.

TRANSPORTATION SYSTEMS FOR DRY DISPOSAL

Dry sludge, as discussed in this section, generally refers to sludge which is sufficiently dewatered so that it no longer exhibits fluid properties (it will maintain its own slope when placed outside a container) and can be handled with conventional equipment. Because of variable sludge properties, it is impossible to define this point exactly. However, in most cases, a minimum solids content of 75% is necessary for sludge to be handled dry (see Section 9 - PROCESSING ALTERNATIVES).

Sludge properties, both physical and chemical, greatly affect the choice of equipment for transport systems. Typical properties will be listed and the effects on equipment choice noted. Information is presented for types of conveyances and feeders which can be used effectively. Conveyances include equipment where the primary purpose is to transport sludge over horizontal and vertical distances. For the transport of dry sludge, a variety of conveyance equipment can be used, including belt conveyors, trucks, trains, and marine vessels. Continuously operated processing systems usually require feeders where the primary purpose is to meter or control the sludge feed rate within predetermined limits. For short distance transfer, chutes, front-end loaders, dozers and scrapers can be used and are discussed.

Sludge Properties

The physical and chemical properties of FGD sludge require accurate appraisal for successful conveyance and feeder selection and sizing. Consideration should be given to expected bulk density, angle of repose, angle of surcharge, flowability, temperature, corrosiveness, and abrasiveness. Some typical test data on FGD sludge are presented in Table 13-1. These properties are only approximations and carefully conducted tests are necessary to establish sludge properties. For some sludges, the properties may vary with handling, climatic changes or storage. Pertinent characteristics are discussed in the following:

- Sludge bulk density governs the conveyance or feeder tonnage rating.
- Maximum lump size may dictate the conveyance or feeder selection and sizing since lumps may require larger conveyances and feeders to transport the desired tonnage.

Table 13-1

TYPICAL TEST DATA ON FGD SLUDGES
WATER RETENTION AND BULK DENSITY CHARACTERISTICS

	DEWATERING METHOD							
	SETTLED		SETTLED AND DRAINED		CENTRIFUGED		VACUUM FILTERED	
SCRUBBER SYSTEM	PERCENT SOLIDS	DENSITY, g/cc	PERCENT SOLIDS	DENSITY, g/cc	PERCENT SOLIDS	DENSITY, g/cc	PERCENT SOLIDS	DENSITY, g/cc
Lime	40 to 48	1.34-1.40	43 to 53	1.36-1.50	50 to 57	1.39-1.52	56 to 57	1.48-1.54
Lime-stone	47 to 67	1.39-1.65	56 to 67	1.44-1.67	60 to 77	1.56-1.86	53 to 80	1.48-1.78
Double-Alkali	37 to 40	1.30-1.35	41 to 44	1.33-1.44	50 to 62	1.38-1.62	55 to 58	1.50-1.61

Source: Leo, P. P. and Rossoff, J., Controlling SO_2 Emissions from Coal-Fired Steam-Electric Generators: Solid Waste Impact, The Aerospace Corporation, EPA 600/7-78-044b, March, 1978.

- The angle of repose is the angle to the horizontal made by the surface of a normal, freely-formed pile.
- The angle of surcharge is the angle to the horizontal assumed by the surface of the sludge when at rest on a conveyance or feeder such as a moving conveyor belt. This angle usually is 5° to 20° less than the angle of repose.
- The angle of repose and angle of surcharge vary with the sludge flowability, which is determined by the size and shape of fine particles and lumps, proportion of fines and lumps, roughness or smoothness of particles and lump surfaces, and the sludge moisture content.
- The sludge temperature often is critical since freezing temperatures can cause severe operating problems with certain conveyance and feeder components.
- Corrosiveness usually is governed by the sludge pH, with a pH of one to five being corrosive, five to seven being mildly corrosive, and greater than seven being generally noncorrosive. High chloride concentration may lead to stress corrosion failure of stainless steel components.
- Abrasiveness of the sludge may be deleterious to unprotected (uncoated) metal surfaces, but there is no easy way to determine this. The extent of attack will probably be more severe with increased quantities of flyash.

Equipment Selection

Before actual selection of equipment types, it is necessary to prepare layout drawings to establish conveyance routes including distances, elevations, physical constraints, and sludge transfer methods which influence selection. The facilities layout also provides similar data for feeders. Where the breakdown of a single conveyance or feeder could disrupt the power plant capacity and/or scrubber operation, standby equipment is desirable.

Conveyance Types. The design of a dry sludge transport system is not an exact science and usually is based on personal preference, local conditions, experience, and engineering expertise. When designing a sludge transport system, including the selection, sizing, and engineering of conveyance equipment, the design engineer should consult with equipment manufacturers, suppliers, engineering firms, and plant operators for assistance, advice, and detailed information.

Information necessary for the selection of conveyances and feeders include (1) sludge transfer methods for loading on and discharging from the conveyance or feeder, (2) conveyance and feeder profile, and (3) physical and chemical properties of the sludge. Additional factors affecting selection may be plant layout, space limitations, sludge processing methods, any existing equipment, future requirements, geography, topography,

climate and past experience. Based on this information, the various conveyance and feeder types can be evaluated and preliminary selections can be made by comparing suitability, adaptability and efficiency. Table 13-2 shows the major alternative transport modes available and summarizes their limitations and applicability. A more detailed discussion of important design factors and alternatives is given in following paragraphs.

Final selection often requires detailed evaluations of several preliminary selections. These detailed evaluations should include sizing of equipment, determining power requirements, and estimating fixed and variable costs.

Belt Conveyors. Conveyors of many different types are used for material transport including belt, screw, apron, flight, vibrating, and en masse conveyors. Of these conveyor types, the belt conveyor is the only type suitable for the transport of FGD sludge.

A belt conveyor is an endless belt, usually rubber-covered, operating over carrying and return idlers and a suitable drive, tail end, and bend pulleys with the belt components and belt supported on a frame structure suitable for maintaining accurate alignment of the components and belt. Figure 13-1 illustrates the belt conveyor components less supporting structure.

Belt conveyors are a low cost method of transporting sludge continuously for both short and long distances when both the loading and discharge points are fixed. These conveyors can be designed for a wide range of capacities by various combinations of belt width and speed. Table 13-3 provides maximum belt conveyor capacities for various belt widths, idler troughing angles, and surcharge angles. Although the capacities in Table 13-3 are for sludge weighing 100 lbs/ft^3 and moving on the belt at 100 ft/min, the capacities can be corrected for other sludge weights and belt speeds.

Belt conveyors require that the sludge be loaded on the conveyor or belt surface from one or more points in a controlled manner, sometimes requiring one or more feeders. Thus, the belt conveyor is provided with a continuous, even flow of sludge to match the conveyor designed flow rate. Belt conveyors are arranged in a direct line between terminals and may have almost unlimited number of elevation profiles or paths of travel. These include horizontal, inclined, declined, concave or convex vertical curves, or any combination, as illustrated in Figure 13-2. The incline or decline slope is limited by the properties of the sludge being conveyed but is effectively limited to slopes of up to 25°.

The rubber belt conveyor is rugged and durable and can adequately handle sludges with variable characteristics. However, freezing conditions may cause operating difficulties with conveyor components.

Belt conveyors are widely used for short transport distances, often for moving sludge from one processing step to the next or

Table 13-2

ALTERNATIVE TRANSPORTATION MODES

CONVEYANCE TYPE	HAUL LENGTH								GROUND CONDITIONS		MAXIMUM ADVERSE GRADE						TOTAL TONNAGE		
	0-300 ft	300-500 ft	500-1,000 ft	1,000-1,500 ft	1,500-5,000 ft	5,000-10,000 ft	10,000-15,000 ft	15,000+ ft	Good	Wet, soft	3%	5%	10%	15%	20%	+20%	Small	Medium	Large
Front-end loader - rubber tires	2	1	2	4					1	3	1	1	1	2	3	4	1	1	
Front-end loader - crawler	1	3	4						1	1	1	1	1	2	3	4	1	1	
Dozer - rubber tires	1	1	2						1	4	1	1	2	4			1	1	
Dozer - crawler	1	4							1	1	1	1	2	2	4			1	
Wheeled scraper - conventional		2	1	1	1	2	4	4	1	2	1	1	2	4			2	1	1
Wheeled scraper - tandem powered		2	1	1	1	3	4		1	1	1	1	1	2	2	4	2	1	1
Wheeled scraper - elevated	2	1	1	1	2	4			1	3	1	1	2	4			2	1	
Truck - rear dump		3	1	1	1	1	1	1	1	3	1	1	1	3	4			1	1
Truck - semi-trailer rear dump		3	1	1	1	1	1	1	1	4	1	1	1	4	4			1	1
Truck - semi-trailer bottom dump			3	2	1	1	1	1	1		1	2	3	4				2	1
Train							4	1	1		1	4							1
Conveyor	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	4			1

1 - Should be considered

2 - May be considered

3 - May be considered under certain conditions

4 - May be considered, special situation

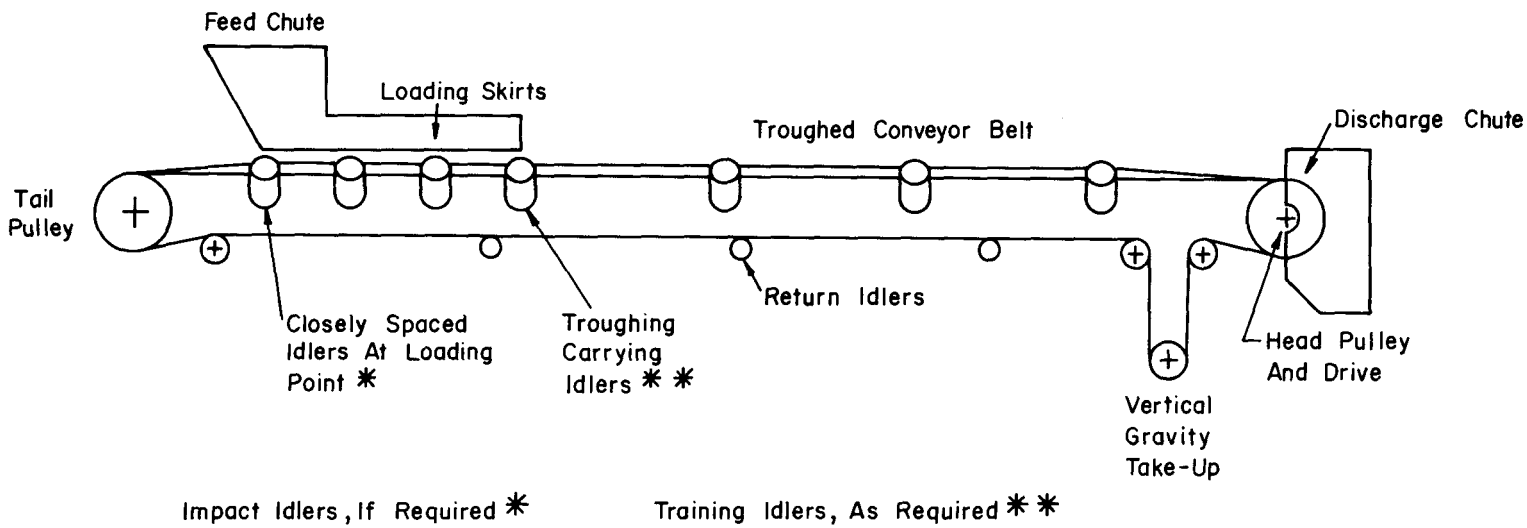
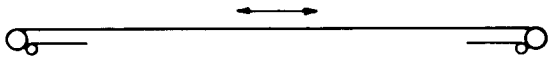


Figure 13-1. Belt Conveyor Components.

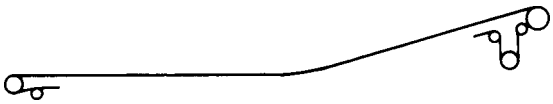
Table 13-3

BELT CONVEYOR CAPACITIES AND LOAD CROSS-SECTIONAL AREAS
(Based on Bulk Density of 100 lb/ft^3 and
Belt Speed of 100 ft/min)

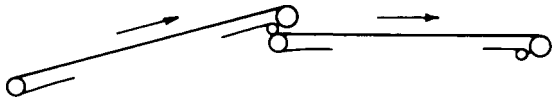
IDLER TROUGHING ANGLE	CONVEYOR WIDTH in.	ANGLE OF SURCHARGE					
		5°		20°		30°	
		ft	TPH	ft	TPH	ft	TPH
20°	14	0.060	18.00	0.093	27.90	0.116	34.80
	16	0.082	24.60	0.127	38.10	0.159	47.70
	18	0.109	32.70	0.168	50.40	0.209	62.70
	20	0.139	41.70	0.213	63.90	0.266	79.80
	24	0.209	62.70	0.321	96.30	0.399	119.70
	30	0.342	102.70	0.523	156.90	0.649	194.70
35°	14	0.088	20.40	0.117	35.10	0.138	41.40
	16	0.122	36.60	0.161	48.30	0.189	56.70
	18	0.161	48.30	0.212	63.60	0.249	74.70
	20	0.205	61.50	0.270	81.00	0.316	94.80
	24	0.309	92.70	0.406	121.80	0.475	142.50
	30	0.506	151.80	0.663	198.90	0.773	231.90
45°	14	0.102	30.60	0.128	38.40	0.146	43.80
	16	0.140	42.00	0.175	52.50	0.200	60.00
	18	0.185	55.50	0.230	69.00	0.262	78.60
	20	0.236	70.80	0.293	87.90	0.333	100.00
	24	0.355	106.50	0.440	132.00	0.499	149.70
	30	0.580	174.00	0.716	214.80	0.812	243.60



Horizontal Belt.



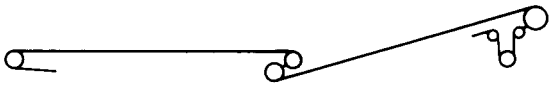
Horizontal and ascending path, when space will permit vertical curve and belt strength will permit one belt.



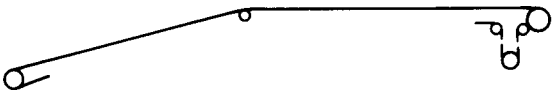
Ascending and horizontal path, when advisable to use two conveyor belts.



Ascending and horizontal path, when belt tensions will permit one belt and space will permit vertical curve.



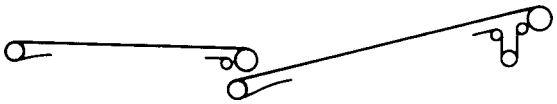
Possible horizontal and ascending path, when space will not permit vertical curve but belt strength will permit one belt.



Ascending and horizontal path; or horizontal and descending path, when space will not permit vertical curve but one belt can be used.



Compound path with declines, horizontal portions, vertical curves, and incline.



Possible horizontal and ascending path, when space will not permit a vertical curve or when the conveyor belt strength requires two belts.



Loading can be accomplished, as shown, on minor inclines or declines.

Figure 13-2. Belt Conveyor Arrangements.

from final processing to truck loadout. However, there are no belt conveyors in use to carry sludge from the plant to the ultimate disposal site. Long enclosed belt conveyors are possible but have not yet been used for sludge disposal applications. Long belt conveyors have high maintenance costs and are inflexible, requiring essentially fixed starting and ending points. They also represent a high capital investment, which may not be justified for the life of the facility.

In designing a conveyor system, the belt conveyor profile, capacity required, sludge characteristics, and operating conditions must be known for proper selection of conveyor idlers, determination of belt tension and drive horsepower, and the selection of conveyor belting. The daily hours of operation, ambient temperatures (minimum and maximum), reversing or one-directional operation, enclosed or exposed conditions, seasonal or continuous service, and other significant factors also must be considered.

The process of sizing, designing and specifying a belt conveyor for sludge is much the same as for any similar material. Specific design procedures are described in detail in Belt Conveyors for Bulk Materials. (13-3)

Trucks. Truck transport is highly mobile and can be used to economically transport dry sludge over relatively long distances. Both on-highway and off-highway trucks are available for use, varying primarily in capacity. On-highway trucks are designed for use on public highways. These trucks are subject to width limits and to roadway weight limits and restrictions. Off-highway trucks travel on private roadways. In recent years, the off-highway truck has become the major transport vehicle for bulk material which is to be transported between 500 and 15,000 ft.

Trucks are of three types: conventional rear-dump, semi-trailer rear-dump, and semi-trailer bottom-dump. The conventional rear-dump truck, has a body mounted on a truck chassis with the body raised by an integrally mounted hydraulic hoist system for dumping. Rear dump trucks may have two or three axles. Semi-trailer rear-dump trucks have separate tractor and trailer units. The trailer has a mounted hydraulic hoist system for dumping. Semi-trailer bottom-dump trucks also have separate tractor and trailer units. The trailer has either drop bottom or clam shell doors for material dumping. The bottom-dump truck works well with free-flowing materials being dumped into hoppers. Capacities range from small 13 t trucks to large 200 t plus vehicles. All trucks require haul roads with maximum road grade limited to 10 to 15%.

For conventional rear-dump trucks, the basic body styles are the quarry, standard, and "V". The quarry type has vertically flared sides and a flat bottom. The standard type has vertical sides tapered from front to rear for easy dumping of material. The "V" type has vertical sides with no taper and a bottom sloping downwards from the rear to the front. In colder areas, many truck bodies are exhaust gas heated as standard equipment or have provisions for heating as an option to prevent sludge from freezing to the truck body and eventually building up and reducing the truck pay load. Many truck bodies are constructed of low alloy, high strength steel which decreases body weight and correspondingly increases the truck pay load. In some cases, bodies are constructed using aluminum and steel to reduce body weight and increase the pay load.

Trains. Trains can be used for the transport of dry FGD sludge over long or short distances over a fixed track to the ultimate sludge disposal site. The train may operate as a unit train or as a common carrier. Common carrier railroads have extensive rail or track networks which often have existing tracks near both the power plant and the ultimate disposal site. If common carriers do not serve either the origin or the destination, then it may be necessary to obtain a private right-of-way and operate as a private railroad.

Conceptually, it is possible to use empty coal cars to haul FGD sludge back to the mine, thus avoiding dead-heading costs. This idea has been explored, but not used at several operating stations. The possibility of using empty coal cars, especially on unit coal trains, may become more attractive with the passage of legislation requiring that strip mines be restored to near-original contour.

Railroad freight cars suitable for transport of dry FGD sludge are available in 50, 70, 100, and 125 t capacity cars. Until recently, the 50 and 70 t cars were most common, but the 100 t car is now becoming more popular. The larger capacity cars require heavier and stronger track, trestle, and dumping facilities. The cars may be of the gondola design with a solid bottom, of hopper design for bottom dumping or of the side dumping design. Cars are constructed of steel with car capacity determining the size and strength of wheels, axles, bearings, body side-frames and bolsters, springs, and braking system. Gondola cars may be equipped with a rotary coupler at one end so that the car can be rotary-dumped without uncoupling from adjacent cars. However, this system is fairly expensive. Hopper cars may be equipped with either manually or power operated hopper doors. The car configuration, including hoppers and doors, often is designed for specific applications. Side-dump cars, such as those in use at the Martin Lake facility of Texas Utilities, are most cost effective for sludge operations.

A major consideration in using trains to transport dry FGD sludge is car loading and unloading. Cars usually can be loaded with front-end loaders, belt conveyors, or chutes. The front-end loader loads the car from a surge pile by dumping directly into the car. The stationary belt conveyor, using a spill-eliminating transfer gate, discharges into the car with the car being moved and positioned under the discharge for distribution of the sludge in the car. The chute can load directly from the outlet of processing equipment such as centrifuges or mullers, operating in an area above the rail car. This type of system is in operation at Martin Lake.

Gondola cars can be unloaded using a rotary car dumper which rotates the car upside down to dump the sludge. Rotary dumpers are massive equipment representing a high capital cost. When using hopper cars, the sludge must be free flowing for unloading of the sludge through the hopper bottom. The side dump car is self-unloading using air cylinders to tip the car body and dump the sludge.

Barges. Barges can be used to ship dry FGD sludge over long distances where the origin and destination are along inland waterways or are separated by large bodies of open water. When power plants are located near waterways, these waterways sometimes can serve as economic transport routes. While barge transport is inexpensive when measured in terms of cost/t-mi, it is not usually justified except under special circumstances. The cost of loading and unloading and associated double handling of the sludge will usually rule out the use of barges as an economical alternative except for very long transport distances (which are rarely anticipated) or for ocean disposal which is only available for tidewater utilities.

If the ultimate disposal site is an ocean dump site, the sludge would be transported using ocean barges. If the ultimate disposal site is on-land and both the disposal site and power plant are adjacent to waterways, conventional river barges would be used to transport the sludge.

Inland waterway barges are constructed to take maximum advantage of the width and length of the lock chambers through which they pass. The standard open-hopper barge is 175 ft long by 26 ft wide by 10 ft, 8 in. deep. The standard barge has a cargo compartment capacity of 26,191 ft^3 and an 8 ft, 9 in. draft when loaded with 1,000 net t. Barges used on the Gulf, Great Lakes, and oceans are covered with doors having a seal and locking device to prevent water from entering the cargo compartment when encountering swells.

A major consideration in using barges to transport dry FGD sludge is barge loading and unloading. Standard barges usually are loaded and unloaded by stationary equipment with the barge moved and positioned under the stationary equipment. Traveling loading-unloading equipment usually requires very large vessels for economic justification.

Belt conveyors often are used to load standard barges with the barge moved under the discharge. The belt conveyor loader must be designed so that (1) discharge height can be adjusted to allow for changes of water level and barge draft as the barge is loaded and (2) the barge cargo can be trimmed to either side to keep the vessel on even keel. Often it is necessary to use a revolving spout or slinger attached to a conveyor discharge to properly distribute the sludge in the barge.

Short-Distance Transfer. Equipment for this purpose is used for feeding sludge at a controlled rate, for vertical short transfer from one processing step to another or for surge stocking or reclamation. The various types are discussed in the following:

Feeders. Feeders have very limited application in the transport of FGD sludges. The primary purpose of a feeder is to meter or control sludge feed rate within predetermined limits. In most cases, the conveyance is removing the dry sludge from process equipment as quickly as the sludge is discharged. Thus, there is no need for a feeder. However, if a feeder is necessary in certain instances, a belt feeder is the only type suitable for FGD sludges. The design of belt feeders is similar to belt conveyors with flat idlers and skirt plates to contain the sludge. The belt feeder should have belt scales to weigh the sludge on the belt and determine the rate

of sludge discharge from the feeder. The discharge from the belt feeder usually is controlled by a gate or by varying the belt speed or travel rate.

Chutes. Chutes are vertical or inclined enclosures that guide and direct the sludge flow as the sludge is transported from a higher to a lower elevation by the force of gravity. Chutes usually are designed with a rectangular cross-section with an open top or a removable cover for easy access to the chute interior for clean-out in case of plugging and for replacing wear linings or protective coatings. A freely flowing chute which has little downtime due to plugging and maintenance is a very low cost transfer method.

The rectangular chute is easy to fabricate from flat plate steel. The chute should be of welded construction with a stiffening flange along the top edge of the side plates. This will provide the chute with some structural rigidity and facilitate the addition of a removable cover plate. If the sludge is abrasive or corrosive, the chute can be constructed of special steel or lined with rubber, plastic, or ceramic materials. If the sludge tends to stick to the surface and plug the chute, lining with stainless steel or Teflon may be effective. If the chute is exposed to below-freezing temperatures, it may be necessary to insulate or heat trace it to prevent the sludge from freezing.

Front-End Loader. The front-end loader is available in a wide range of sizes, either mounted on crawler tracks or rubber-tired wheels. The front-end loader can be used as a loader for other transport vehicles or as a load-haul-dump vehicle. A typical application is reclaiming or loading sludge from a surge pile into a truck. When used as a haulage vehicle, the front-end loader usually is limited to a maximum haul distance of 1,000 ft. The inherent characteristics of the crawler-mounted or track type front-end loader are (1) relatively slow travel speeds, (2) relatively high maintenance cost for abrasive materials, (3) relatively low ground-bearing pressure, (4) good steep slope capability, (5) strong digging ability, (6) a high degree of maneuverability, and (7) good stability. In comparison, the inherent characteristics of the rubber-tired or wheel front-end loader are (1) high degree of mobility, (2) relatively low maintenance cost, (3) relatively high ground-bearing pressure, (4) good performance on gentle slopes, (5) ability to dig and transport its own load and (6) more space required to maneuver. Information on equipment specifications and proper sizing can be obtained from equipment manufacturers.

Dozers. Dozers are available in a wide range of sizes with both crawler tracks and rubber-tired, two- and all-wheel drives. Rubber-tired units are highly mobile with relatively low operating costs. Crawler units are used principally where ground conditions require low ground-bearing pressure or high stability. Dozers can be used for a variety of applications. These include transporting sludge over distances usually less than 400 ft by pushing the sludge and by assisting wheeled scrapers during loading. The dozer can be used for other construction purposes at the power station, so it is a popular, flexible tool. The inherent characteristics of the crawler and rubber-tired dozers are similar to those for crawler-mounted and rubber-tired front-end loaders.

A variety of dozer blade types are available, depending on the specific dozer application. However, the straight blade and universal blade are the most common. The straight blade is the most versatile dozer blade and is excellent for land clearing, fill spreading, and final grading. The universal blade with its large wings is efficient for pushing sludge over longer distances as in stockpile work, charging hoppers, spreading fill, and reclaiming land.

Scraper. The wheeled or rubber-tired scraper digs its own load, transports and dumps and spreads at the dump site. Wheeled scrapers can be used economically to transport sludge when haul distances are less than 4,000 ft. The use of scrapers eliminates the need for front-end loaders to load the transport vehicle. However, a dozer usually is needed to push the scraper for efficient loading. In addition, since scrapers operate on the surface of the sludge being removed during digging, the sludge surface must have adequate bearing pressure. At the present time there is very little experience in transporting FGD sludge with scrapers, and additional experience is necessary before specific use recommendations can be developed.

There are three basic wheeled scraper types: conventional, tandem powered, and elevated scrapers. The conventional scraper is powered by the tractor wheels while the tandem scraper is powered by both the tractor and scraper wheels. The conventional and tandem scrapers usually require a dozer for assistance during loading while the elevated scrapers are designed for self-loading. Elevated scrapers may be powered by the tractor wheels or both tractor and scraper wheels. Scraper capacities range from 10 to more than 50 yd^3. Equipment specifications for a particular application can be obtained from the equipment manufacturer.

Surge Capacity

Purpose. The purpose of surge storage is to provide storage capacity for (1) waste produced by the scrubbers during unmanned shifts of the processing system, (2) reducing sludge surges at different process and transport points, (3) collecting and distributing sludge at different process and transport points, and (4) storing sludge ahead of equipment that may be shut down for maintenance. Storage for dewatered sludge is in surge piles, usually placed at ground level and exposed or unprotected. Surge piles vary in size and shape, with the sludge placed and reclaimed by various methods. Storage in bins and reclamation through gravity fed hoppers is not recommended because the sludge is usually not free-flowing and will clog this equipment.

Sludge Properties. A number of physical and chemical properties of the FGD sludge are important in the design of surge storage.

- The bulk density determines surge pile volume required for storage of a specified tonnage of dry sludge. Knowledge of the bulk density is also necessary for the sizing of placement and reclaim equipment.

- The angle of repose is the angle to the horizontal made by the surface of a normal, freely-formed surge pile and is important in determining the surge pile slope, configuration and volume. The value is highly dependent on the sludge composition, varying from virtually zero for sulfite sludges to values approaching 60° for dewatered gypsum.
- Sludges of high porosity will pick up and retain moisture. In cold climates, freezing of surface moisture will bind the sludge together in a solid mass and make reclaiming difficult, if not impossible.
- If portions of the sludge are water soluble (such as with dual-alkali sludges), it may be necessary to collect stormwater runoff and seepage from the surge pile.
- The cementing tendency of some FGD sludge may affect reclaiming.
- Corrosiveness can be controlled by using protective coatings on equipment, but when abrasion also is present, the effectiveness of the coating is reduced. Protection against the combination of corrosion and abrasion is necessary to keep maintenance costs at a reasonable level.

Table 13-1 indicates some of the important physical characteristics of dry FGD sludges relative to the design of surge piles and reclaim facilities.

Location. The surface selected for the surge pile should be firm, solid, well-drained and not subject to flooding. The surface should be raised with a good slope away from the pile area. Drainage from the pile should be collected in a ditch along the low point or line of the raised area. The surge pile area should be cleared of all debris and organic matter before the pile is laid down.

Size. Surge pile size is based on the FGD sludge production rate and the desired retention time. The capacity required for dry sludge surge piles usually is limited to a maximum of five-days sludge production. However, both available land area and surge pile height limitations may restrict surge pile capacity. Pile height may be limited by soil conditions, characteristics of the sludge, placing and reclaiming equipment, and the need to insure a safe operation.

The common surge pile types used for dry FGD sludge storage are (1) conical, (2) parallel windrow, and (3) radial windrow. The volume of a surge pile, V, is determined by

$$V = C/\gamma$$

where C is the required surge pile capacity and γ is the sludge bulk density. For a conical surge pile, the surge pile volume, V, is

$$V = \frac{1}{3}\pi r^3 \tan\theta$$

where r is the radius at the base of the pile and θ is the angle of repose of the sludge. Using this same formula, the radius at the base of the conical pile, r, can be determined by

$$r = \left(\frac{3V}{\pi \tan\theta}\right)^{1/3}$$

As an example, consider a conical surge pile requiring 3,000 t of capacity with the sludge having a bulk density of 95 lb/ft and an angle of repose of 37°. The surge pile volume then is calculated as

$$V = \frac{3{,}000 \text{ t} \times 2{,}000 \text{ lb/t}}{95 \text{ lb/ft}^3}$$

$$V = 63{,}158 \text{ ft}^3$$

Based on the volume of 63,158 ft^3, the radius at the base of the surge pile now is calculated as

$$r = \left(\frac{3 \times 63{,}158 \text{ ft}^3}{\pi \tan 37^{\circ}}\right)^{1/3} = 43.1 \text{ ft}$$

Figure 13-3 presents a nomograph for determing conical surge pile volumes. As an example, an angle of repose of 37° and a base diameter of 40 ft are assumed, giving a storage volume of 6200 ft^3.

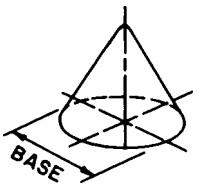
Windrow surge piles can be parallel or radial. For both parallel and radial windrow surge piles, the surge pile volume, V, is determined by

$$V = \frac{\pi w^3 \tan\theta}{24} + \frac{Lw^2 \tan\theta}{4}$$

where w is the width at the base of the pile, L is the length of the pile at top of of the pile and θ is the angle of repose. The length at the bottom of the pile is the length at the top of the pile plus the width at the bottom of the pile or (L + w). For radial windrows (Figure 13-4), the sludge usually is placed on the surge pile by a radial stacker where the length of the pile at the top, L, is the same as the stacker length of arc. This length of arc is determined by

$$L = \frac{\pi R \alpha}{180}$$

where R is the radius of the windrow and α is the angle over which the stacker swings.



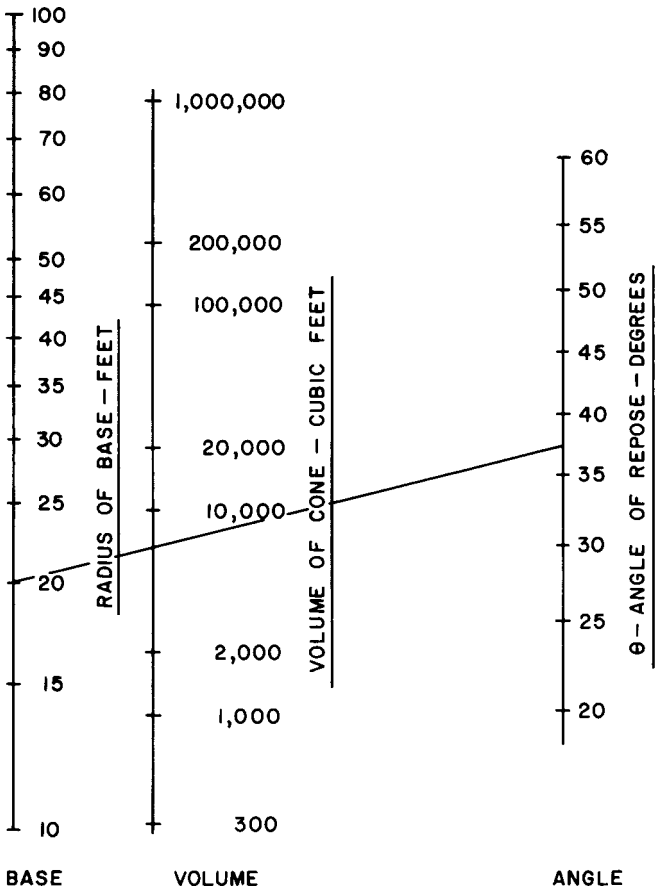


Figure 13-3. Nomograph for Determining the Volume of Conical Surge Piles.

Enter with base diameter and angle of repose, read volume at intercept.

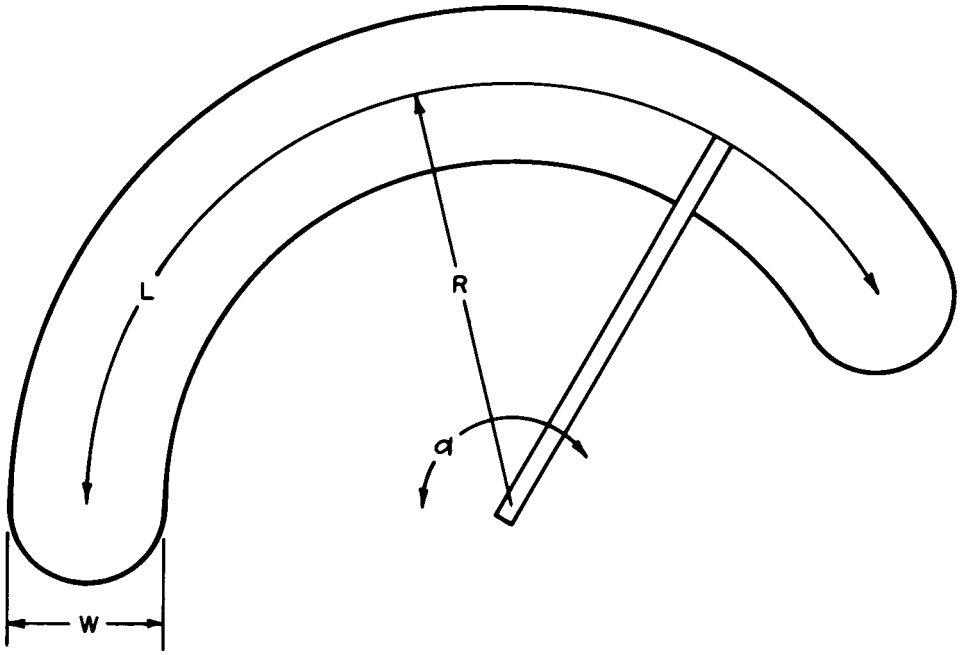


Figure 13-4. Windrow Formed by a Radial Stacker.

Placement Equipment. Equipment for placing dry sludge in surge piles includes belt conveyors and surface equipment such as front-end loaders, dozers, and wheeled scrapers. Belt conveyors are the most common method. Suggested arrangements of belt conveyors and ancillary equipment are presented in Figure 13-5.

The single stationary conveyor is satisfactory for delivering dry sludge to surge piles of moderate size. However, only a conical pile can be built with a single conveyor.

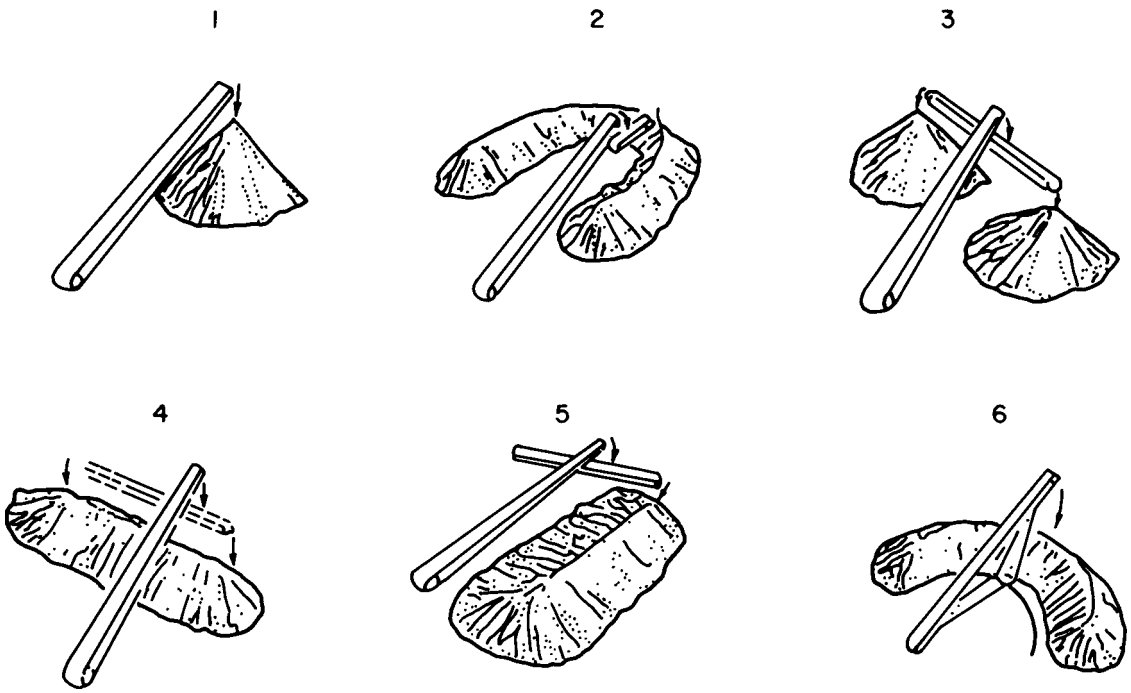
Because of surge pile height limitation, it often is necessary to distribute the surge pile over a larger area than possible with a single stationary conveyor. Thus, the single stationary conveyor in conjunction with ancillary conveyors and equipment is used for placing sludge in surge piles as shown in Examples 3 to 6 of Figure 13-5.

A single stationary conveyor with a pivoted boom will distribute the sludge over a larger area than the fixed conveyor. This arrangement uses a stationary conveyor with a horizontal belt conveyor supported on a boom truss and arranged to pivot on the centerline of the conveyor discharge, as shown in Example 2 of Figure 13-5. The boom conveyor can discharge material along an arc of about 270°, building a large radial windrow surge pile.

A single stationary conveyor with reversible belt conveyor can be used to make free-standing, non-overlapping conical surge piles. With the arrangement shown in Example 3 of Figure 13-5, a short reversible conveyor is added under the stationary conveyor discharge so that sludge can be placed in either of the two piles. This arrangement has the advantage that sludge can be reclaimed from one surge pile while sludge is placed on the other surge pile.

A single stationary conveyor with a shuttle conveyor, Example 4 in Figure 13-5, uses a reversing shuttle conveyor on a wheeled frame under the stationary conveyor discharge. The shuttle conveyor moves back and forth on an elevated track to place sludge in long parallel windrows. Shuttle conveyors are good for handling lumpy and sticky sludge.

The stacker is a cantilevered boom mounted on a wheeled or crawler-tread carriage which travels along a straight path or arc of up to 270°. A stacker with a single-wing conveyor has a boom located on one side of its tower structure, usually fixed at a right angle to the stacker's line of travel. The stacker with a single-wing



1. Single stationary conveyor.
2. Single stationary conveyor with pivoted boom.
3. Single stationary conveyor with reversible conveyor.
4. Single stationary conveyor with shuttle conveyor.
5. Stacker with single wing conveyor.
6. Radial stacker.

Figure 13-5. Conveyor Belt Placement of FGD Sludge in Surge Piles.

conveyor places the sludge in a parallel windrow with the windrow length being the same as the stacker travel distance. Refer to Example 5, Figure 13-5.

The radial stacker is a single, inclined conveyor pivoted at the tail end on the loading point centerline, as shown in Example 6 of Figure 13-5. The conveyor structure is supported near the midpoint by a tower. The tower support may make an arc up to 270° in central angle. Radial stackers are available with rubber tires, flanged wheels and crawler tracks, and the carriage usually is self-propelled. Radial stackers are used only for large radial windrow surge piles. These stackers are used only when the surge pile capacity cannot be achieved by using a single stationary conveyor for placing sludge. Figure 13-6 shows a photograph of the radial stacker in use at the IUCS facility at the Conesville Station of Columbus and Southern Ohio Electric Company. This stacker is 101 ft long with an effective radius of 92 ft at maximum height and a turning radius of 160°. The estimated storage is 9,000 yd or about six days production.

Surface equipment, such as front-end loaders, dozers and wheeled scrapers, can be used to place dry FGD sludge in surge piles. However, the operation of surface equipment on the surge pile can be difficult if the pile surface is loose, soft or wet. Also, operation of surface quipment may compact the sludge, making it difficult to reclaim. Thus, using surface equipment for the placement of sludge in single piles is not recommended except in emergencies. However, surface equipment may be a preferred method of sludge placement for ultimate disposal.

TRANSPORTATION SYSTEMS FOR WET DISPOSAL

Wet sludge, as used in this section, refers to sludge in a slurry form which is pumpable. While the solids content will vary, the solids content for pumpable sludge can vary from 30 to 70%. (13-1)

Conceptually, slurried sludge can be transported by front-end loader, truck, rail, barge, or pipeline. Of these, pipeline transport is the most practical and the only one in current use. Of the 30 utility scrubber systems in operation April 1, 1978, 18 employed pipeline transport of sludge.

Slurries flowing in pipes may behave as homogeneous or heterogeneous suspensions. Homogeneous slurries are nonsettling slurries characterized by the solid particles being uniformly distributed in the liquid medium. Homogenous slurries usually require fine solid particles of low specific gravity and have a high percentage of solids.

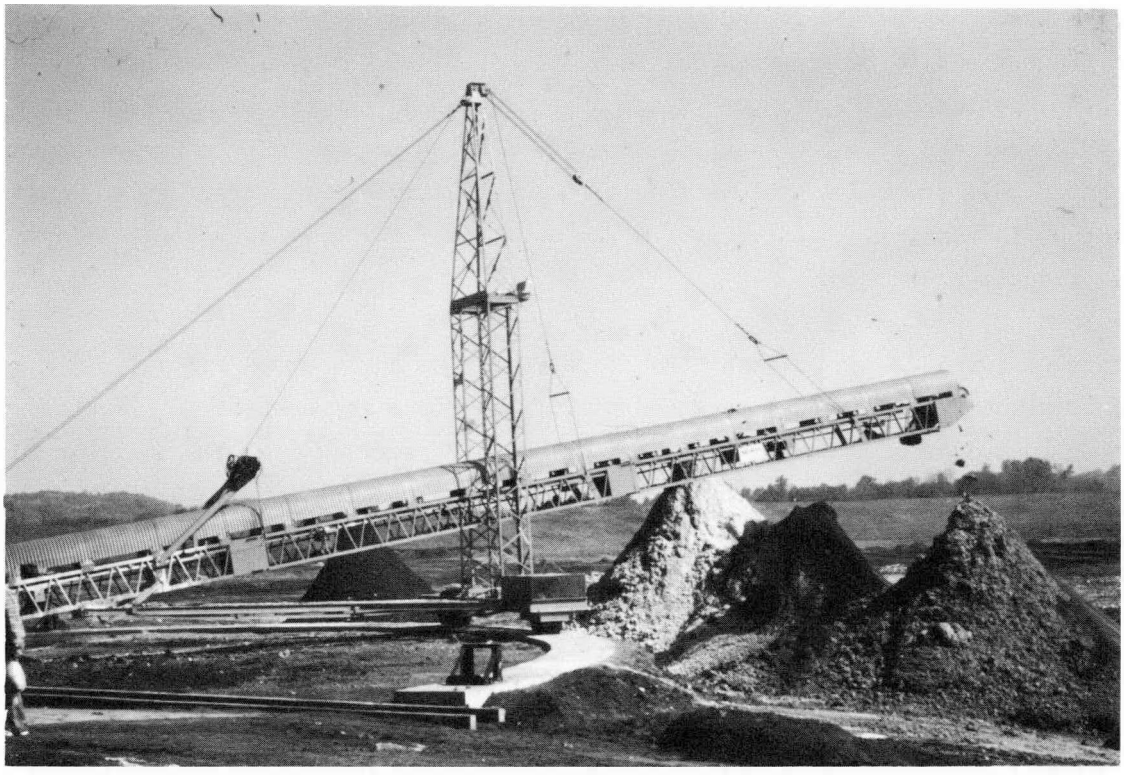


Figure 13-6. Radial Stacker, Conesville Station,
Columbus & Southern Ohio Electric Company.

Two distinct flow regimes may occur with homogeneous slurries: turbulent flow and laminar flow. Heterogeneous slurries are slurries characterized by coarse solid particles settling to the pipe bottom. Heterogeneous slurries usually contain coarse, poorly-graded particles of high specific gravity and have a low percent solids. In heterogeneous slurries, concentration gradients exist with a higher percent solids at the pipe bottom. Three distinct flow regimes may occur with heterogeneous slurries. At high velocities, all the solids may be suspended with pseudo-homogeneous flow. At a lower velocity, saltation or moving-bed flow occurs with larger particles bouncing along the pipe bottom. Moving-bed flow has a narrow velocity range and friction losses are at a minimum. At a still lower velocity, fixed-bed flow occurs with the finer particles moving over a stationary bed on the pipe bottom. Slight decreases in slurry velocity during fixed-bed flow may result in plugging. Slurry velocity should be about one ft/sec higher than the particle deposition velocity for heterogeneous slurries, while the minimum Reynolds number of 2,100 to 4,000 usually is the governing factor for homogeneous slurries. Most slurry pipelines are designed to operate with velocities between 4 to 10 ft/sec.

Slurry Properties

The properties of FGD sludges are important in the design of surge capacity and pipeline systems. Particle shape, size and size distribution, and solids content all affect viscosity which, in turn, determine pumpability. A knowledge of viscosity is essential in determining system design and the cost of pumping. Variation in temperature of the sludge slurry will affect the slurry viscosity. In cold climates, it may be necessary to insulate storage tanks or heat trace the slurry lines to prevent freezing.

Figure 13-7 illustrates typical sludge viscosities as affected by the solids content. The unit volume of a slurry depends on the percent by weight of solids. The volume of a given quantity of slurry can be determined by methods given in Section 4 - WASTE QUANTITIES.

Equipment Selection

The wet disposal of FGD sludge is dependent on reliable and efficient transport of the sludge slurry. The only method considered for transporting sludge slurries is pipelines. The energy required to overcome the friction losses due to the slurry flowing in the pipe and the elevation difference between pipe intake and discharge

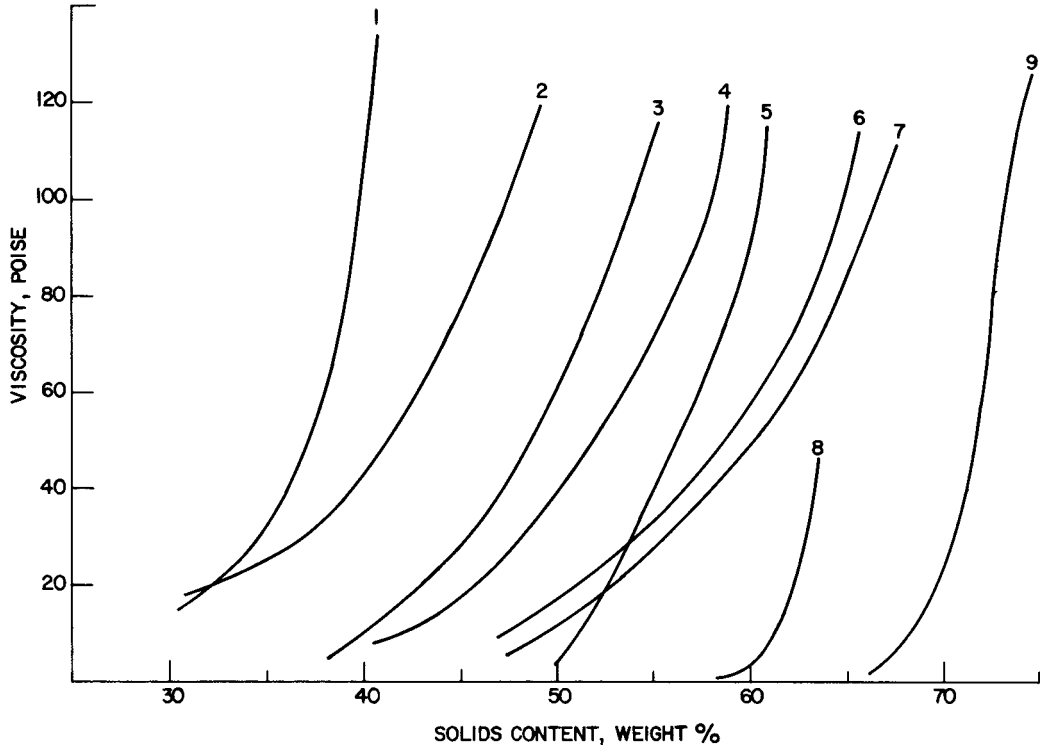


Figure 13-7. Viscosity of Typical Sludges.

Source: Rossoff, J., et al., "Disposal of By-Products from Non-Regenerable Flue Gas Desulfurization Systems: Second Progress Report," The Aerospace Corporation, EPA 600/7-77-052, May, 1977.

usually is supplied by pumps. In some cases, pumps may not be required if the slurry is lowered in elevation, and gravitational force is adequate to overcome pipe friction losses.

A layout for FGD sludge disposal facilities establishes pipeline routes, including distances, elevations and physical constraints. Pump overflows and pipeline drains should have controlled drainage to reduce clean-up costs. When the breakdown or plugging of a single pump or pipeline could reduce the power plant capacity and/or scrubber operation, standby pumps and pipelines are desirable.

Sizing of pumps and pipelines must be given careful consideration. Pumps and pipelines are designed to operate at a specific capacity and cannot be operated with large capacity fluctuations. If the required capacity decreases, slurry velocity in the pipeline decreases with the possibility of plugging the pipeline. If the required capacity increases, the pump may have inadequate capacity and/or horsepower. Thus, surge capacity is important to insure that the pump and pipeline can operate at the design capacity. If flow fluctuations are large and adequate surge capacity cannot be provided, it may be necessary to have parallel pumping and piping systems.

Pumps

Pumps and pipelines are the main components of a wet disposal system and will be discussed, along with pertinent ancillary features and equipment. Pumps suitable for FGD sludge slurries are of two principal types: positive displacement and centrifugal pumps. Both pump types have specific fields of application. In general, the positive displacement pump is used for long distance pipelines which have very high pressures or heads. The centrifugal pump is used for high flow rates and relatively low pressures.

Positive displacement pumps normally are considered for pressure above 500 lb/in.^{2} and can generate pressures of up to 2,400 lb/in.^{2}. Only positive displacement pumps can be utilized in high pressure slurry applications because of casing pressure limitations of about 650 lb/in.^{2} for centrifugal pumps. The principal positive displacement pumps suitable for pumping FGD sludge slurries are (1) direct acting plunger or piston type, (2) reciprocating oil pressure transfer type and (3) direct pressure transfer type.

Direct acting plunger or piston type pumps are the most common for pumping slurries. The plunger type is preferred over the piston type for abrasive slurries because the plunger can be flushed synchronously with clear water during the suction stroke. For direct acting plunger and piston type pumps, the slurry is in direct contact with the pump's plunger or piston, cylinder and valves. Thus, these parts are subject to wear, requiring replacement and resulting in high maintenance costs. However, flushing of the plunger type pump during the suction stroke will prevent excessive wear.

For the reciprocating oil pressure transfer type pump, the plungers are operated in oil and pressure is transferred from the oil to the slurry in intermediate pressure chambers. This arrangement eliminates slurry wear on the pump's plungers and cylinder and only the valves are in contact with the slurry.

The advantage of positive displacement pumps is the ability to produce high pumping pressures with relatively high efficiency. The disadvantages are the high capital cost; the need for high-power, low-speed drive and speed reducers; the high wear rate for plungers or pistons, cylinders and valves; a maximum particle size of about 1/8 in.; and limited volumetric capacity. Because positive displacement pumps have limited volumetric capacity, several pumps usually are required to operate in parallel. Manufacturers should be consulted for additional information.

Centrifugal slurry pumps are suitable for pressures or heads in excess of 100 $lb/in.^2$ per pumping stage, and centrifugal pumps can be operated in series to produce pressures up to 600 to 800 $lb/in.^2$. Characteristically, a slurry pump is larger in size than a conventional water pump of comparable pressure and capacity.

The wetted parts of the slurry pump usually are made of an alloy with hardness of approximately 600 Brinell. To reduce wear, the wetted parts often are lined with elastomeric materials such as natural rubber, neoprene, butyl rubber or one of a variety of other synthetics. Rubber has the ability to withstand most abrasion and will outlast the hardest alloys. However, rubber lacks mechanical strength and must be fully supported or reinforced. Thus, the use of rubber in high head centrifugal pumps is limited, and special design and pump construction are needed to avoid rubber breakdown at points of high energy dissipation. Suitable elastomer liners reduce direct impact wear which is the most serious problem in pump maintenance. In addition, inadvertent application of suction to the pump lining may pull it from the metal.

Centrifugal slurry pump design is a balancing between pump efficiency or hydraulic performance and the wear life of the wetted parts. Large diameter impellers are operated at lower speeds and, therefore, reduce wear at the vane inlet. However, larger impellers result in lower pump efficiency.

Because centrifugal slurry pumps are limited in pumping pressure, centrifugal pumps often are operated in series for high pumping pressure applications, such as long-distance pipelines. Centrifugal slurry pumps may be installed in series by placing several close-coupled pumps in one pumping station or placing single pumps at spaced intervals along the pipeline. The advantages of placing close-coupled pumps in one station are simplicity of control, inspection and operation; a single electrical distribution system; centralized electrical controls and instrumentation; and centralized maintenance and spare parts handling. The principal disadvantages are the higher slurry pressure to be contained and its effects on pump glands, bearings and casings, and on the pipeline.

Centrifugal slurry pumps can be operated in parallel to multiply pumping capacity. Pumps also are installed in parallel so that pumping can continue while a pump is down for maintenance.

Interlocked controls for pumps are necessary to assure continuous sludge slurry pumping and plant operation and to insure that startup and shutdown of the entire process and pipeline occur in proper sequence. The interlock should provide for emergency shutdown in case of equipment failure or an accident requiring immediate shutdown of a specific pumping station.

Pipelines

The design of slurry pipelines is not an exact science and usually is based on personal preference, local conditions, experience, and engineering expertise. Pipelines can be designed based entirely on laboratory testing. However, when possible, it often is desirable to confirm laboratory tests and minimize risk by conducting hydraulic loop tests, especially for long distance pipelines. A hydraulic test loop usually consists of a pump, head tank, weigh tank, appropriate instrumentation, and several hundred feet of two to six in. diameter pipe. Loop testing develops slurry flow data which can be scaled up to commercial operating conditions. When designing the pumping and piping system, the design engineer should consult with equipment manufacturers, suppliers, engineering firms, and plant operators for assistance, advice, and detailed information.

Materials. The principal materials used for pipe are steel, rubber-lined steel, rubber hose, and plastic. Steel is the most common pipe material. Steel pipe is easy to install, is relatively easy to support because of the pipe's rigidity, and has reasonable wear resistance.

Rubber-lined steel pipe usually consists of a 50 to 100 mm rubber lining cemented inside standard or thin-wall steel pipe. The wear resistance of rubber-lined pipe is many times greater than the wear resistance of plain steel pipe. Thus, rubber-lined steel pipe should be considered if the FGD sludge is highly abrasive.

Rubber hoses commonly are used for short piping applications and for easy disassembly where plugging may occur. The rubber hose is flexible and easy to install. It has high wear resistance and often is used for high wear points such as bends in piping systems. The rubber hose is available in diameters up to 30 in. for use with pressures up to 250 lb/in.^{2}. The rubber hose consists of a lining, carcass and cover. The lining usually is rubber between 25 to 50 mm thick to resist abrasion. Rubber hose in smaller sizes has been used to facilitate scale removal in locations where build-ups may be encountered.

Plastic-lined steel pipe is comparable in erosion resistance to rubber-lined steel pipe. Polyurethane linings are used with standard and thin-wall steel pipes to increase pipe life for abrasive materials. Some difficulty has been experienced with loosening of the lining. Plastic pipe is made entirely of plastic in diameters up to 40 in. High density polyethylene or fiberglas reinforced plastics have been used in some cases. Results have been varied, a number of failures having occurred at flanged joints. Polyethylene has a limited high temperature range of about 120° F and a high thermal expansion. Plastic pipe usually must be fully supported, either by support structures or the ground.

Valves. Slurry pipelines require valves to control the slurry flow. The valve types used for slurry applications are pinch, diaphragm, plug, ball, and gate valves.

- The pinch valve consists of a length of rubber-lined hose with an external clamp with no wetted parts. Pinch valves can be operated manually or hydraulically and are used as process control valves. Pinch valves are available for pipe diameters up to 20 in. and for pressure up to 85 lb/in^2.
- Diaphragm valves operate similarly to pinch valves but with a moving diaphragm closing against a fixed valve body. The diaphragm valve also can be operated manually or hydraulically and is used frequently as a process control valve.

- A plug valve consists of the plug and valve body. The plug valve is suitable for relatively high pressures and fine slurries. The plug valve can be operated manually or mechanically.
- Ball valves are similar to plug valves. Ball valves are not as abrasion-resistant to slurries as plug valves and generally are not recommended for slurry applications.
- Gate valves consist of gate, seal and valve body. Gate valves are not recommended for abrasive slurries, but are suitable for non-abrasive slurries and for supernatant.

Cleanout and Drains. Slurry pipe requires cleanouts to clear plugged lines and to drain lines when shutdown. Cleanouts should be readily accessible and have adequate space for the use of tools and equipment. Cleanouts are located at tees, elbows, and line low points with a removable plug installed in the fitting or pipe. Pipe drainage from cleanouts should be controlled for convenient cleanup. Facilities for flush back with clean water may be advisable at some locations.

Freeze Protection

In cold climates, freezing of slurry in the pipe can cause serious operating difficulties. Except for long distance pipelines, the slurry will not freeze as long as the slurry is kept in motion. However, if the pipeline is shut down and all the slurry is not drained quickly from the pipes, freezing can occur. To provide a longer possible downtime without draining the pipeline, the pipes can be insulated or equipped with heat tracing. In some instances, the pipeline can be buried below the frost line, but this will increase both installation and maintenance costs. Below-ground installation was used for part of the pipeline runs at the Bruce Mansfield Plant of the Pennsylvania Power Company.

Surge Capacity

Purpose. The purpose of surge storage for FGD sludge slurries is the same as for dry sludges. Surge storage capacity is needed to (1) insure an adequate FGD sludge reserve to enable processing the sludge at a production rate different than the rate at which the sludge is produced by the scrubbers, (2) reduce sludge surges at different process and transport points, (3) collect and distribute sludge at different process and transport points, and (4) store sludge ahead of equipment that may be shut down for temporary maintenance. Sludge slurries may be stored in tanks built above ground and/or in tanks or ponds built into the ground. Above-ground tanks commonly are used for surge storage. Special circumstances which may require in-ground storage are the necessity to (1) store very large volumes of sludge slurry, (2) provide a large surface

area for the settling of solids and decantation of a clear supernatant, (3) blend different sludge slurries on a large scale, and (4) minimize the discharge heads of pumps feeding the surge storage.

Slurry Tanks. Non-agitated slurry tanks are not recommended because of the possibility of solids separation and clogging. Mixers commonly are used for tank agitation. The mixer consists of a motor, reducer, shaft and impeller. Common types of impellers are paddle, turbine and propeller. The mixer may be top, side, or bottom mounted. The tank may be constructed with baffles to cause turbulence during agitation. The energy transmitted from the impellers to the slurry must be adequate to maintain sludge circulation, suspension and dispersion. For agitated tanks, it is recommended that mixer manufacturers be consulted for both tank design and mixer selection. Agitated tanks can discharge by gravity through ports controlled by valves, or can serve as suction supply to a pump or pumps for forwarding to the next processing step or to ultimate disposal. The EPRI Lime Slurry Databook (to be published) supplies details on tank design and agitation.

The sludge slurry usually is added to the tank through a feed well in the center of the tank. The feed well minimizes slurry splash and allows the mixer to disperse the slurry. Sludge should be reclaimed through ports at the tank bottom. This will prevent the build up of sludge on the tank bottom and maintain the entire tank volume as live storage capacity. For agitated tanks, a bottom build up also increases torque on the mixer shaft and can cause the mixer to stall.

Ponds. Ponds are excavated or built up (dammed or diked) storage facilities designed so that the sludge can be reclaimed by surface mounted equipment such as dredges and hydraulic monitors. In some rare cases, dry material handling techniques such as front-end loaders, grab buckets, or drag lines may be used to reclaim waste from a pond. Ponds are constructed by excavating, damming of a valley or building earthen dikes. Details on pond design and construction are given in Section 8 - DESIGN OF DISPOSAL AREAS.

FGD sludge slurry usually is placed in the pond by discharge pipes located on the pond perimeter. Individual discharge pipes should have valves for regulation of slurry flow. Thus, sludge slurry can be placed in one section of the pond while sludge is reclaimed from another section.

Hydraulic dredges are sometimes used to reclaim ponds. The dredge floats on the pond surface and excavates sludge ahead of the dredge under the pond surface and pumps the slurry to a discharge point. The dredge consists of a barge and superstructure, suction pipe, dredge motor and pump, and a flexible discharge line supported on floats. Dredges used on ponds usually are moved and anchored by lines attached to the pond banks. The suction pipe can be inclined below the horizontal to an angle of approximately 45°, commonly excavating 20 to 30 ft below the pond surface. The suction pipe may have an open-ended suction intake or a cutter head mounted around the suction intake. The cutter head is a rotating frame consisting of curved blades with or without teeth for dislodging and breaking up the sludge to be excavated. If the dredge is to be operated in cold climates, the barge, superstructure and suction pipe must be designed to withstand the load caused by ice formation and accumulation. If the pond surface freezes with thick ice or if the sludge freezes, dredging will have to be halted since the dredge cannot be repositioned or successfully dredge frozen sludge.

Hydraulic monitors also can be used to reclaim sludge ponds, but these are not used normally because of the required dilution water. The hydraulic monitor is a special nozzle which directs a high pressure stream of water at the sludge face, loosening and disintegrating the in-place sludge. The sludge slurry then flows to a pump suction well and is pumped through a pipe to a discharge point.

Supernatant Return

The water separated from an FGD sludge slurry pumped to an ultimate disposal site is usually recovered and returned to the power plant. The usual method for supernatant return is by pipeline using clear water centrifugal pumps.

Centrifugal pumps used for water can be classified by flow pattern and structural design. The three impeller flow paths are radial, mixed and axial. Common structural design variations are vertical or horizontal; single or double suction; single or multi-stage; single-volute, double-volute, or diffuser; and radial (vertical) or horizontal (axial) split casing. Vertical turbine pumps have impellers with either mixed or axial flow with diffuser-type casing. Vertical pumps are compact in design and are gaining wide acceptance in a variety of applications. Manufacturers should be consulted for assistance in pump selection.

The friction head loss due to water flowing in the pipe is a major consideration in water pipelines. For proper pipe selection, the increased capital cost and lower

operating cost of larger diameter pipe operated at lower flow velocity must be balanced against the decreased capital cost and higher operating cost of small diameter pipe operated at a higher flow velocity.

REFERENCES

13-1 Leo, P. P. and Rossoff, J., "Controlling SO_2 Emissions from Coal-Fired Steam-Electric Generators: Solid Waste Impact," The Aerospace Corporation, EPA-600/7-78-044b, March, 1978.

13-2 Lobdell, L. W., et al, "Eighteen Months of Operation - Waste Disposal System - Bruce Mansfield Power Plant - Pennsylvania Power Company," EPA Symposium on Flue Gas Desulfurization, November, 1977, EPA-600/7-78-058b.

13-3 Belt Conveyors for Bulk Materials, prepared by the Engineering Conference of the staff of Modern Materials Handling magazine, Cahners Publishing Company, Inc., Boston, MA, 1966.

Section 14

SYSTEM COSTS

PURPOSE

This section reports cost data from published figures and provides tools which can be used for first order estimates of overall system costs. This section also explains how to estimate costs for FGD sludge disposal systems and provides examples of cost computations.

ECONOMIC BASIS

System costs presented herein are based on economics applicable to investor-owned utilities as given in the EPRI Technical Assessment Guide (1). Alternative disposal systems can be compared on a basis of the total capital investment, annual fixed capital costs and the total annual revenue required. Most utilities prefer to express costs on an annual basis in order to reflect decreasing capacities, plant life and inflation. This is accomplished by determining the annual levelized operating costs, fixed charges (capital) and the revenue requirements. Each of these is discussed below.

Levelized Operating Costs

Inflation will tend to increase the operating costs (in current dollars) over the life of the disposal system. To represent these varying revenue requirements, a single "levelized" revenue requirement is computed using the "present worth" concept of money. Assuming an inflation rate, a discount rate, and a constant operating load throughout the plant life, the levelization factor for operating and maintenance costs can be computed. Table 14-1 lists typical assumptions used to compute the levelized fixed charge rate. The levelized annual operation and maintenance costs are then computed by multiplying the first year operating costs by the levelizing factor. Based on the assumptions in Table 14-1 the economic factors in Table 14-2 can be computed. References (1) and (2) indicate how these variables can be computed.

Table 14-1

TYPICAL ASSUMPTIONS USED TO DETERMINE
THE 30-YEAR LEVELIZED FIXED CHARGE RATE

Long-Term Inflation Rate	6%/yr
Debt/Equity Ratio	50/50
Debt Cost	8%/yr
Preferred Stock Ratio	15%
Preferred Stock Cost	8.5%/yr
Common Stock Ratio	35%
Common Stock Cost	13.5%/yr
Weighted Cost of Capital	10%/yr
Federal-State Income Tax Rate	50%
Property Taxes and Insurance	2%/yr
Investment Tax Credit	0
Book Life	30 yr
Tax Life	20 yr
Iowa Type S Retirement Dispersion	

Source: Economic Premises for Electric Power Generating Systems, EPRI, Palo Alto, CA, Reference Date: July 26, 1978.

Table 14-2

ECONOMIC FACTORS

FACILITY LIFE (Years)	FIXED CHARGE RATE	LEVELIZING FACTORS	PRESENT-WORTH FACTORS
5	0.34	1.182	0.8309
10	0.23	1.335	0.6904
15	0.20	1.484	0.5737
20	0.19	1.629	0.4767
25	0.18	1.763	0.3961
30	0.18	1.886	0.3291
35	0.18	1.996	0.2735
40	0.18	2.094	0.2273

Annual Levelized Capital

The annual cost of capital will vary depending upon the facility life as shown in Table 14-2. The levelized fixed charges are determined by multiplying the fixed charge rate by the total capital requirement.

Note that in some cases, major portions of the disposal system have a life which is considerably shorter than the life of the plant. For example, trucks and earth-moving equipment may be expected to last only six to 10 yr and are, therefore, replaced more frequently than typical process equipment. In these cases, a fixed charge rate consistent with the shorter life must be applied to these capital items. Reference (2) explains how to make this computation and shows an example.

Levelized Annual Revenue Requirement

The total levelized annual revenue requirement is simply the sum of the levelized fixed charges and the levelized operating revenue requirement. The sum is expressed in $/yr. This figure can be expressed in mills/kWh or $/t of sludge using the following equations:

$$\text{mills/kWh} = \frac{(\text{Levelized Annual Revenue Requirement in \$/yr})\ (1000\ \text{mills/\$})}{(\text{capacity in kW})(\text{capacity factor})(8760\ \text{hr/yr})}$$

$$\text{\$/t of sludge} = \frac{\text{Levelized Annual Revenue Requirement in \$}}{\text{Annual production of dry sludge in t}}$$

FUNDAMENTALS

Estimating the cost of a disposal system is probably the most difficult, yet one of the most important steps, in the selection of a disposal system. Note that the term "disposal" in this discussion includes processing, transportation and disposal. Because of its importance, considerable time and attention should be devoted to developing a reasonably accurate set of estimates. To reduce the overall effort, it is generally advisable to reduce the number of alternatives considered to a reasonably small number (approximately three to six) before attempting detailed cost estimates.

In developing cost estimates, several fundamental tenets should be observed:

- Include disposal costs for all the flue gas cleaning solids--Flyash as well as scrubber solids should be considered. This is true whether or not flyash is collected separately from the sulfur oxides. As previous sections have indicated, flyash can be collected upstream of and separate from the sulfur oxide absorber vessel, or concurrent with the sulfur oxides. In addition, dry flyash collected separately can be disposed of by itself, or mixed for final disposal. In other words, the flyash collected may or may not be

disposed of along with the scrubber sludge. Where these kinds of alternatives are being considered, it is usually appropriate to consider the disposal costs for all the flue gas cleaning wastes--flyash and scrubber sludge. This insures a fair and proper comparison between alternative disposal systems. If bottom ash is to be disposed of in the same system, then these solids should be considered as well.

- Report costs on a uniform basis--While any system of economic comparison could be used, most people compare systems on the basis of annual levelized revenue requirements, including levelized capital investment. The units of expression will vary, depending on the intended use of the figures. Annual revenue requirements expressed as $/dry ton of solids, is the most useful figure, and is the preferred unit of expression. These units are versatile and permit comparison of disposal costs, factoring out variables such as unit size, coal characteristics, and solids concentration in the sludge. Dollars per ton of wet solids is not as useful because the number will vary, depending on the solids concentration of the sludge.

  Other useful units of expression are dollars per ton of coal, and mills/kWh. These values are useful for a particular facility in gaining some perspective on the cost of sludge disposal relative to other costs or in comparing systems. However, they should not be used to compare costs of one facility with another using a different coal, because they include variabilities in sulfur, ash, and heat content of the coal, which distort the dollar figures.

- Develop site-specific costs--Disposal costs are highly site-dependent. For general preliminary planning purposes, it may be adequate to use literature values for the various cost elements in the system. However, these values are rarely accurate or adequate for specific situations not exactly comparable with the literature source.

  It must be recognized that costs vary widely, depending on local conditions such as availability of land, materials and labor. It is, therefore, appropriate to narrow the number of alternatives to be considered based on a relatively broad analysis, and then develop detailed cost information for the limited number of alternatives. The subsection below, SIMPLIFIED COST ESTIMATING, shows one method of estimating overall system costs.

- Consider the entire system--Be certain to include costs for the entire disposal system, from scrubber bleed through processing, transportation, and ultimate disposal. Insofar as it is consistent with the utility accounting system, include indirect costs such as engineering costs, contractor fees and construction expenses, as well as direct costs such as installed equipment. Consider, also, the need for working capital, allowances for start-up and modification, interest during construction, and applicable overhead. (See the subsection DETAILED COST ESTIMATES below for more details.)

- Use a systematic approach--The best approach is to start from the beginning, lay out the system components, size the different components of the system, fit the concept to the site conditions, systematically estimate component costs of the system, and then total the system costs. It is not necessary to have a fully-designed system, but the alternatives must be well-defined and a preliminary concept design developed in sufficient detail to estimate sizes, number and capacity of equipment and facilities.

Cost estimates can be prepared with varying levels of accuracy based on the amount of information available and the exact development of the design process. Table 14-3 shows the four primary classifications for design and cost estimates used by EPRI. This section presents methods for preparation of Class I, II, III and IV cost estimates.

REPORTED TOTAL DISPOSAL COSTS

There is no data base from which to accurately predict the cost of a disposal system without a detailed accounting of the items making up the cost of the system. Disposal costs reported in the literature vary widely and are extremely difficult to compare. Costs are reported for a wide range of conditions: different size plants; different coals; different processing, transport, and disposal systems; and different base years. In addition, most are estimates of expected costs from hypothetical plants. There are, in fact, published costs on sludge process disposal for only four operating utility stations using non-regenerable FGD. The most recent cost figures for these installations are shown in Table 14-4a.

Table 14-4a

REPORTED FGD DISPOSAL COSTS FROM OPERATING SYSTEMS

	$/DRY t OF SLUDGE IN 1979 DOLLARS	REFERENCE
Phillips and Elrama Stations Duquesne Light Company	$15.10 to $17.40	14-3
Conesville Station Columbus & Southern Ohio Electric Company	$9.90	14-4
Will County Station Commonwealth Edison Company	$26.10	14-5

Because of the unusual nature of the disposal operation at Commonwealth Edison Company's Will County Station, the disposal cost is much higher than might be anticipated at a more typical operation (5). The data from Duquesne Light Company and

Table 14-3

DESIGN AND COST ESTIMATE CLASSIFICATIONS

ITEM	DESIGN/ ESTIMATE DESCRIPTION	PROJECT CONTINGENCY RANGE	DESIGN INFORMATION REQUIRED	COST ESTIMATE BASIS		
				MAJOR EQUIPMENT	OTHER MATERIALS	LABOR
Class I	Simplified	20% to 30%	General site conditions, geographic location and plant layout. Process flow/operation block diagram. Product output capacities.	By overall project or section-by-section based on capacity/cost graphs, ratio methods, and comparison with similar work completed by the contractor, with material adjusted to current cost indexes and labor adjusted to site conditions.		
Class II	Preliminary	15% to 20%	As for Type Class I plus engineering specifics, e.g.: Major equipment specifications. Preliminary P&I flow diagrams.	Recent purchase costs (including freight) adjusted to current cost index.	By ratio to major equipment costs on plant parameters.	Labor/material ratios for similar work, adjusted for site conditions and using expected average labor rates.
Class III	Detailed	10% to 15%	Complete process design. Engineering design usually 20% to 40% complete. Project construction schedule. Contractual conditions and local labor conditions. Actual site defined.	Firm quotations adjusted for possible price escalation with some critical items committed Pertinent taxes and freight included.	Firm unit cost quotes (or current billing costs) based on detailed quantity take-off.	Estimated man-hour units (including assessment) using expected labor rate for each job classification.
Class IV	Finalized	5% to 10%	As for Class III - with engineering essentially complete.	As for Class III - with most items committed	As for Class III - with material on approximately 100% firm basis	As for Class III - some actual field labor productivity may be available

Source: Economic Premises for Electric Power Generating Systems, EPRI, Palo Alto, CA, Reference Date: July 26, 1978.

Columbus and Southern Ohio Electric are more representative, although that of Duquesne Light does not represent their current method of processing and disposal (3,4).

Other data reported in the literature are primarily estimates of expected costs from hypothetical stations. In some cases, the assumptions underlying these estimates are unknown. Recognizing these differences and uncertainties, data derived from the literature have been collated, updated to a 1979 dollar data base, and summarized in Table 14-4b.

It is important to note that the numbers reported are taken from many different examples and situations, using many different assumptions. For this reason, individual comparison of the numbers is difficult. Taken collectively, however, the various estimates can be utilized to determine the approximate overall range of disposal cost expected.

In some cases, the source reported the cost in terms of $/wet t of sludge. Where this occurred, the figure was converted to dry tons of sludge, using actual percent solids reported for that case, or if the percent solids was not reported, then by assuming the percent solids was 50%.

If not otherwise specified, it was assumed that the cost figures applied to the year in which the figures were reported. The Chemical Engineering cost index was then utilized to update these estimates to 1979 dollar figures.

The data in Table 14-4b show total estimated or actual disposal costs ranging from approximately $1.00 to $29.00/dry t of sludge solids (in 1979 dollars). Excluding the extreme from either end of the data base and relying more heavily on more recent data, it is apparent that the total disposal cost for non-regenerable FGD systems is in the range of $6.00 to $17.00/t of dry sludge solids. In general, the lower range of costs (roughly $6.00 to $11.00) reflect simple ponding with no processing other than thickening. The costs at the higher end ($11.00 to $17.00), reflect more extensive and elaborate processing and disposal operations.

SIMPLIFIED COST ESTIMATING

It is not always necessary or desirable to prepare detailed cost estimates where more approximate estimates will suffice. Therefore, this subsection explains and demonstrates a simplified method for quickly estimating total disposal system costs.

Table 14-4b

SUMMARY OF ESTIMATES OF
TOTAL FGD SLUDGE DISPOSAL COSTS REPORTED IN THE LITERATURE

DISPOSAL METHOD	YEAR OF ESTIMATE	COST/DRY TON IN YEAR OF ESTIMATE	COST/DRY TON IN 1979 DOLLARS	REFERENCE
1. Wet disposal in ponds with artificial liner				
a.	1973	$ 2.50 to 13.00	$ 4.10 to 20.90	6 Aerospace Corporation
b.	1973	3.00 to 7.40	4.80 to 11.60	6 Aerospace Corporation
c.	1974	5.93 to 6.09	8.70 to 8.90	7 TVA
d.	1974	5.00 to 9.00	7.00 to 12.80	8 Aerospace Corporation
e.	1975	5.70 to 7.80	7.50 to 10.30	9 Aerospace Corporation
f.	1977	10.90	12.60	10 Michael Baker, Jr., Inc.
g.	1977	8.43	9.80	22 TVA
h.	1979	5.00 to 12.00	5.00 to 12.00	11 TVA
2. Wet disposal in ponds with natural liner				
a.	1975	3.50	4.60	12 Aerospace Corporation
b.	1977	5.62	6.50	22 TVA
3. Wet disposal in ponds with fixation				
a.	1973	3.00 to 6.00	4.60 to 9.30	13 Dravo Corporation
b.	1974	1.00 to 3.00	1.20 to 4.60	14 Dravo Corporation
c.	1975	5.80 to 8.80	7.70 to 11.60	15 Aerospace Corporation
d.	1975	10.00	12.80	16 TVA
e.	1977	14.60	16.90	10 Michael Baker, Jr., Inc.
f.	1979	10.00 to 20.00	10.00 to 20.00	11 TVA

Table 14-4b (Cont.)

DISPOSAL METHOD	YEAR OF ESTIMATE	COST/DRY TON IN YEAR OF ESTIMATE	COST/DRY TON IN 1979 DOLLARS	REFERENCE
4. Dry disposal without fixation				
a.	1977	$ 3.70	$ 4.30	17 Research Cottrell
b.	1977	11.00	12.80	10 Michael Baker, Jr., Inc.
5. Dry disposal with fixation				
a.	1973	14.00 to 15.00	22.00 to 23.20	18 Duquesne Light Company
b.	1974	15.00 to 20.00	22.00 to 29.00	19 Duquesne Light Company
c.	1974	14.00 to 18.00	20.90 to 26.70	8 Aerospace Corporation
d.	1975	7.30 to 9.20	9.60 to 12.20	15 Aerospace Corporation
e.	1975	19.69	26.10	5 Commonwealth Edison Co.
f.	1976	12.00 to 14.00	15.10 to 17.40	3 Duquesne Light Company
g.	1977	10.00 to 15.00	11.60 to 17.40	20 Duquesne Light Company
h.	1977	12.40	14.40	10 Michael Baker, Jr., Inc.
i.	1977	12.27	14.20	22 TVA
j.	1977	8.53	9.90	4 Columbus & Southern Ohio Electric
k.	1979	9.00 to 22.00	9.00 to 22.00	11 TVA
6. Disposal with fixation (not specified wet or dry)				
a.	1973	5.00 to 10.00	8.00 to 16.20	6 Aerospace Corporation
b.	1974	4.00 to 12.00	5.80 to 17.40	9 Aerospace Corporation
c.	1975	7.30 to 11.40	9.60 to 15.10	14 Dravo Corporation
d.	1976	9.90 to 11.00	12.20 to 13.60	21 Aerospace Corporation

The method is intended to provide Class I estimates only and should not be substituted for more detailed estimates prepared from detailed site-specific information. At the level of analysis which Class I estimates are intended to be used effects such as geology, soil conditions, changes in elevation, etc., are not specifically addressed. In addition, the simplified cost estimating procedure described below results in a geometric compounding of cost adjustment factors. The degree of compounding is, however, insignificant at this level of cost estimation. It should be recognized that simplified cost estimating is primarily used for comparison of disposal alternatives for which the site specific effects and compounding effects have an insignificant impact. A method for preparing more detailed cost estimates which addresses these factors is shown in subsequent subsections.

The cost estimating methodology given here is based on detailed estimates prepared by TVA on over 500 different situations (2,11,23,24,25). The data have been reformatted to allow generalizations, but the cost curves utilized are developed from TVA cost estimates. Correction factors for transport distances from 25 to 200 miles are based on cost estimating procedures developed by the Center for Advanced Computation, University of Illinois (26).

Basic Premises

The basic assumptions established for the power plants and FGD systems are given in the following:

ASSUMPTIONS FOR COST CURVES

Power Plant

a. Newly-constructed plants have a 30-yr life. Existing plants have variable lives of 25, 20 and 15 yr.

b. For a new plant, the total operating life is 127,500 hr with an average annual operating time of 4,250 hr.

c. The power unit input heat requirement is 9000 Btu/kWh.

d. Coal heating value varies from 9,900 to 11,100 Btu/lb, depending on ash and sulfur content.

FGD System

a. A limestone scrubbing process is used for SO_2 removal.

b. SO_2 and flyash are removed to meet an SO_2 emission of 1.2 lb/MBtu heat input and a particulate emission of 0.1 lb/MBtu heat input.

c. 85% of the ash present in the coal is emitted as flyash.

d. 95% of the S in the coal is emitted as SO_2.

e. Effluent from the scrubber system contains 15% solids.

f. All storage facilities have a 30-day capacity and feed bins, intermediate storage tanks, etc., have an 8-hr capacity.

ECONOMIC ASSUMPTIONS

a. Midwestern plant location.

b. All capital cost estimates are based on Chemical Engineering cost indexes (1979 plant index - 237.2, material index - 263.0, labor index - 192.5). Capital costs are projected to mid-1979 using these indexes. Construction on the project is assumed to have started in mid-1977 and to be completed in mid-1980.

c. Direct capital costs cover process equipment, piping and insulation, transport lines, foundations and structural, excavation and site preparation, roads and railroads, electrical instrumentation, buildings, and trucks and earthmoving equipment. Material and labor (fabrication and installation) costs are included.

d. Indirect capital costs include engineering design and supervision, architect and engineering contractor expenses, construction expenses, contractor fees, contingency, allowance for start-up and modifications, and interest during construction. Two other capital costs not included as indirect costs, but in the total capital investment are working capital and land.

e. Direct costs for revenue requirements include raw materials, labor, electricity, equipment fuel and maintenance, and analyses. These costs are projected to mid-1980.

f. Indirect costs for revenue requirements are capital charges and overheads.

g. Capital charges are based on regulated utility economics.

h. Revenue requirements are projected for an annual 7,000-hr/yr (first year) operation.

Fundamental Cases

In all, four basic systems are considered. These basic systems and fundamental assumptions are:

1. Ponding without fixation.

   a. Effluent (15% solids) from the scrubber system is pumped to a clay-lined disposal pond.

   b. The pond is located one mile from the scrubber facilities.

   c. The sludge settles to 50% solids in the pond and excess water is recycled to the scrubber system.

   d. The FGD process stoichiometry is 1.5 mols calcium oxide (CaO)/mol SO_2 removed.

   e. Flyash and SO_2 are removed simultaneously in the scrubber system; therefore, the sludge contains both flyash and Ca wastes.

   f. 15% of the SO_2 removed is converted to gypsum and the remaining 85%, $CaSO_3$.

   g. Treatment of storm-water runoff and system blowdown are not considered.

2. Landfill with stabilization.

   a. Dewatered sludge (60% solids) is blended with dry flyash to yield a physically stable material.

   b. Flyash is removed from the flue gas to meet NSPS using an ESP and pneumatically conveyed to the sludge treatment area for blending with sludge.

   c. The blended material (about 75% solids) is transported one mile to a landfill disposal site by truck.

   d. Typical earthmoving equipment is used for placement and compaction in a landfill.

   e. The FGD process stoichiometry is 1.5 mols CaO/mol SO_2 removed.

   f. 15% of the SO_2 removed is converted to gypsum and the remaining 85%, $CaSO_3$.

3. Landfill with fixation

   a. Dewatered sludge (60% solids) is treated with lime (4% by weight of dry solids).

   b. Trucks are used to transport the treated material to a landfill disposal site located one mile from the scrubber.

   c. Treated sludge is assumed to have clay-like properties and can be placed and compacted in a landfill with typical earthmoving equipment.

   d. The FGD process stoichiometry is 1.5 mols CaO/mol SO_2 removed.

   e. Flyash and SO_2 are removed simultaneously in the scrubber system; therefore, the sludge contains both flyash and Ca wastes.

   f. 15% of the SO_2 removed is converted to gypsum and the remaining 85%, $CaSO_3$.

4. Landfill with forced oxidation.

   a. The limestone FGD process is modified to provide forced oxidation of $CaSO_3$ sludge to gypsum. The FGD process stoichiometry is 1.1 mols CaO/mol SO_2 removed.

   b. 95% of the SO_2 removed is converted to gypsum and the remaining 5%, $CaSO_3$.

   c. Flyash and SO_2 are removed simultaneously in the scrubber to meet NSPS; therefore, sludge contains both gypsum and flyash.

   d. Dewatered gypsum (about 80% solids) is transported by truck one mile to the landfill disposal site.

   e. Typical earthmoving equipment is used for placement and compaction of the gypsum in the landfill.

Variables Considered

Several variables are considered which may significantly affect the overall system cost. These variables are:

1. For landfill options:
   a. plant size--from 200 to 1500 MW
   b. plant life--new plant with 30-yr life and retrofitted plants with 15, 20, and 25-yr life
   c. % sulfur in coal--from 2 to 5%
   d. % ash in coal--from 12 to 20%
   e. distance to disposal area--from one to 200 mi. For distance between 25 and 200 miles the landfilled material is transported by unit train--a high capital investment option but one with a lower annual revenue requirement. See Figures 14-7a and 7b. Between distances of 10 and 25 miles the decision to transport by truck or rail is a site specific question since at those distances the two modes are cost competitive based on annual revenue requirements.
   f. levelized annual capital and operating costs for new plants
2. For ponding option:
   a. plant size--from 200 to 1500 MW
   b. plant life--new plant with 30-yr life and retrofitted plants with 15, 20, and 25-yr life
   c. % sulfur in coal--from 2 to 5%
   d. % ash in coal--from 12 to 20%
   e. distance to disposal area--from one to 10 mi, consider pumping unthickened sludge at 15% solids or thickened sludge at 35% solids. In most cases it would be impractical to pump unthickened sludge at distances greater than 10 miles.
   f. availability of land--from 50 to 100% of optimum. 100% optimum available land represents the lowest cost associated with constructing a pond under the most favorable conditions of excavating and lowest land cost. Land availability may limit the acreage on which a pond can be constructed. Conditions less than optimum are thus expressed as a % of optimum and are completely subjective.
   g. types of liner--consider the case of no liner, or the case of synthetic liners at installed costs of \$1.50/yd^2 to \$4.50/yd^2.
   h. levelized annual capital and operating costs for new plants.

Methodology

The method of cost estimating is performed by using nomographs and graphs. First, determine the cost of the basic disposal plant by using the nomographs in Figures 14-1a and 14-1b. These are used by 1) selecting the appropriate power plant size for the disposal alternative shown as four separate vertical lines at the left of

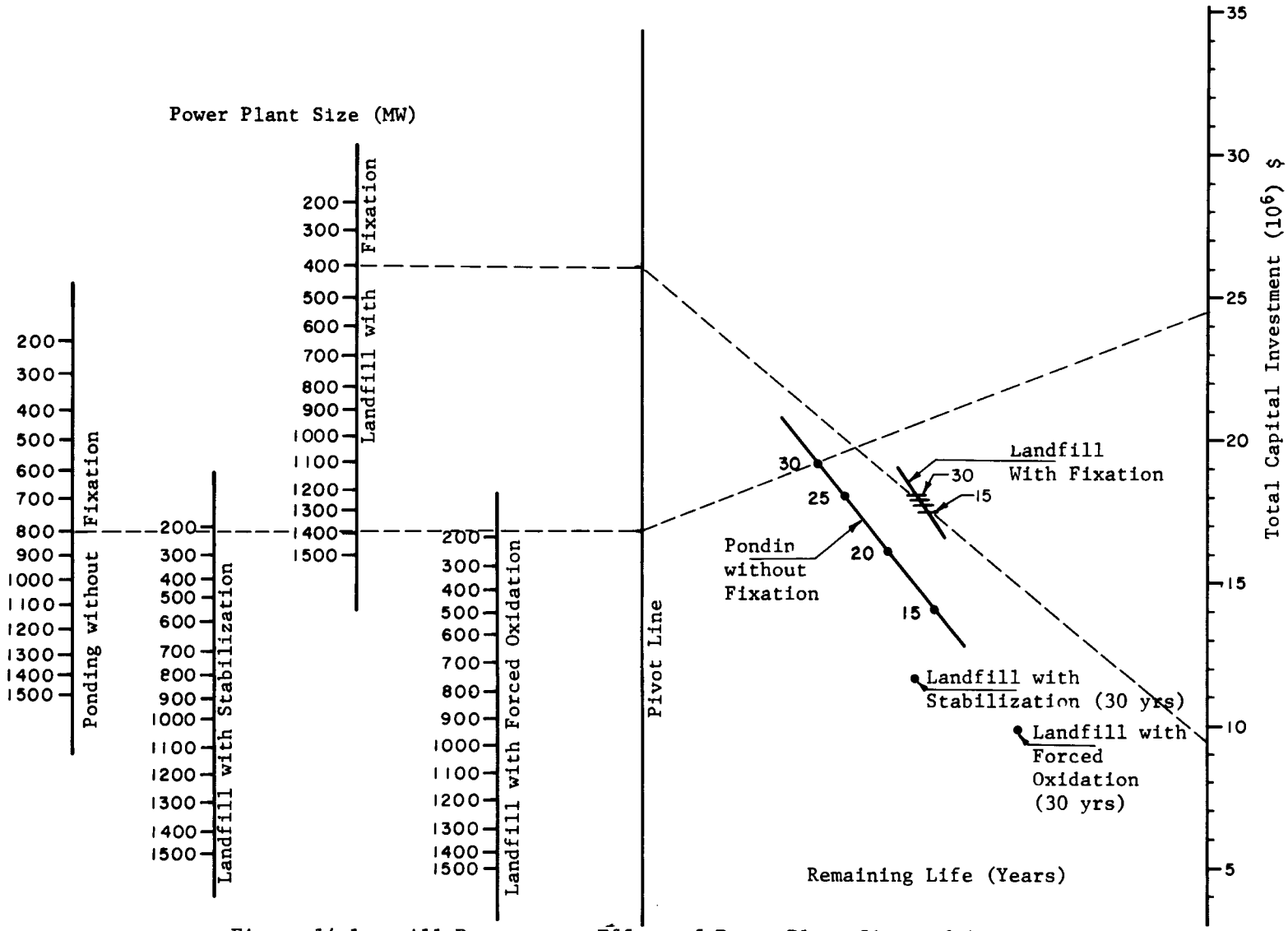


Figure 14-1a. All Processes - Effect of Power Plant Size and Age on Total Capital Investment.

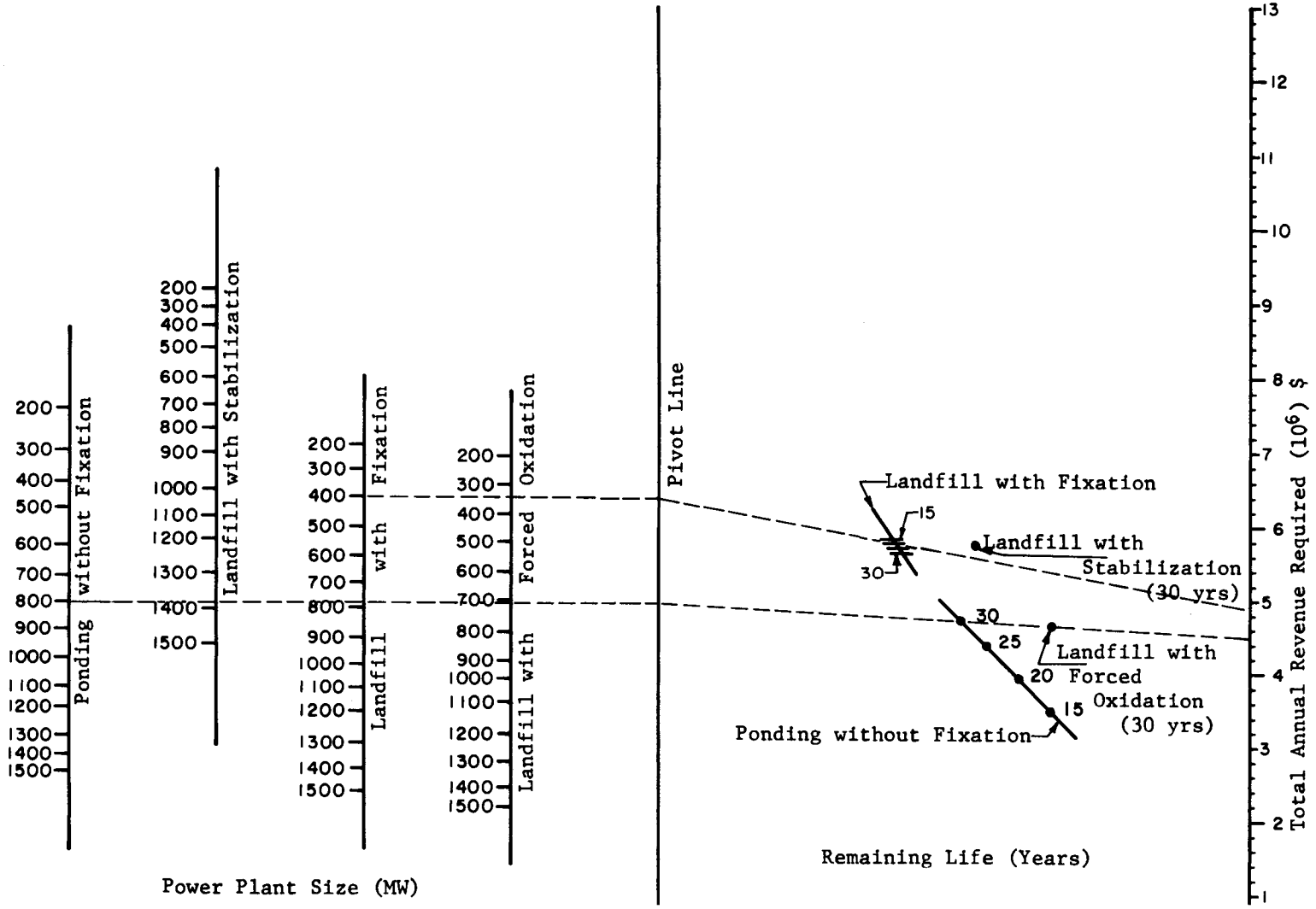


Figure 14-1b. All Processes. Effect of Power Plant Size and Age on Total Annual Revenue Requirements.

the nomograph; 2) drawing a horizontal line to the pivot line; 3) drawing a straight line from the pivot line through the age of the plant for the disposal alternative; and 4) reading off the appropriate total capital investment or total annual revenue requirement from the line extension. Two examples are shown on each of the nomographs. Then apply correction factors derived from Figures 14-2 through 14-10 to the base cost for the different variables described above. Table 14-5 shows which curves to use for all the variables. The following two examples illustrate how to use the cost curves.

Table 14-5

INDEX OF FIGURES TO BE USED TO OBTAIN
CORRECTION FACTORS FOR ESTIMATING SYSTEM COSTS

	PONDING WITHOUT FIXATION	LANDFILL WITH STABILIZATION	LANDFILL WITH FIXATION	LANDFILL WITH FORCED OXIDATION
Base Case Conditions	14-1	14-1	14-1	14-1
% S in Coal	14-2	14-2	14-2	14-2
% Ash in Coal	14-3	14-4	14-4	14-4
Transport Distance, 1 to 10 miles	14-5	14-6	14-6	14-6
Transport Distance, Greater than 10 miles	--	14-7	14-7	14-7
Land Availability	14-8	--	--	--
Synthetic Liners	14-9	--	--	--
Levelized Costs	14-10	14-10	14-10	14-10

Ponding Example. The problem is to determine the total capital investment, total annual revenue requirement, and cost per ton of dry sludge and flyash for a new 800 MW plant using ponding without fixation.

Step 1: Estimate or determine the basic parameters

Plant size - 800 MW
Plant life - 30-yr
% S in Coal - 2.5%
% Ash in Coal - 16%
Distance to disposal area - 6 mi
Land Availability - 80%
Liner Type - no liner

Step 2: Determine base costs

From Figure 14-1a, Total Capital Investment - $24,500,000
From Figure 14-1b, Total Annual Revenue Requirement - $4,500,000

Step 3: Determine Correction Factors

	Total Capital Investment	Total Annual Revenue Requirement
% S in Coal - From Figure 14-2	0.84	0.87
% Ash in Coal - From Figure 14-3	1.00	1.00
Distance to Disposal Area - From Figure 14-5 (Use 35% solids because of lower cost)	1.53	1.65
Land Availability - From Figure 14-8	1.03	1.00
Liner Type - From Figure 14-9	0.84	0.84
Levelized Cost - From Figure 14-10	--	1.43

Step 4: Calculate Corrected Costs

Total Capital Investment = Base Investment x Correction Factors

= ($24,500,000)(.84)(1.0)(1.53)(1.03)(0.84)

= $27,240,000

Total Annual Revenue Requirement

= Base Revenue Requirement x Correction Factors

= ($4,500,000)(0.87)(1.00)(1.65)(1.00)(0.84)

= $5,430,000

Step 5: Calculate Levelized Annual Revenue Requirement = Total Annual Revenue Requirement x Correction Factor

= ($5,430,000)(1.43)

= ($7,760,000

Step 6: Calculate tons of dry solids produced (Flyash and FGD Solids from Section 4 - WASTE QUANTITIES. For this example, it is assumed to be 534,000 t/yr.

Step 7: Calculate $/dry t of sludge solids

$$\$/\text{dry t} = \frac{\text{total annual revenue requirement}}{\text{t of dry solids/yr}}$$

$$\$/\text{dry t} = \frac{\$7,760,000}{534,000\ \text{t}}$$

$/dry t = $14.53

Landfill Example. The problem is to determine the total capital investment, total annual revenue requirement, and cost per ton of dry sludge and flyash for a retrofit 400 MW plant using landfill with fixation.

Step 1: Estimate or determine the basic parameters.

Plant size - 400 MW
Plant life - 20 yr.
% S in Coal - 4%
% Ash in Coal - 14%
Distance to disposal area - 3 mi.

Step 2: Determine Base Costs

From Figure 14-1a, Total Capital Investment = $9.3 million
From Figure 14-1b, Total Annual Revenue Requirement = $4.9 million

Step 3: Determine Correction Factors

	Total Capital Investment	Total Annual Revenue Requirement
% S in Coal - From Figure 14-2	1.04	0.04
% Ash in Coal - From Figure 14-4	0.92	0.93
Distance to Disposal Area From Figure 14-6	1.03	1.12

Step 4: Calculate Corrected Costs

Total Capital Investment = Base Investment x Correction Factors
= $9,300,000 (1.04)(0.92)(1.03)
= $9,160,000

Total Annual Revenue Requirement
= Base Revenue Requirement x Correction Factors
= $4,900,000 (1.04)(0.93)(1.12)
= $5,310,000

Step 5: Calculate tons of dry solids produced (flyash and FGD solids) from Section 4 - WASTE QUANTITIES. For this example, it is assumed to be 316,000 t/yr.

Step 6: Calculate $/dry t of sludge solids (first year)

$$\$/\text{dry t} = \frac{\text{total annual revenue requirement}}{\text{t of dry solids/yr}}$$

$$\$/\text{dry t} = \frac{\$5,310,000/\text{yr}}{316,000\ \text{t/yr}}$$

$/dry t = $16.80 dry t

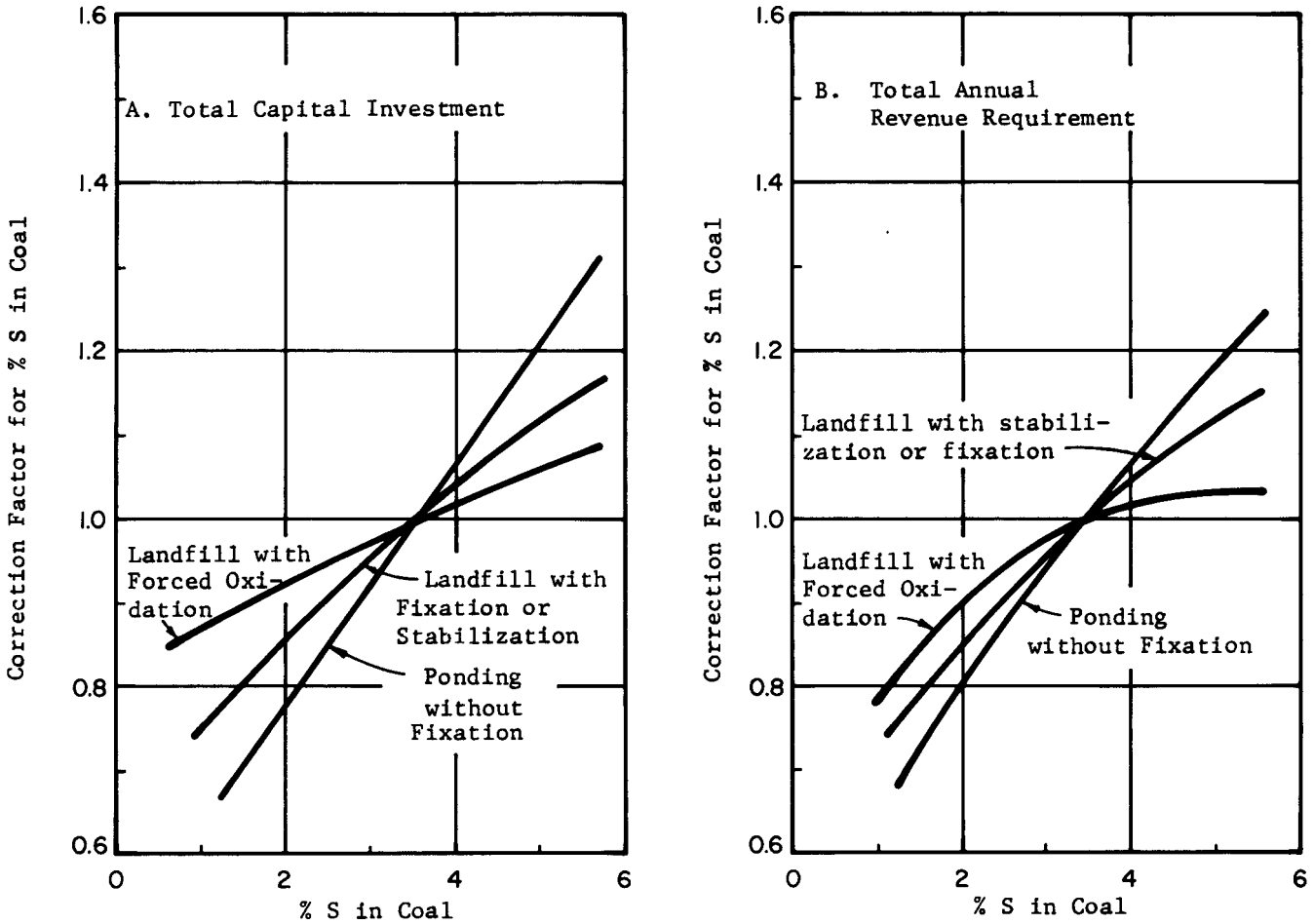


Figure 14-2. All Alternatives.
Correction Factors for % S in Coal.

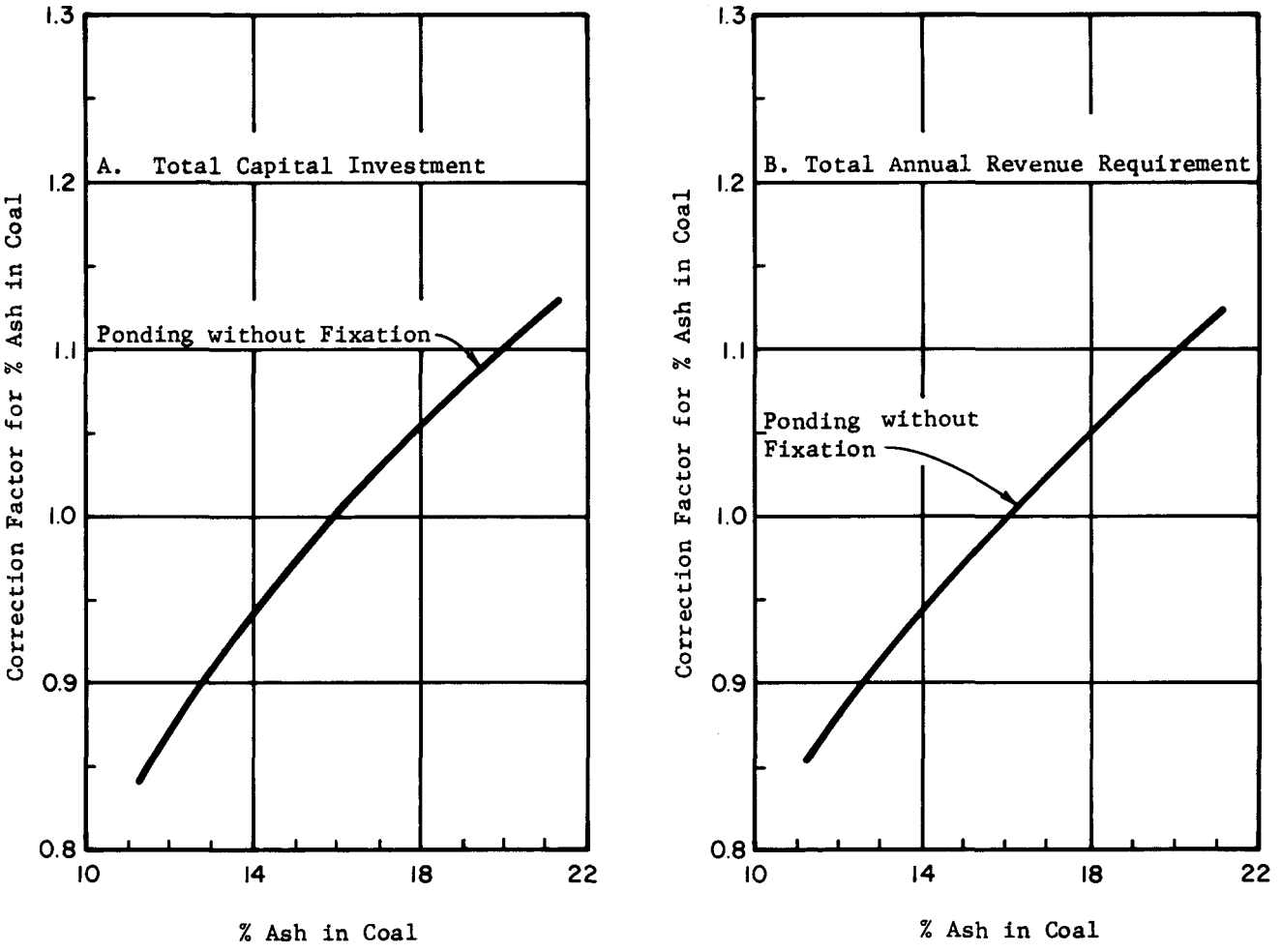


Figure 14-3. Ponding without Fixation.
Correction Factors for % Ash in Coal.

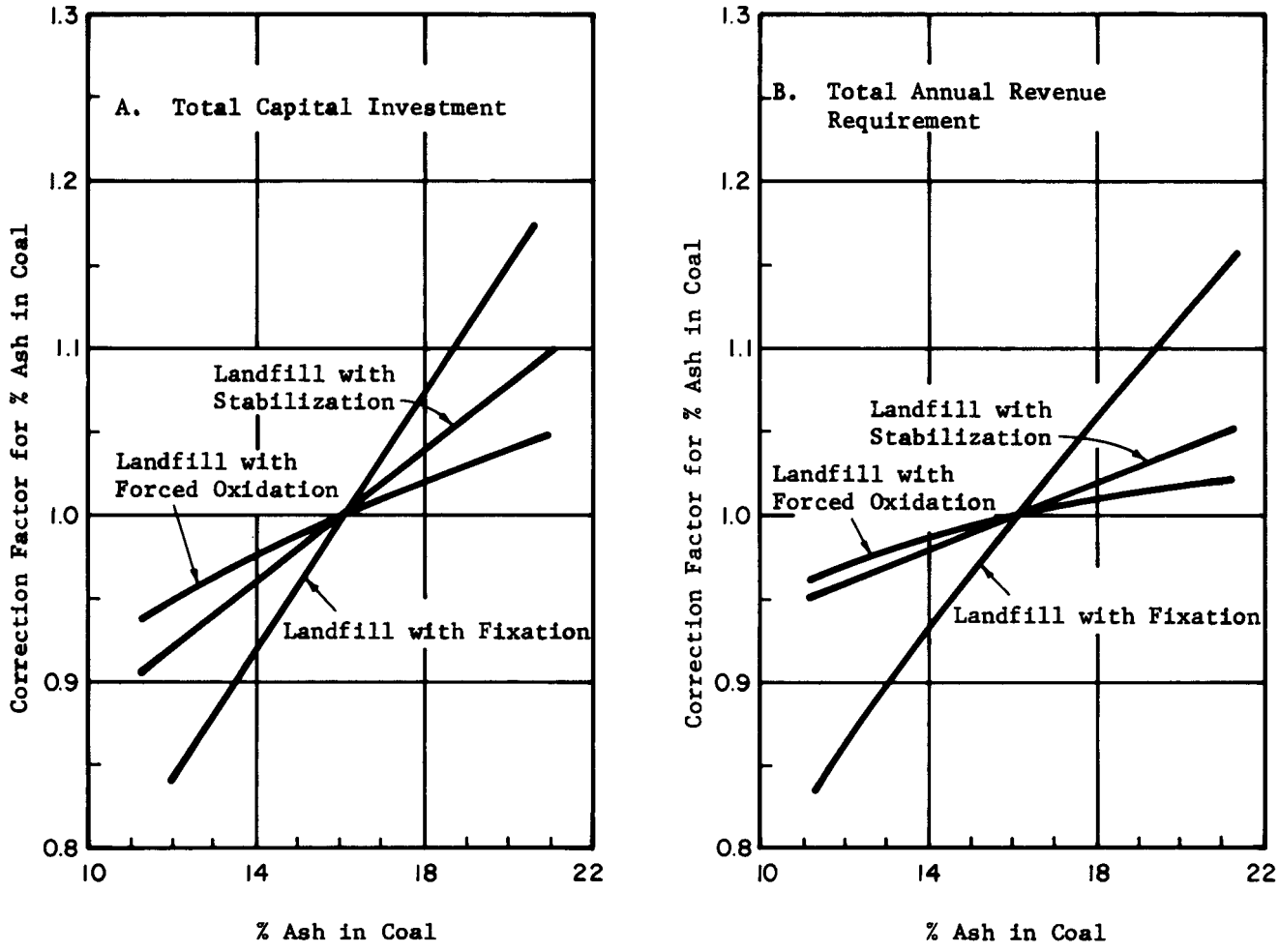


Figure 14-4. Landfill Alternatives.
Correction Factors for % Ash in Coal.

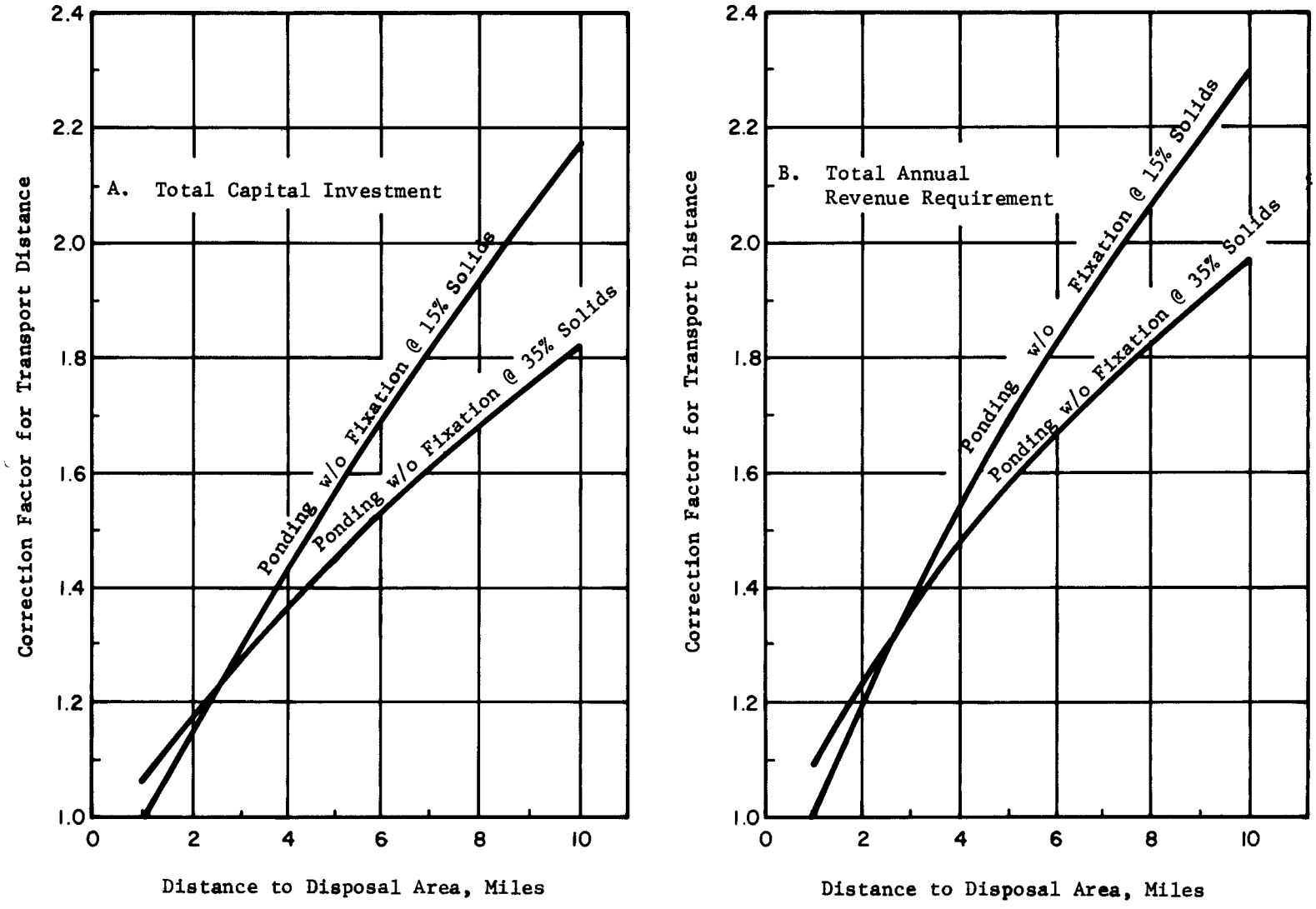


Figure 14-5. Ponding without Fixation Correction Factors for Distance to Disposal Site. (Includes transport of unthickened sludge at 15% solids and thickened sludge of 35% solids. Includes cost of thickener.)

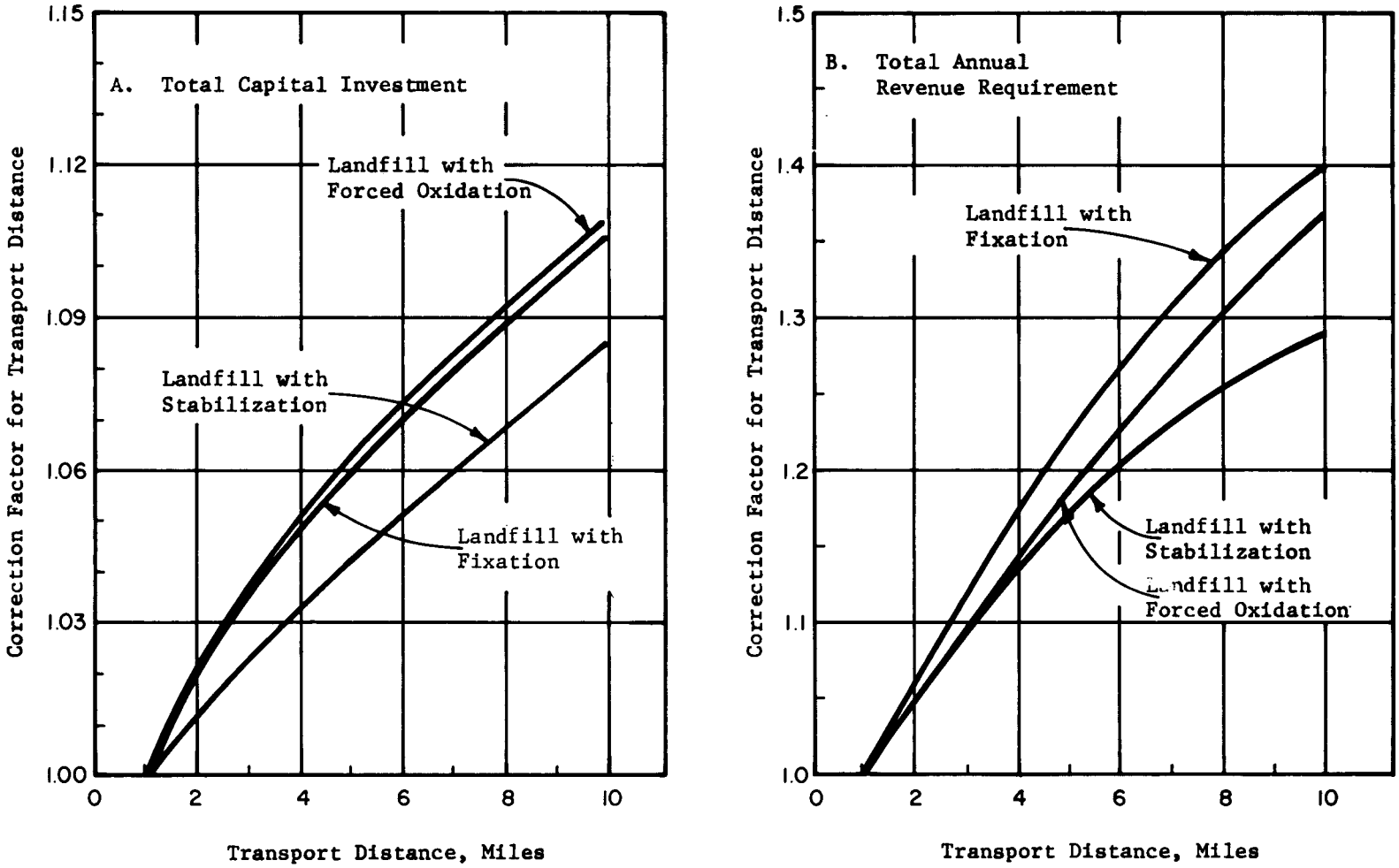


Figure 14-6. Landfill Alternatives.
Correction Factors for Distance to Disposal Site.

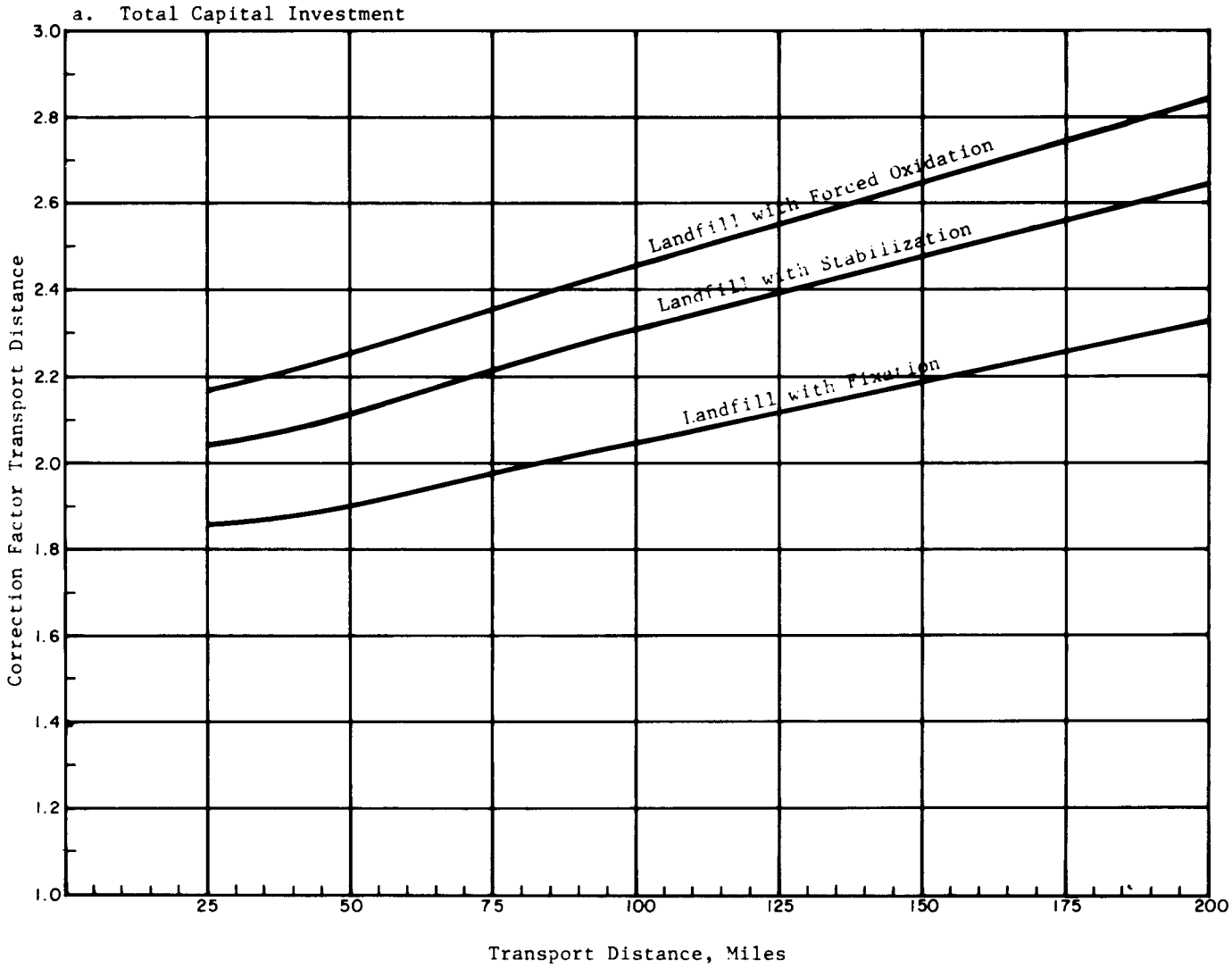


Figure 14-7a. Landfill Alternatives.
Correction Factors for Long Distances to Disposal Site.

b. Total Annual Revenue Requirement

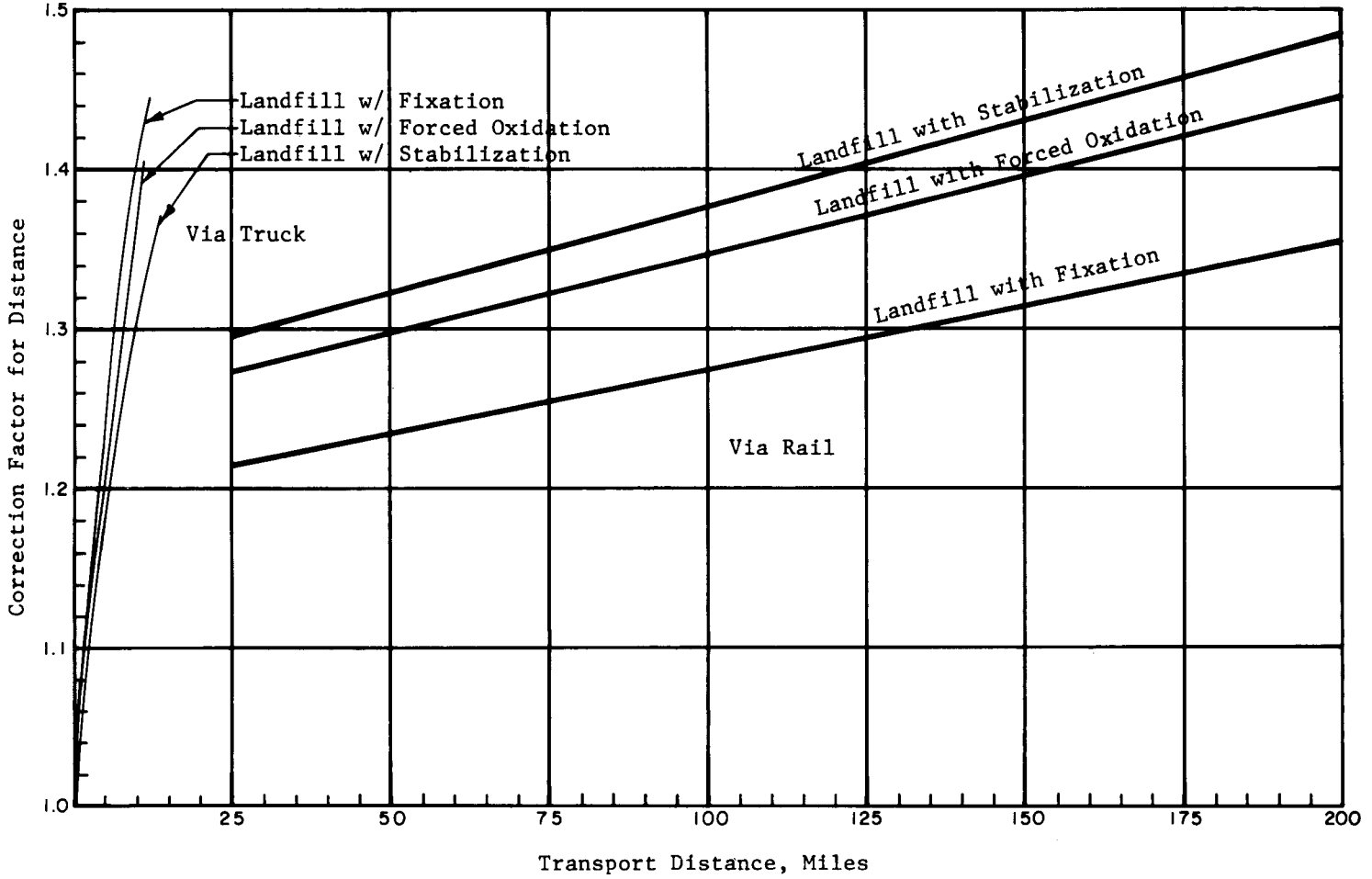


Figure 14-7b. Landfill Alternatives
Correction Factors for Long Distances to Disposal Site.

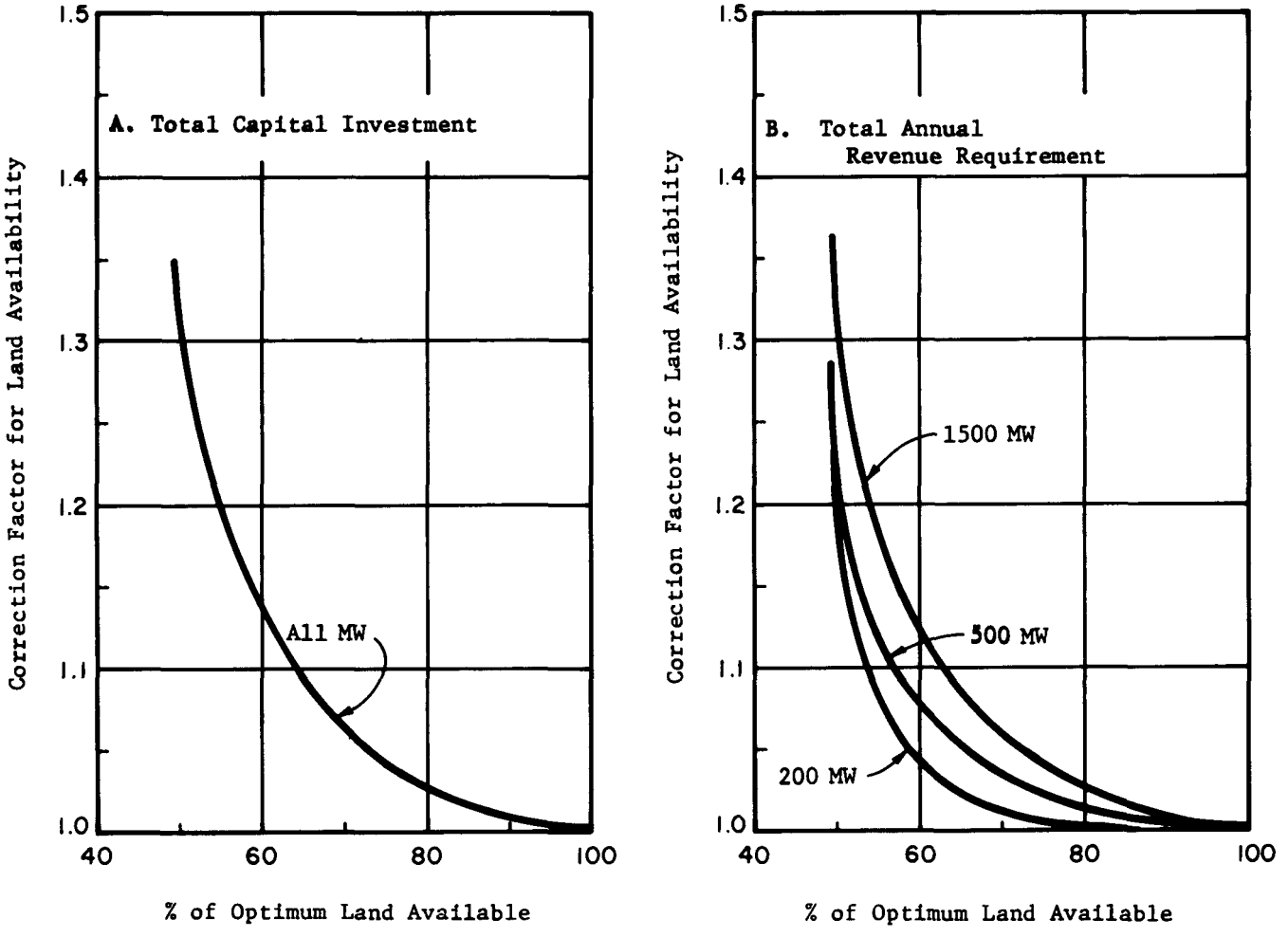


Figure 14-8. Ponding without Fixation.
Correction Factors for Land Availability.

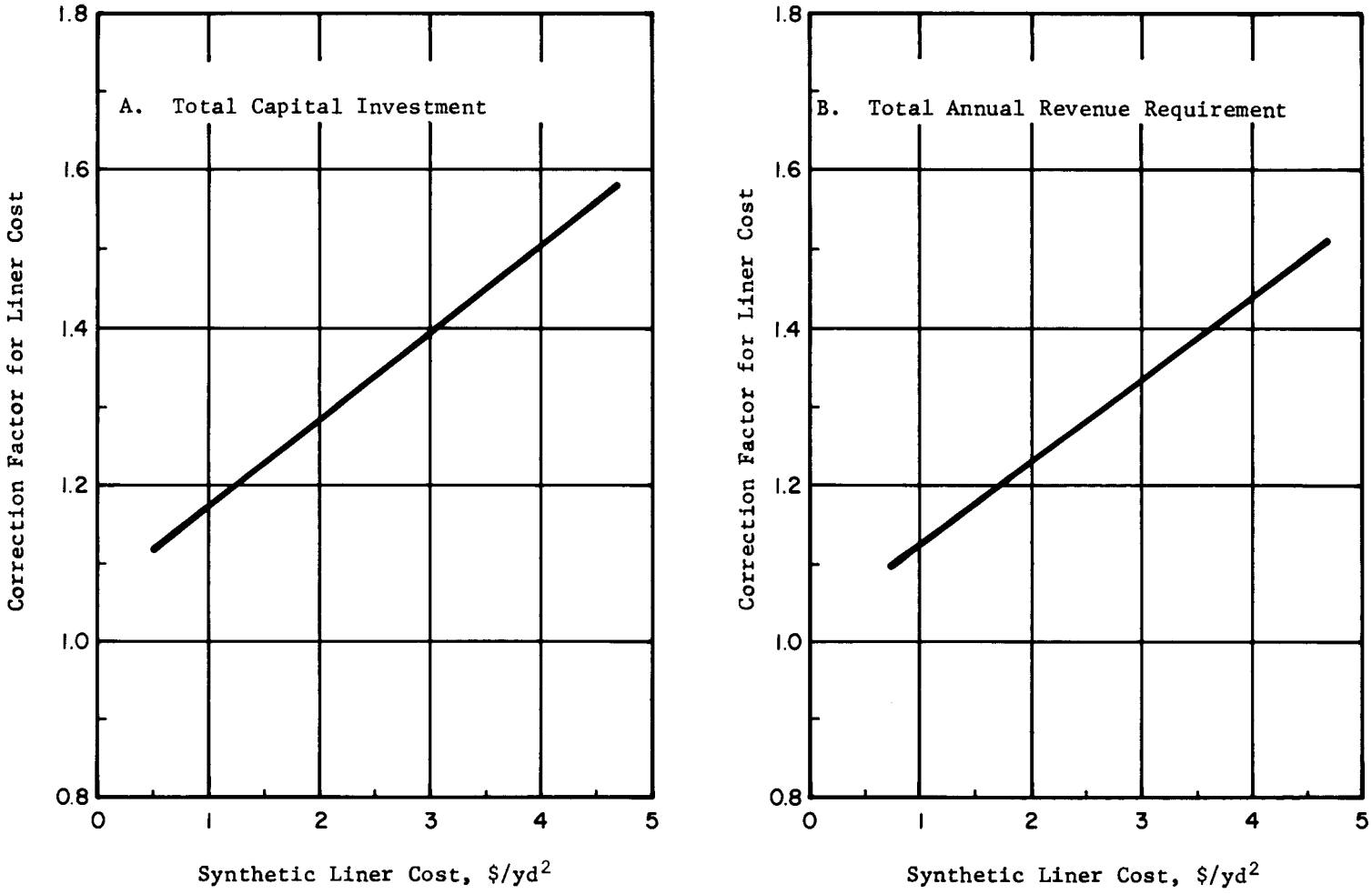


Figure 14-9. Ponding without Fixation.
Correction Factors for Synthetic Liner Costs.

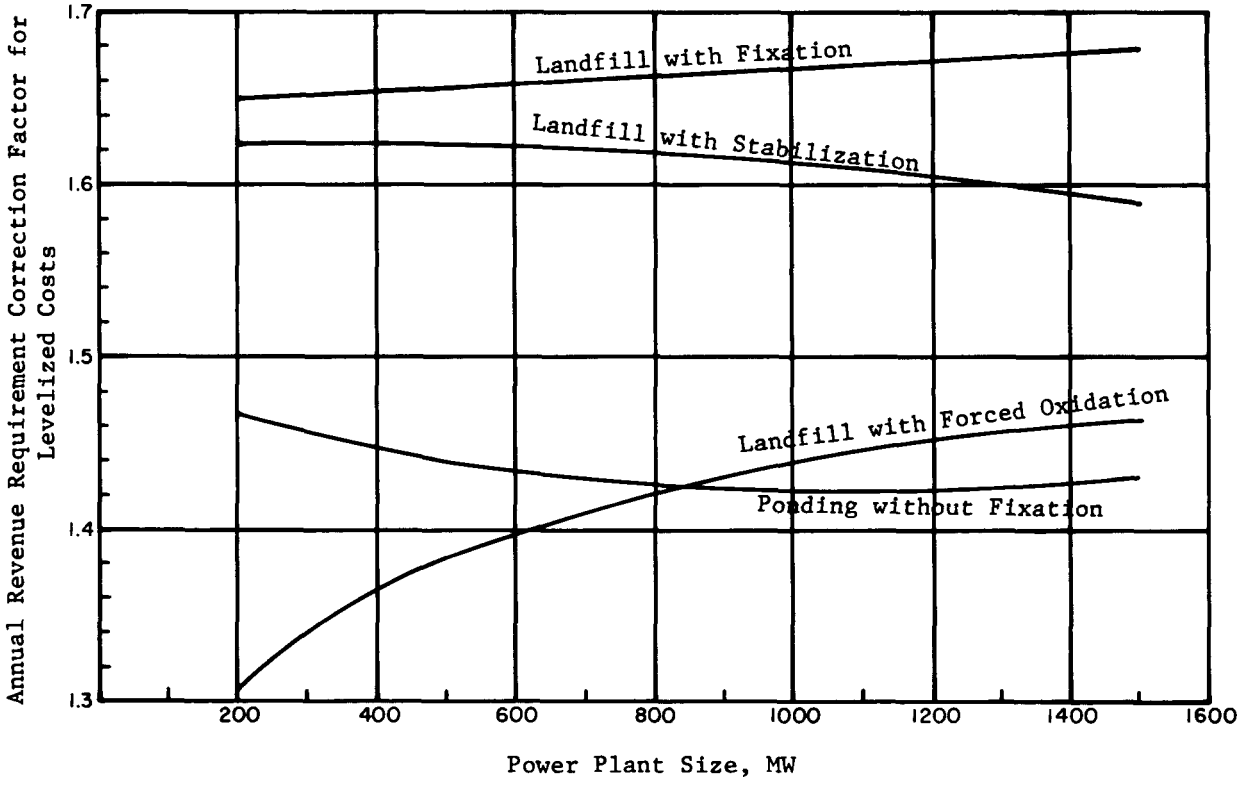


Figure 14-10. All Alternatives.
Correction Factors for Levelized Annual Revenue Requirement.

DETAILED COST ESTIMATES

The preparation of detailed cost estimates will be necessary at some point in time to fully evaluate the revenue requirements for the disposal alternatives being considered. This subsection shows how to make these detailed cost estimates using regulated utility economics for untreated pond disposal and the IUCS process.

In all, there are seven basic steps to be taken in developing detailed estimates. There are:

Step 1: Establish design premises and assumptions
Step 2: Establish the disposal system
Step 3: Determine the total capital requirements
Step 4: Determine the first year operating costs
Step 5: Determine the levelized operating costs
Step 6: Determine the annual cost of capital
Step 7: Determine the levelized annual revenue requirements

Step 1. Establish Design Premises

Basic design assumptions must be established for the power plant and the FGD system. These are necessary primarily to size the various components of the system. The steps to establish these assumptions are:

- Establish the sulfur, ash and heating value of the coal to be used.
- Establish the station rated capacity to be used in the evaluation. For larger plants, determine the size of the individual units. For example, a 1500 MW plant might consist of three 500 MW units; an 800 MW plant could consist of two 400 MW units.
- Establish the life, operating time, and capacity factor for the power plant. New plants are usually estimated to have a 30-yr life based on guidelines suggested by the Federal Power Commission (27). Other useful life periods will be necessary for plants retrofitted with scrubbers. EPRI suggests the following capacity factors as design values: (1)

Type of Plant	Design Capacity Factor
Base	70%
Intermediate	30%
Peaking	10%

The capacity factor can be assumed to be constant over the life of the plant (i.e., levelized) or can be variable based on operating experience. Power unit operating schedules for TVA, for example, are shown in Table 14-6.

Table 14-6

POWER UNIT OPERATING SCHEDULES FOR TVA FACILITIES

YEARS OF LIFE	CAPACITY FACTOR, % (Nameplate Rating)	ANNUAL OPERATING TIME, hr
1 to 10	80	7,000
11 to 15	57	5,000
16 to 20	40	3,500
21 to 30	17	1,500
Average for 30-yr life	48.5	4,250

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes: Untreated and Chemically Treated Wastes, Tennessee Valley Authority, TVA Bulletin Y-123, EPA 600/7-78-023a, February, 1978.

- Establish whether the reagent will be lime, limestone, alkaline flyash, or double-alkali.
- Determine the basic flow diagram for the scrubber. This need not be detailed, but is necessary to determine whether flyash will be collected separate from or concurrent with SO_2 and other similar factors. A scheme similar to that shown in Figures 3-1 and 3-2 in Section 3 - WASTE COMPOSITION is necessary.

Step 2. Establish the Disposal System

This item consists of several activities which are necessary to define and size the various components of the system. Collectively, these constitute a preliminary (Class II) design of the disposal system. The important steps are:

- Determine the sludge quantity and characteristics as explained in Section 3 - WASTE CHARACTERISTICS and in Section 4 - WASTE QUANTITY.
- Prepare detailed flow diagrams similar to those shown in Figure 14-12.
- Prepare a system description similar to those shown in Table 14-7 and 14-10.
- Prepare a material balance similar to that illustrated in Table 14-8 and Figure 14-12.
- Develop equipment lists and descriptions such as those shown in Tables 14-9 and 14-11. In developing this list, decide what level of redundancy will provide required operational availability.
- Prepare layout drawings like those shown in Figures 14-11, 14-13, and 14-14.

Step 3. Determine Total Capital Requirements

The total capital requirements represent the total of all costs, both direct and indirect, which are attributed to the sludge disposal system. The total capital requirements are made up of:

1. Total Plant Investment
   a. Direct Investment
      -- Process equipment
      -- Field equipment
   b. Indirect Investment
      -- Engineering design and supervision
      -- Architect and engineering contractor expenses
      -- Contractor fees
      -- Construction expense
   c. Process contingency
   d. Project contingency

Table 14-7

TYPICAL SYSTEM DESCRIPTION[a]

UNTREATED DISPOSAL
Underflow containing 15% solids from the scrubber system is pumped to an agitated pond feed tank. The slurry is then pumped one mile to a disposal pond where the slurry is allowed to settle to form a material containing 60% solids. Excess water is returned to the scrubber system for reuse. Carbon steel, rubber-lined pipelines are used to transport the sludge to the disposal pond, which is clay-lined to prevent leachate from the wastes from entering groundwater. A material balance for the base untreated case is shown in Table 14-8 and provides information concerning each process stream.

[a]Since this system involves only a few items of equipment, the layout drawings, flow diagrams, and instrumentation diagrams are not presented in this report.

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes: Untreated and Chemically Treated Wastes, Tennessee Valley Authority, TVA Bulletin Y-123, EPA 600/7-78-023a, February, 1978.

Table 14-8

MATERIAL BALANCE - UNTREATED PROCESS

	Description of Stream			
	Spent Slurry to Pond Feed Tank	Spent Slurry to Pond	Settled Slurry	Recycle Water
Rate, lb/hr	772,000	772,000	232,000	540,000
Rate, gpm	1,404	1,404	320	1,081
Specific Gravity	1.10	1.10	1.45	1.00
% Solids (undissolved)	15	15	50	0

Table 14-9

UNTREATED DISPOSAL - BASE CASE
EQUIPMENT LIST

Item	No.	Description
Tank, pond feed	1	63,000 gal, field erected, 21 ft diameter, 26 ft high, vertical with open top, carbon steel, 1/4 in neoprene lined
Agitator	1	15 hp, neoprene lined
Pump, pond feed	3	1,404 gpm, 1.28 sp. gr., 300-ft head, neoprene lined, with 125 hp motor
Pump, recycle pond water	2	1,081 gpm, 200-ft head, multistage turbine, cast iron bowl, stainless steel impellers with 100 hp motor

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes: Untreated and Chemically Treated Wastes, Tennessee Valley Authority, TVA Bulletin Y-123, EPA 600/7-78-023a, February, 1978.

Table 14-10

TYPICAL SYSTEM DESCRIPTION

IUCS PROCESS

"An earthlike material that can be used for landfill disposal is produced using the IUCS sludge fixation process. This material has physical and structural properties that make it suitable for handling with belt conveyors, trucks, and typical earthmoving equipment."

"Spent slurry containing 15% solids from the FGD system is pumped to an agitated storage tank (8-hr capacity). The slurry is fed to a thickener in which the solids content in the slurry is increased from 15 to 35%. Thickener overflow water is returned to the scrubber facility for reuse. Underflow is pumped to a rotary drum filter and the sludge is dewatered to form a material containing 60% solids. Filtrate is also returned to the scrubber system for reuse. The filter cake is transferred by belt conveyor to a blade-type mixer for blending with the fixation additives. The fixed material is conveyed to a small disposal pile where it is loaded with a front-end loader into a truck and subsequently hauled to a disposal site. Lime is used as the additive and is received by truck or rail at the sludge fixation facilities. Pneumatic conveyors are used for transporting the lime to storage silos (30-day storage capacity) and for transferring the additive to feed bins (8-hr capacity) above the mixers. Weigh feeders are used to meter the lime to the mixers and the standard amount of additive is 4% by weight of dry sludge solids. A flow diagram and material balance for the IUCS base case are shown in Figure 14-12.

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes: Untreated and Chemically Treated Wastes, Tennessee Valley Authority, TVA Bulletin Y-123, EPA 600/7-78-023a, February 1978.

Table 14-11

IUCS PROCESS - BASE CASE EQUIPMENT LIST

Item	No.	Description
1. Pneumatic conveying system, lime	1	Complete system with blower, cyclone receiver, receiver filter, motor
2. Storage silo, lime	3	18,532 ft^3, 510 tons, field erected, 22.8 ft diameter, 45.6 ft high, carbon steel, with top, 60-degree cone bottom
3. Feeder, discharge	3	Rotary air lock type, 4,633 lb/hr, 8 in diameter, 8 in long, carbon steel
4. Vibrator, lime storage silo	24	Electromechanical, rotary vibrators, 1 hp motor
5. Feed bin, lime	1	618 ft^3, 7 ft diameter, 15 ft high, with top, 60-degree cone bottom, carbon steel
6. Feeder, bin discharge	1	Rotary air lock type, 8 in diameter, 8 in long, carbon steel
7. Vibrator, lime feed bin	4	Electromechanical, rotary vibrators, 1 hp motor
8. Weigh feeder, lime	1	5 ft long, 14 in belt, 3/4 hp D.C. motor, carbon steel
9. Car puller	1	15,000 lb, 500 ft, 15 hp motor
10. Sump pump	1	5 gpm, 10 ft head, carbon steel, 1/4 hp motor
11. Tank, thickener feed	1	63,000 gal, field erected, 21 ft diameter, 26 ft high, open top, four 1 ft 9 in x 26 ft baffles offset 3-1/2 in from wall, neoprene lined, carbon steel
12. Agitator, thickener feed tank	1	15 hp, 72 in diameter blade, neoprene coated
13. Pump, thickener feed	2	1500 gpm, 75 ft head, neoprene lined, 60 hp motor
14. Thickener	1	219 ft diameter, stainless steel or neoprene lined concrete basin with rake and motor with 1 spare
15. Tank, thickener overflow	1	26,500 gal, 16-1/2 ft diameter, 16-1/2 ft high, neoprene lined, carbon steel
16. Pump, thickener overflow recycle	2	881 gpm, 75 ft head, neoprene lined, 25 hp motor
17. Pump, thickener underflow to filter	2	517 gpm, 75 ft head, neoprene lined, 25 hp motor
18. Sump pump, thickener tunnel	1	5 gpm, 10 ft head, carbon steel, 1/4 hp motor
19. Rotary drum filter	3	464 ft^2, 10 ft diameter x 16 ft long drum, stainless steel (wetted parts), vacuum and filtrate pumps
20. Pump, filtrate recycle	2	276 gpm, 75 ft head, neoprene lined, 10 hp motor
21. Conveyor, horizontal filter	3	18 ft long, 45 t/hr, 1/2 hp motor
22. Conveyor, sloping filter cake	3	30 ft long, 24 in belt, 48 t/hr, 10 hp motor
23. Mixer	1	Carbon steel, 75 hp motor
24. Conveyor, horizontal fixed cake	1	30 in belt, 30 ft long, 99 t/hr, 3/4 hp motor
25. Conveyor, sloping fixed cake	1	30 in belt, 150 ft long, 99 t/hr, 15 hp motor

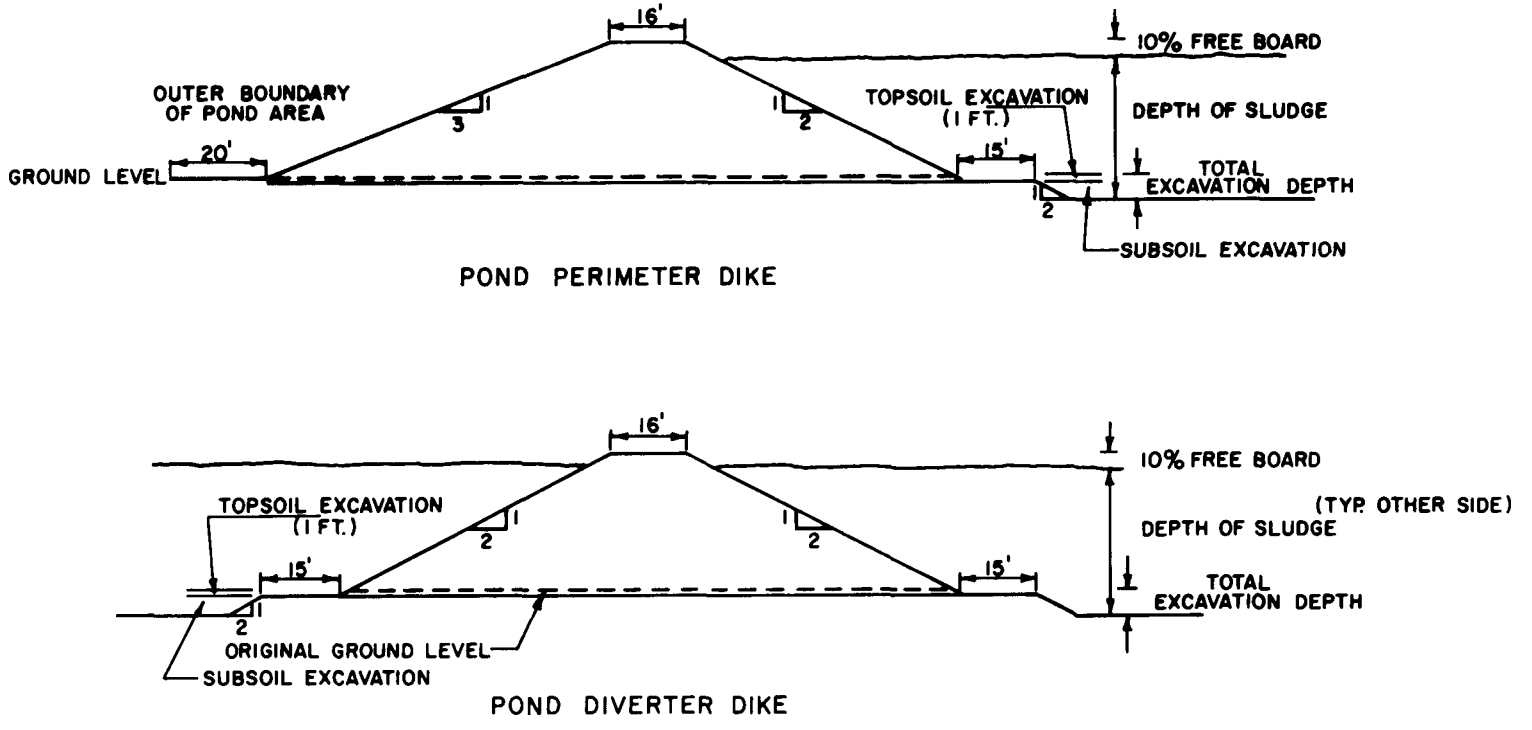
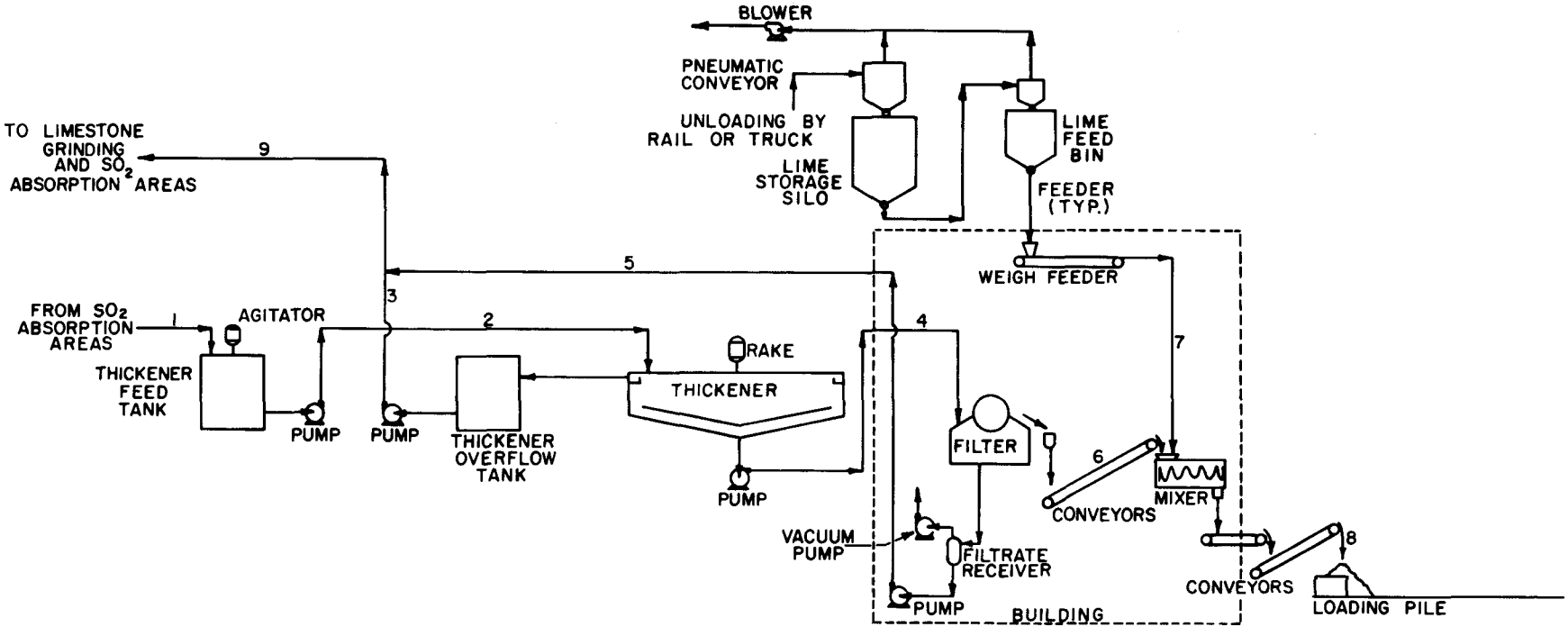


Figure 14-11. Limestone Slurry Process Dike Construction Drawing.

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes, TVA, EPA 600/7-78-023a, February 1978.



STREAM NO.	1	2	3	4	5	6	7	8	9
DECRIPTION	SLURRY TO THICKENER FEED TANK	SLURRY TO THICKENER	THICKENER OVERFLOW	UNDERFLOW TO FILTER	RECYCLE FILTRATE	CAKE TO MIXER	LIME TO MIXER	TREATED SLUDGE TO DISPOSAL	RECYCLE WATER TO SYSTEM
LB./HR.	772 k	772 k	441 k	331 k	138 k	193 k	4633	198 k	579 k
G.P.M.	1404	1404	883	517	276	241			1159
SP. GR.	1.10	1.10		1.28		1.60			
UND SLVD. SLDS. %	15	15		35		60			

Figure 14-12. IUCS Process. Flow Diagram and Material Balance.

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes, TVA, EPA 600/7-78-023a, February 1978.

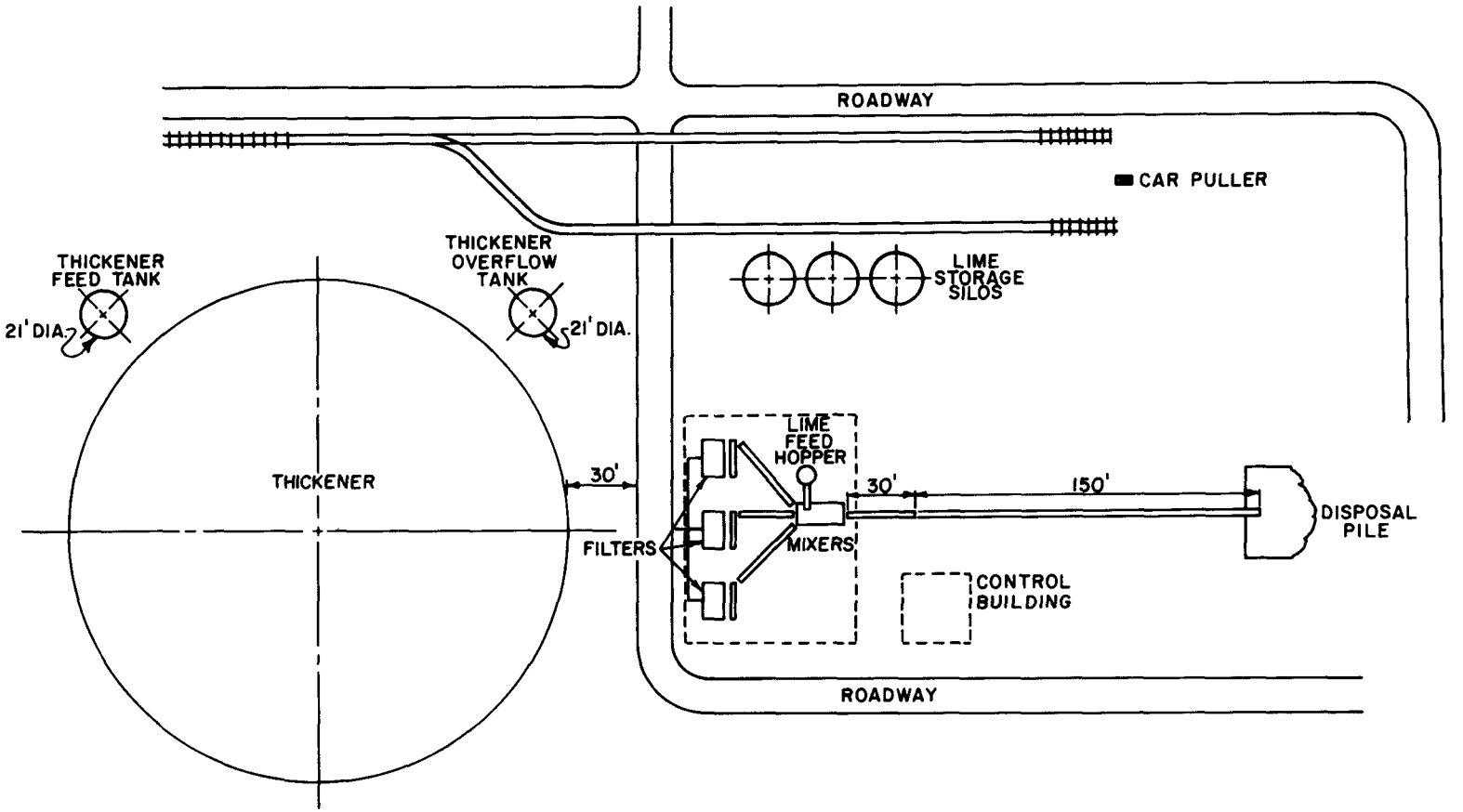


Figure 14-13. IUCS Process - Overall Plot Plan.

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes, TVA, EPA 600/7-78-023a, February 1978.

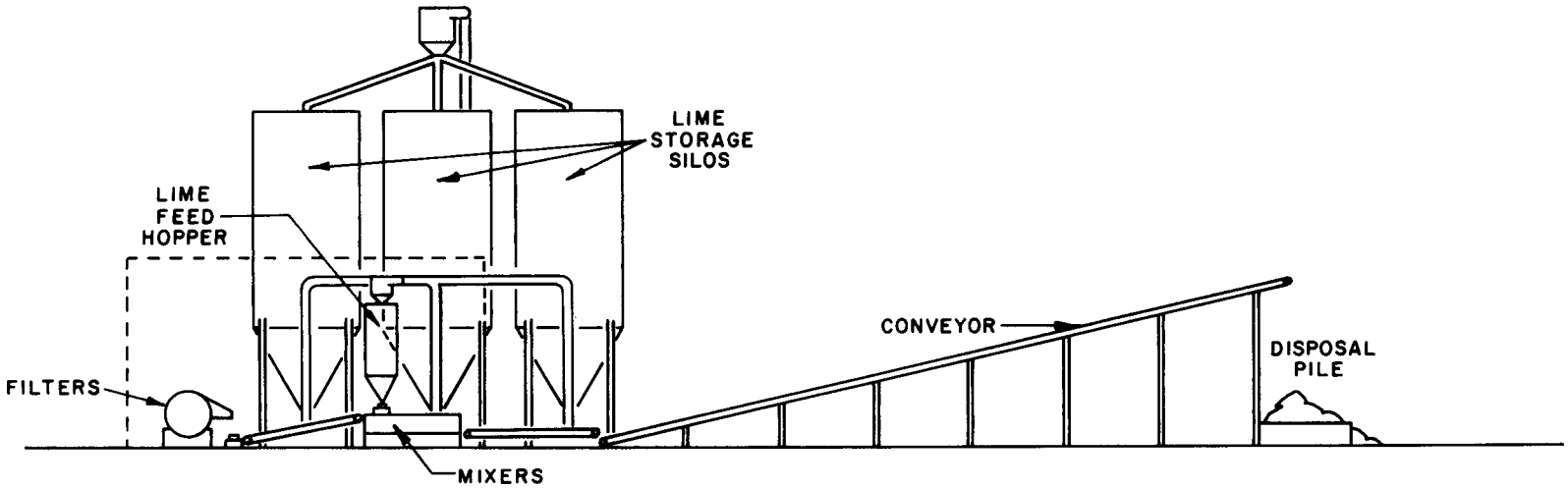


Figure 14-14. IUCS Process - Elevation Plot Plan.

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes, TVA, EPA 600/7-78-023a, February 1978.

2. Other Capital Requirements
   a. Prepaid royalties
   b. Allowance for startup and modification
   c. Inventory capital
   d. Allowance for funds during construction
   e. Land

An example of the tabulation of capital requirements for the disposal examples described in Tables 14-7 and 14-10 are given in Tables 14-12 and 14-13.

Plant Investment. This is the sum of all direct and indirect cost items necessary to undertake the project. Plant investment consists of the following items:

Direct Investment. The direct investment includes the total constructed cost of all process equipment (on-site costs) and field equipment (off-site costs) including all direct and indirect construction costs, both material and labor. Sales tax should also be included. Table 14-8 shows process equipment items included in the estimate of direct investment for the example being discussed here. Process equipment costs can be obtained from price quotations of vendors and suppliers and review of recent purchase costs from other utilities.

The additional items of cost other than major process equipment are:

- Piping. Pipe and valve size and materials are determined as part of the design effort. Costs are figured accordingly.
- Foundations and Structural. Foundations for each equipment item should be determined from equipment sizes. Foundations for major structures are estimated on the basis of the weight and size of the structure. Structural estimates are based on the arrangement and types of equipment.
- Electrical. Electrical costs should include: (1) cost of feeder cables from station transformer yard to the sludge disposal system, (2) transformer costs for each area, (3) costs of power supply from field modules to individual motors, and (4) motor control costs. Total connected motor horsepower is used to calculate costs for feeder cables and transformers. Costs for power supplies and motor controls are based on individual motor sizes and the number of connected motors.
- Instrumentation. Instrumentation costs should be estimated for all the process elements for both monitoring and control functions. Costs should include control valves, visual display boards, annunciators and alarms, air dryers and piping, and instrument cable and wiring systems.
- Excavation and Site Preparation. The excavation and site preparation costs will depend on the amount of excavation and type and size of equipment utilized. Estimates are usually based on the number of cubic yards of material that is to be moved. Typical significant excavation costs are for underground piping (including slurry pipeline) and for the sludge disposal pond.

Table 14-12

UNTREATED DISPOSAL[a]
TOTAL CAPITAL INVESTMENT - PROCESS EQUIPMENT AND INSTALLATION ANALYSIS

	Total, k$	Percent of Direct Investment	Percent of Total Capital Investment
Process equipment	128	1.4	0.7
Piping and insulation	121	1.3	0.7
Transport lines	1,109	12.1	6.4
Foundation and structural	7	0.1	0.1
Excavation, site preparation, roads and railroads	73	0.8	0.4
Electrical	395	4.3	2.3
Instrumentation	53	0.6	0.3
Buildings	0	-	-
Subtotal	1,886	20.6	10.9
Services and miscellaneous	28	0.3	0.2
Subtotal excluding pond	1,914	20.9	11.1
Pond construction	7,251	79.1	42.2
Subtotal direct investment	9,165	100.0	53.3
Engineering design and supervision	367	4.0	2.1
Architect and engineering contractor	49	0.5	0.3
Construction expense	1,102	12.1	6.4
Contractor fees	517	5.6	3.0
Subtotal	11,200	122.2	65.1
Contingency	2,240	24.4	13.0
Subtotal fixed investment	13,440	146.6	78.1
Allowance for startup and modifications	619	6.8	3.6
Interest during construction	1,613	17.6	9.3
Subtotal capital investment	15,672	171.0	91.0
Land	1,423	15.5	8.3
Working capital	116	1.3	0.7
TOTAL CAPITAL INVESTMENT	17,211	187.8	100.0

[a]Basis: New 500-MW plant (30-yr life); 772 klb/hr (15% solids) sludge. Midwest plant location; average basis for cost scaling, mid-1979. Coal analysis (by weight): 3.5% S (dry basis), 16% ash. Flyash removed with SO_2. SO_2 and flyash removed to meet NSPS. Limestone process with 1.5 stoichiometry based on SO_2 removed. Pond characteristics: clay-lined, 1 mi from scrubber facilities, 50% solids settled density, 21.21 ft total depth, 407 acres.

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes: Untreated and Chemically Treated Wastes, Tennessee Valley Authority, TVA Bulletin Y-123, EPA 600/7-78-023a, February, 1978.

Table 14-13

IUCS PROCESS[a]
TOTAL CAPITAL INVESTMENT - PROCESS EQUIPMENT AND INSTALLATION ANALYSIS

(Base Case)

	Total, k$	Percent of Direct Investment	Percent of Total Capital Investment
Process equipment	2,551	52.2	23.7
Piping and insulation	176	3.6	1.6
Transport lines	-	-	-
Foundation and structural	136	2.8	1.3
Excavation, site preparation, roads and railroads	115	2.4	1.1
Electrical	639	13.1	6.0
Instrumentation	70	1.4	0.7
Buildings	550	11.3	5.1
Subtotal	4,237	86.8	39.5
Services and miscellaneous	64	1.3	0.6
Subtotal excluding trucks and equipment	4,301	88.1	40.1
Trucks and earthmoving equipment	581	11.9	5.4
Subtotal direct investment	4,882	100.0	45.5
Engineering design and supervision	392	8.0	3.7
Architect and engineering contractor	98	2.0	0.9
Construction expense	839	17.2	7.8
Contractor fees	320	6.6	3.0
Subtotal	6,531	133.8	60.9
Contingency	1,306	26.7	12.2
Subtotal fixed investment	7,837	160.5	73.1
Allowance for startup and modifications	726	14.9	6.8
Interest during construction	940	19.3	8.8
Subtotal capital investment	9,503	194.7	88.7
Land	676	13.8	6.3
Working capital	538	11.0	5.0
TOTAL CAPITAL INVESTMENT	10,717	219.5	100.0

[a]Basis: New 500-MW plant (30-yr life); 198 klb/hr (60% solids) sludge. Midwest plant location; average basis for cost scaling, mid-1979. Coal analysis (by weight): 3.5% S (dry basis), 16% ash. Flyash removed with SO_2. SO_2 and flyash removed to meet NSPS. Limestone process with 1.5 stoichiometry based on SO_2 removed. Disposal in landfill 1 mi from scrubber facilities, 60% solids cake. Land required for disposal, 193 acres at 30 ft deep. Trucks used for transport of treated sludge to disposal area. Lime added at 4% of dry solids.

- Buildings. Costs for constructing buildings to house process equipment and pumps may be necessary in some cases. Where dry disposal is utilized, the secondary dewatering and chemical addition facilities are usually housed in a building specifically for this equipment. A separate control building is also sometimes required.
- Services. The cost of services such as vehicles, maintenance and instrument shop equipment, laboratory, lockers, offices, restrooms, storage area, parking area, walkway, landscaping, fencing, communications, and security should all be included. TVA estimates the cost of services to be about 1.5% of the direct investment (21).
- Roads and Railroads. Include the cost of roads or railroads which will be used for general access, raw material unloading (lime, Calcilox, etc.), and/or sludge hauling.
- Earthmoving Equipment. For dry disposal alternatives, the cost of earthmoving equipment such as conveyors, dozers, graders, scrapers, compactors, and/or trucks must be included.
- Pond Construction. For wet disposal alternatives, the cost of constructing the pond must be established. This is a function of the amount of earth to be moved, liners, drainage, and other special features which must be incorporated into the design.

Indirect Investment. Indirect investment items include the following:

- Engineering Design and Supervision. This item, which ordinarily amounts to between 2 and 8% of the total direct investment, can be calculated in a number of ways. TVA correlates the number of major equipment items with drafting room manhours and engineering design costs (2). Alternately, the actual number of man-hours required by the utility to prepare drawings and specifications and to supervise this activity can be estimated.
- Architect and Engineering Contractor Expense. This cost represents the costs for engineering work performed by the contractor related to the project. Typically this expense can be estimated as about 25% of the engineering design and supervision expense associated with major equipment and 10% of the same expense for pond construction (2).
- Contractor Fees. TVA indicates the following formula can be used to estimate contractor fees: (2)

$$\text{Contractor fees} = 0.096(a)^{0.76}$$

where: a = direct investment in million dollars

- Construction Expense. This expense can be estimated using the equation: (2).

$$\text{Construction expense} = 0.25(b)^{0.83} + 0.13(c)^{0.83}$$

where: b = direct investment excluding pond or landfill equipment costs in million dollars

c = direct pond cost in million dollars

Process Contingency. A capital cost contingency should be applied to new technology in order to quantify the uncertainty in the design and cost of the commercial scale equipment. EPRI provides the guidelines shown in Table 14-14 to aid in assigning process contingency allowances to the sludge disposal system (1). Because the process contingency will vary with different components of the disposal system, it should be applied separately as necessary to each component.

TABLE 14-14

GUIDELINES FOR ASSIGNING
PROCESS CONTINGENCY ALLOWANCES

STATE OF TECHNOLOGY DEVELOPMENT	% INSTALLED SECTION COST
New concept with limited data	25% and up
Concept with bench-scale data available	15 to 25
Small pilot plant data (e.g., 1 Mw size) available	10 to 15
A full-size module has been operated (e.g., 20-100 Mw)	5 to 10
The process is used commercially	0 to 5

Source: Economic Premises for Electric Power Generating Systems, EPRI, Palo Alto, CA, Reference Date: July 26, 1978.

Project Contingency. A capital cost contingency factor should be developed for the disposal system which covers additional equipment or other costs that would result from a more detailed design of the project. Table 14-14 presents EPRI guidelines for relating the project contingency to the level of design/estimating effort.

Other Capital Requirements. The total capital requirement for a regulated utility includes all the capital necessary to complete the entire project. Therefore, the following additional items of expenses must be included:

Paid-Up Royalties. These are normally estimated at 0.5% of process equipment capital costs.

Allowance for Start-up and Modification. These costs are intended to cover operator training, equipment checkout, major changes in plant equipment, extra maintenance, and inefficient use of fuel and other materials during plant start-up. TVA estimates this expense as 10% of direct investment excluding pond construction plus all other indirect investment costs, except interest, during construction (2). EPRI suggests estimating start-up costs as the sum of: (1)

- One month fixed-operating costs (operating and maintenance labor, administrative and support labor, and maintenance materials)
- One month of variable operating costs at full capacity (variable costs include chemicals, water and other consumables)
- 2% of total plant investment

Inventory Capital. The value of one month supply of reagents and other consumables (and by-products) is capitalized and included in the estimate of total capital required.

Allowance for Funds During Construction (AFDC). Using EPRI methods, the AFDC charge is computed based on the time period from the center of gravity (cg) of expenditures until the plant is in commercial operation (1). Assuming an interest rate of 8%/yr, the AFDC can be calculated from the total plant investment (TPI) as follows:

$$AFDC = [(1.08)^{cg} - 1] \ (TPI)$$

Numerical Example:

$TPI = \$100$

$cg = 2$ yr

$AFDC = [(1.08^2) - 1] \ (100) = \$16.6$

The center of gravity time period can be estimated using the method shown in Table 14-15, assuming a construction cash flow schedule.

Land. Land costs are site-specific and variable. Estimates should include actual direct costs plus related items such as transfer costs, legal fees, and taxes required to obtain the property.

Table 14-15

EXAMPLE OF AFDC CALCULATION FROM THE CONSTRUCTION PERIOD CASH FLOW

EXAMPLE:

Total Plant Investment (TPI) = $100 (yr 1 $)

Construction Expenditure Schedule (Assumed)

Year	$(yr 1 $)
1	5
2	15
3	30
4	35
5	15

Assuming expenditures are uniform over a given year, the effective interest rate for the first year is 1/2 the annual interest rate. (Using annual end-of-year compounding)

Annual Interest Rate = 8%

Calculation of AFDC

$5 \times (1.04)(1.08)^4 =$	7.07
$15 \times (1.04)(1.08)^3 =$	19.65
$30 \times (1.04)(1.08)^2 =$	36.39
$35 \times (1.04)(1.08) =$	39.31
$15 \times (1.04) =$	15.60
Total (TPI + AFDC)	118.02

$$\text{Center of Gravity (cg)} = \frac{\log\left(\frac{\text{AFDC}}{\text{TPI}} + 1\right)}{\log (1.08)}$$

$$\text{cg} = \frac{\log\left(\frac{18.02}{100} + 1\right)}{\log (1.08)} = 2.15 \text{ yr}$$

Therefore, 2.15 yr is the center of gravity (cg) for the construction expenditure schedule shown above.

Source: Economic Premises for Electric Power Generating Systems, EPRI, Palo Alto, CA, Reference Date: July 26, 1978.

Step 4. Determine First Year Operating Costs

The operating costs should be estimated on a first year basis and then presented on a 30-yr levelized basis. The operating costs are divided into fixed and variable costs. The fixed costs are independent of capacity factor, while the variable costs are directly proportional to the amount of power produced. Tables 14-16 and 14-17 show typical tabulations of first year operating costs for the examples described in the foregoing tables and figures.

The calculations relating to annual revenue requirements should be based on the same process operation schedules as the power plant operating profile and remaining life assumptions made in Step 1. The costs should be projected to the commercial operation date for the disposal system. The average annual Chemical Engineering cost indexes and projections shown in Table 14-18 may be used for this projection.

First year operating costs represent the sum of costs for raw materials, operating labor, maintenance, disposal area land preparation, utilities, overhead, and by-product credit.

Raw Materials (Consumables). The principal variable raw materials requirements are for lime and/or Calcilox for fixation of the sludge. Typical projected 1980 values for these chemicals are: (2)

Pebble lime	$48.00/t
Thiosorbic lime	$51.00/t
Calcilox	$58.00/t

Other consumables will include fuel for operating trucks and landfill equipment, if used.

Operating Labor. Operating labor is determined by estimating the number of operating jobs (OJ) that are required to operate the disposal system. The operating labor charges (OLC) are then computed using the average labor rate (ALR) as follows:

$$OLC = (OJ) \times (ALR) \times \text{hr of operation in the first yr}$$

Typical mid-west average labor rates including payroll burden (about 35%) are: (2)

Plant operation and supervision	$12.50/hr
Analyses	$17.00/hr
Landfill equipment and truck operators	$17.00/hr

Table 14-16

UNTREATED DISPOSAL
TOTAL ANNUAL REVENUE REQUIREMENTS - REGULATED UTILITY ECONOMICS

	Annual Quantity	Unit Cost, $	Total Annual Revenue Requirements, $	Percent Of Total Annual Revenue Requirements
Direct Costs				
Conversion costs				
Operating labor and supervision	17,520 man-hr	12.50/man-hr	219,000	0.7
Maintenance				
Labor and materials				
4% of direct investment (plant)			76,600	2.3
3% of direct investment (pond)			217,500	6.6
Electricity	1,906 kkWh	0.029/kWh	55,300	1.7
Analyses	500 hr	17.00/man-hr	8,500	0.3
Subtotal conversion costs			576,900	17.6
Subtotal direct costs			576,900	17.6
Indirect Costs				
Capital charges				
Depreciation, interim replacement, and insurance at 6% of total capital investment less land and working capital			940,300	28.7
Average cost of capital and taxes at 8.6% of total capital investment			1,480,100	45.1
Overhead				
Plant, 50% of conversion costs less utilities			260,800	7.9
Administrative, 10% of operating labor			21,900	0.7
Subtotal indirect costs			2,703,100	82.4
Total annual revenue requirements			3,280,000	100.0

Basis: Remaining plant life, 30 yr. Coal burned, 428,571 lb/hr, 9,000 Btu/kWh. Power plant on-stream time, 7,000 hr/yr. Total capital investment, $17,211,000. Midwest plant location, mid-1980 operating costs.

Table 14-17

IUCS PROCESS

TOTAL ANNUAL REVENUE REQUIREMENTS - REGULATED UTILITY ECONOMICS

	ANNUAL QUANTITY	UNIT COST, $	TOTAL ANNUAL REVENUE REQUIREMENTS, $	PERCENT OF TOTAL ANNUAL REVENUE REQUIREMENTS
Direct Costs				
Delivered raw materials				
Lime (ground)	16,216 tons	53.00 /ton	859,400	16.2
Subtotal raw materials cost			859,400	16.2
Conversion costs				
Operating labor and supervision				
Plant	35,040 man-hr	12.50 /man-hr	438,000	8.3
Solids disposal equipment	52,560 man-hr	17.00 /man-hr	893,500	16.9
Maintenance--plant labor and material, 4% of direct investment			172,000	3.3
Landfill operation				
Land preparation			11,000	0.2
Trucks (fuel and maintenance)	693,000 tons	0.06 /ton	41,600	0.8
Earthmoving equipment (fuel and maintenance)	693,000 tons	0.16 /ton	110,900	2.1
Electricity	3,688 kkWh	0.029/kWh	107,000	2.0
Analyses	1,000 hr	17.00 /man-hr	17,000	0.3
Subtotal conversion costs			1,791,000	33.0
Subtotal Direct Costs			2,650,400	50.1
Indirect Costs				
Capital charges				
Depreciation, interim replacement, and insurance at 7.83% of total capital investment less land and working capital			744,100	14.1
Average cost of capital and taxes at 8.6% of total capital investment			921,700	17.4
Overhead				
Plant, 50% of conversion costs less utilities			842,000	15.9
Administrative, 10% of operating labor			133,200	2.5
Subtotal indirect costs			2,641,000	49.9
Total annual revenue requirements			5,291,400	100.0

Basis: Remaining plant life, 30 yrs.

Coal burned, 482,571 lb/hr, 9000 Btu/kWh.

Power plant on-stream time, 7000 hr/yr.

Total capital investment, $10,717,000.

Midwest plant location, mid-1980 operating costs.

Source: Barrier, J. W., et al., Economics of Disposal of Lime/Limestone Scrubbing Wastes, EPA-600/7-78-023a, February, 1978.

Table 14-18

COST INDEXES AND PROJECTIONS

YEAR	1974	1975	1976	1977	1978	1979[a]	1980[b]	1981[b]	1982[b]	1983[b]	1984[b]
Plant	165.4	182.4	192.1	204.1	218.8	237.2	259.4	278.9	299.8	322.3	344.9
Material[c]	171.2	194.7	205.8	220.9	240.6	263.0	286.1	309.0	333.7	360.4	385.6
Labor[d]	163.3	168.6	174.2	178.2	185.9	192.5	226.5	244.6	264.2	285.3	305.3

[a]Midyear.

[b]Projections.

[c]Same as index in Chemical Engineering for "equipment, machinery, supports."

[d]Same as index in Chemical Engineering for "construction labor."

Source: Personal communication, J. D. Veitch, TVA, February, 1980.

Administrative and support labor can be estimated as approximately 30% of the sum of operating and maintenance labor (1).

Maintenance. If possible, maintenance costs should be separately identified as maintenance labor and maintenance materials. A maintenance labor/materials ratio of 40/60 may be used for this breakdown if other information is not available. A variable component of the maintenance cost should be included if there is a basis for estimating how maintenance costs vary with capacity factor.

TVA estimates maintenance as a function of direct investment (2). For wet disposal systems, maintenance is estimated to be 4% of the direct investment (excluding pond construction) plus 3% of the pond construction cost. A maintenance rate of 4% is used for all dry disposal systems.

Although maintenance costs will increase with the age of the system, they will decrease as annual operating hours decline; therefore, maintenance costs are often assumed to be constant over the life of the plant.

Land Preparation. For landfill disposal systems, an annual charge should be computed covering the annual expense for preparing the disposal site--clearing, excavation, drainage, reclamation, etc.

Utilities. The primary utility used in most disposal systems is electricity. The electricity rate will ordinarily vary with the size of the power plant and sludge disposal facility.

Overhead. The cost of plant, administrative, and marketing overheads vary from company to company. Based on literature sources, TVA calculates plant overhead at 50% of the subtotal conversion costs less utilities (e.g., all direct costs except raw materials costs) and administrative overhead at 10% of operating labor and supervision (2). EPRI suggests that administrative support labor overhead be included as 30% of the operating and maintenance labor and that general and administrative expense not be included in the cost estimate (1).

By-Product Credit. Where a usable by-product such as gypsum will be sold, then a by-product credit should be subtracted from the annual operating expense.

Step 5. Determine Levelized Operating Costs

Inflation will tend to increase the operating costs (in current dollars) over the life of the disposal system. To represent these varying revenue requirements, a single "levelized" revenue requirement is computed using the "present worth" concept of money. Assuming an inflation rate of 6%/yr, a discount rate of 10%/yr, and a constant operating load throughout the 30-yr life, the levelization factor for operating and maintenance costs is 1.886. The 30-yr levelized annual operation and maintenance costs are then computed by multiplying the first year operating costs by 1.886. Other factors must be computed for a shorter life or declining operating profile.

Step 6. Determine Annual Cost of Capital

The annual cost of capital will vary depending upon the particular utility situation. However, using the assumptions shown in Table 14-2, the 30-yr levelized fixed charge rate is 18%/yr. The levelized fixed charges are determined by multiplying the fixed charge rate by the total capital requirement.

Note that in some cases, major portions of the disposal system have a life which is considerably shorter than the 30-yr plant investment. For example, trucks and earthmoving equipment may be expected to last only six to 10 yr and are, therefore, replaced more frequently than typical process equipment. In these cases, a fixed charge rate consistent with the shorter life must be applied to these capital items.

Step 7. Determine Levelized Annual Revenue Requirement

The total levelized annual revenue requirement is simply the sum of the levelized fixed charges and the levelized operating revenue requirement. The sum is expressed in $/yr. This figure can be expressed in mills/kWh or $/t of sludge using the following equations:

$$\text{mills/kWh} = \frac{(\text{Levelized Annual Revenue Requirement in \$/yr})\ (1000\ \text{mills/\$})}{(\text{capacity in kW})(\text{capacity factor})(8760\ \text{hr/yr})}$$

$$\text{\$/t of sludge} = \frac{\text{Levelized Annual Revenue Requirement in \$}}{\text{Annual production of dry sludge in t}}$$

Development of these costs for the previously discussed examples are shown in Table 14-19.

Table 14-19

LEVELIZED ANNUAL REVENUE REQUIREMENTS

	UNTREATED DISPOSAL ($)	IUCS PROCESS ($)
Total Capital Requirement (TCR)	17,211,000	10,717,000
Levelized Capital Requirement (LCR) (0.18 x TCR)	3,098,000	1,929,000
Annual Administration and Overhead (AAO)	283,000	975,000
Direct Operating Costs (DOC)	577,000	2,650,000
First Year Operating Cost (FYOC) (AAO + DOC)	860,000	3,625,000
Levelized Operating Cost (LOC) (1.886 x FYOC)	1,622,000	6,837,000
Levelized Annual Revenue Requirement (LCR + LOC)	4,720,000	8,766,000
Mills/kWh	1.11	2.06
$/t of Sludge	11.63	20.79

Basis: Remaining plant life, 30 yrs.

Coal burned, 482,571 lb/hr, 9000 Btu/kWh.

Average capacity factor, 48.5%.

Annual production of dry sludge, 405,940 for untreated disposal and 421,625 t for IUCS Process.

Midwest plant location, mid-1980 operating costs.

FURTHER INFORMATION

Both TVA and Aerospace Corporation have devoted considerable effort to estimating system costs. Principal reports of their work are described in References 2,7,11, 16,22,23,24 and 25 for TVA and 6,8,9,12,15 and 28 for Aerospace. PEDCo Environmental Specialists, Inc., has also developed a quick method for roughly estimating sludge disposal costs as part of FGD system costs (29).

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Section 15

UTILIZATION

PURPOSE

The purpose of this section is to provide information relative to opportunities for utilization of FGD sludge from lime, limestone, dual-alkali and alkaline-flyash scrubbers. In keeping with the general purpose of this manual, this section does not address by-products (e.g., sulfur and sulfuric acid) from regenerable FGD systems.

BACKGROUND

The general trend in sulfur dioxide control at utility power plants continues to be toward non-regenerable systems, which produce voluminous waste products. The cost of disposing FGD sludge provides inducement for utilization rather than disposal of the sludge. As disposal costs increase due to a variety of reasons, including limited land availability, the economics of utilization become more favorable. However, producing a useful by-product from FGD sludge often requires additional processing. Since the markets for such by-products are generally quite limited, this additional processing may not be justifiable.

Of perhaps 40 different uses or products considered by various investigators, none has been developed to the point of being a practical, commercial alternative to disposal for widespread application (1). The utilization of sludge or sludge by-products requires the displacement of existing materials or commodities. As with most recycled products, the replacement of existing materials with those originating from waste products is generally met with reluctance in the consumer market place. In many respects, the utilization potential of FGD sludge is comparable to that of flyash from utility power plants. There may be local markets or outlets for by-products through which all or a portion of the waste at some plants could be utilized. However, there is currently little chance for widespread utilization.

The utilization potential of FGD sludge is directly related to its quality and characteristics. Because of this, the degree of processing to a large extent controls

the uses of sludge which merit consideration. Oxidizing the sludge allows for its competition for the current uses of naturally occurring gypsum. The following uses of FGD gypsum have been shown to be feasible in small-scale tests at certain locations in the United States:

- In the wallboard products industry
- As a cement retarder in cement production
- As a soil amendment in agriculture

Fixating FGD sludge enhances its physical properties for potential structural uses. Uses which have been demonstrated in limited applications are as follows:

- As a base for parking lots, driveways and roads
- In the construction of liners for wastewater ponds
- In the formation of artificial reefs in the ocean.

CURRENT PRACTICES IN THE GYPSUM MARKET

Gypsum is the dihydrate form of calcium sulfate ($CaSO_4 \cdot 2H_2O$). This non-metallic mineral is found in huge deposits in many parts of the world. Gypsum reserves exist throughout the United States with the exception of the Southeast and coastal areas. Areas deficient in natural reserves are supplied primarily by gypsum imported from Canada which accounts for approximately 35% of domestic needs. Mining of naturally-occurring gypsum is relatively inexpensive accounting for charges of approximately $5.00 per ton for domestic mines and $3.00 per ton for Canadian mines (2).

The major markets for crude gypsum are as follows (3):

- Wallboard products industry - 73%
- Cement industry - 20%
- Agriculture - 7%

Since the first two markets are dependent on the building industry, gypsum consumption varies according to the fortunes of this industry. In recent years total domestic gypsum consumption has been 15 to 20 million tons per year. The gypsum industry is highly integrated with the majority of the companies both operating captive mines and processing gypsum for building products. Many existing wallboard plants are located adjacent to gypsum mines or at points requiring minimum water transportation.

The integrated companies also supply a large percentage of the gypsum used in agriculture and in the cement industry. For these uses, a high percentage of the cost

of crude gypsum is transportation cost rather than product cost, since farms and cement plants are generally not located near gypsum mines. Because of the large volumes and relatively low value of gypsum, freight costs can easily exceed the product value.

UTILIZATION OF OXIDIZED SLUDGE

Calcium sulfate (gypsum) is a principal product generated in calcium based FGD scrubbing systems. It is possible to employ forced oxidation either in the scrubber or as a separate step to convert sulfite to sulfate as described in Section 10 - FORCED OXIDATION. This section addresses the better handling characteristics and fewer disposal problems of oxidized sludges. In addition to these benefits, producing gypsum greatly enhances the potential for sludge utilization - in part or in whole. However, gypsum-producing power plants will have to compete with natural gypsum from domestic and Canadian mines in marketing FGD gypsum.

As can be expected, FGD gypsum (also referred to as abatement gypsum or by-product gypsum) differs from natural gypsum in some respects. The importance of these differences varies with the intended use of the product - wallboard, cement or agriculture.

Wallboard Production

In substituting FGD gypsum for naturally occurring gypsum in wallboard production, the following product variables are of concern: water, flyash and chloride content, particle size, and particle shape. The water content of FGD gypsum is approximately 20%, compared to 3% for natural gypsum. This excessive moisture can be a problem in handling FGD gypsum through the dryer stage and in the calcining step of wallboard production, since this free water must be driven off.

Flyash, while inert, will affect the color of the wallboard. Discoloration due to flyash may render the wallboard unattractive to potential consumers. Excessive chloride concentrations can be corrosive to nails used in installing the wallboard and can interfere with the bond between the paper and the gypsum core.

Particle size and shape may also cause problems since the handling equipment at existing wallboard plants was developed to handle rock-size gypsum rather than the consistently smaller crystals of FGD gypsum. Also, making quality wallboard requires large gypsum crystals and a blocky crystal shape. Smaller crystals of needle or

plate-like shape make it necessary to use more water when the calcined gypsum is rewetted in making wallboard. This may result in increased drying costs and decreased board strength.

Several experimental and demonstration studies have been conducted, exploring the use of abatement gypsum in the U.S. Southern Company Services, Inc., contracted with the U.S. Gypsum Company for two separate test runs of wallboard, utilizing abatement gypsum produced by the Chiyoda Thoroughbred-101 scrubber at the coal-fired Scholz Electric Generating Station of Gulf Power Company. These production runs were conducted in June and December, 1976. The June, 1976 run consisted of a 50:50 mixture of Chiyoda gypsum and natural gypsum. The resultant wallboard was of the same quality as wallboard produced from 100% natural gypsum, except that there was a 25% reduction in the rate of calcining during production. A second production run in December, 1976, was conducted with 100% Chiyoda gypsum. Some separation of the paper from the gypsum occurred in this run, but only when the manufacturer reduced the gypsum density below normally accepted values. No reduction in calcining rate was observed in the December runs (4).

As a part of the recent EPRI-sponsored project of the Chiyoda 121 scrubber at Scholz, the by-product gypsum has been used in the test-manufacture of wallboard. While the results of the tests have not yet been finalized, generally it was found that this process produces a gypsum of acceptable quality for use in wallboard production. Specifically, the by-product has a gypsum content of 97.8%, a calcium carbonate content of 0.37% and a chloride content of 75 ppm, as compared to the wallboard manufacturer specifications of 94.0%, 1.5% and 250 ppm, respectively. Two major wallboard manufacturers had production demonstrations: one processing the by-product gypsum with an equal quantity of natural gypsum; the other processing the by-product without blending. The demonstrations went smoothly except for minor materials handling problems which could be remedied with minor adjustments. The by-product wallboard met the production goals of both manufacturers and could not be distinguished from the natural gypsum board except for a slightly whiter color (5).

Southern California Edison Company (SCE) also experimented with gypsum production from its Highgrove Station Unit No. 4. This was a 10 MW oil-fired facility (6). A 50-ton, full-scale wallboard test with the SCE gypsum was successfully completed, but the results have not been released (7). Figure 15-1 shows both wallboard made from by-product gypsum and that made from natural gypsum.

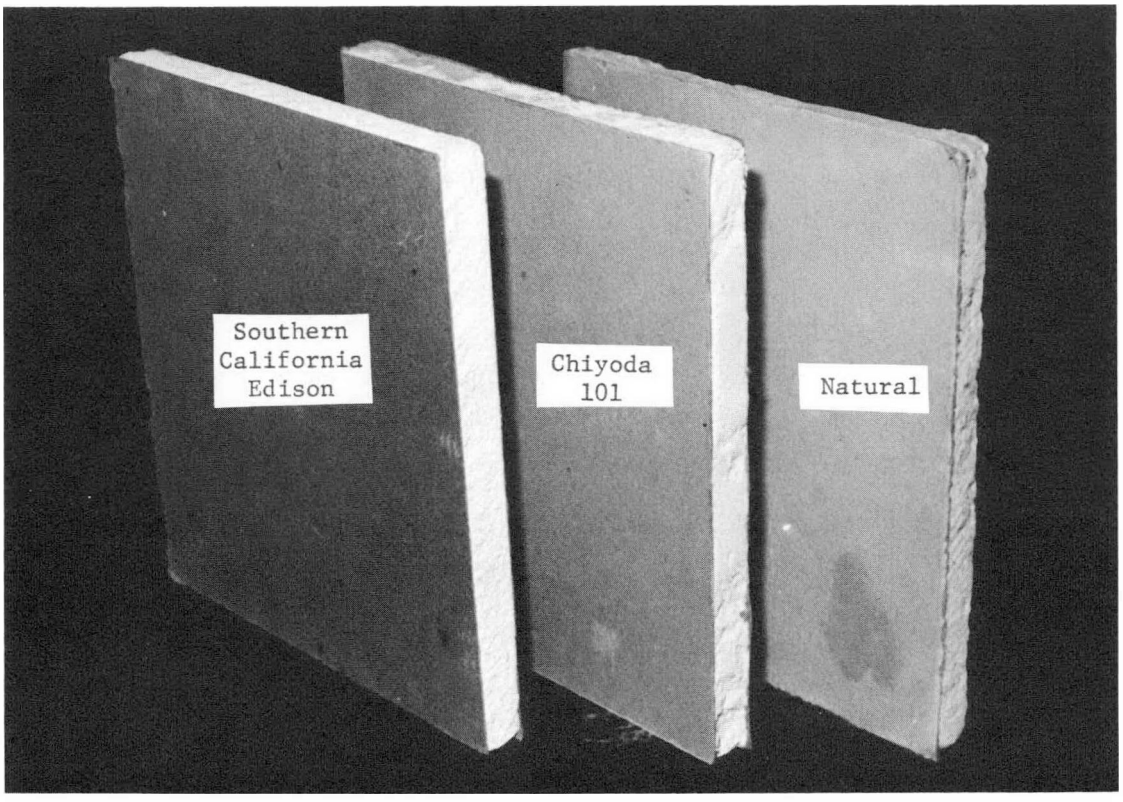


Figure 15-1. Samples of Wallboard Made from FGD Gypsum and Natural Gypsum.

Successful entry of abatement gypsum into the wallboard industry as a replacement and competitor of naturally-mined gypsum, seems uncertain. The wallboard industry appears to be proceeding with caution in accepting abatement gypsum as a substitute, despite some advantageous properties and the several successful demonstrations. Some abatement gypsum is actually more pure than natural gypsum. For example, Chiyoda 121 gypsum exceeded 90% calcium sulfate as compared to about 80% purity for the natural gypsum from Nova Scotia which is used in much of the east coast wallboard.

Concerns expressed by wallboard industry include:

- The amount of contaminants, such as flyash, unreacted reagents, and calcium sulfite remaining in the gypsum, and the effect this may have on production economics and product quality
- Presence of soluble salts and the effect on product quality
- Possible variations in gypsum quality and composition, and the effect on production economics and product quality
- The need for a guaranteed source of supply

The difficulty of entering the wallboard market is enhanced by the current structure of the wallboard industry; i.e., the wallboard manufacturers control gypsum reserves as well as manufacturing plants. Geographic location affects this potential use of abatement gypsum. The current distribution patterns in the industry have done well to minimize transportation costs, thereby increasing the competitive edge for natural gypsum. The midwestern and western wallboard markets are supplied with native gypsum from nearby mines while the eastern markets utilize a large percentage of imported Canadian gypsum.

The U.S. experience in utilizing abatement gypsum in wallboard contrasts sharply with Japanese experience. The Japanese have significant experience in operating scrubbers which produce abatement gypsum. Sixteen percent (16%) of the utility industry steam generating capacity is FGD equipped. While the increase in FGD facilities has slowed recently, the growing use of coal for utility boilers will require more FGD installations. Of the FGD utility capacity in service in 1978, 98% were producing usable gypsum (8). Only three major FGD systems in Japan discard the product solids. The principal factors responsible for most of the by-product being converted to gypsum and utilized are as follows:

- Regulatory agencies discourage disposal of unoxidized waste
- Lack of available land for waste disposal
- High market demand for gypsum because of lack of natural supplies
- Utilization of oil-fired rather than coal-fired boilers

Japan has little or no natural gypsum and, therefore, must depend on imports and on by-product gypsum from chemical processes (e.g., production of phosphoric acid). Thus, when lime/limestone scrubbing was first introduced, there was a ready market for the sludge if it was in the form of gypsum rather than calcium sulfite. An oxidation system was developed by practically all the system suppliers, and with one or two exceptions, all the installations have included facilities for oxidation.

Another major consideration is that most of the Japanese power plants burn oil; the ratio of power produced from oil to that from coal is about 10 to 1. The gypsum from scrubbing coal-fired boiler emissions may be less acceptable for wallboard use because of the higher impurity content from entrained flyash.

Most of the FGD gypsum made in Japan goes to the wallboard industry, where it commands a higher price than in the cement industry. Most of the Japanese installations seem able to produce gypsum of the required water content and crystal size and shape.

Cement Manufacture

The use of abatement gypsum as a set retarder in the manufacture of Portland cement appears to be quite viable. Tests conducted at Gulf Power's Scholz Plant demonstrated that both the Chiyoda 101 and 121 scrubbers can produce gypsum of acceptable quality for this use (5). Significant markets are available in the United States. Portland cement is produced at an annual rate of 100 million tons accounting for approximately 20% of the total domestic consumption of gypsum (9). Cement plants offer the greatest utilization potential for the following reasons:

- There are fewer problems involved than in producing for wallboard use. The impurities are not as critical: gypsum with a higher flyash content can be used and the moisture content is not expected to be a problem, since the heat of reaction drives off excess water.
- Cement plants are more numerous and are located closer to potential sources of abatement gypsum. Proximity to a source of natural gypsum has generally not been a major consideration in locating cement plants. Therefore, the potential is greater for reducing transportation costs by converting to abatement gypsum.
- Gypsum for cement use sells for a higher price than for wallboard manufacture, thus permitting a more competitive position in the market.
- Most natural gypsum used in cement production is purchased from the open market rather than being supplied by captive mines.
- Being from local sources, abatement gypsum would provide a more stable supply than exists with present imports. It is anticipated that most of the natural gypsum replaced will be that which is imported.

Agricultural Use

Abatement gypsum also has considerable potential for use in agriculture as a soil amendment, soil conditioner, fertilizer or soil stabilizer. This potential appears greatest in the Pacific region which presently accounts for 85% of domestic consumption of natural gypsum. Some agricultural use of abatement gypsum may also occur in the southeastern states.

Research conducted by the Coal Research Bureau, West Virginia University, has shown that scrubber sludges may be utilized in soil amendment (10). Calcium compounds contained in scrubber wastes may be beneficial to plant growth and yield, and tend to have neutralizing or conditioning effects on the soil. Some of the benefits of scrubber sludge used in this manner reportedly are:

- Amendment of the soil from a sandy or clay form to almost a pure loam with increased rates of addition. As with flyash, FGD sludge can improve the texture and drainage characteristics of some soils.
- Adjusting pH and improving cation exchange capacity
- Solving problem of soil sulfur deficiency which is expected to increase in the future
- Providing beneficial trace elements not available in conventional amendments or fertilizers
- Enhancing the production of root nodules which promote the conversion of nitrogen to nitrogenous compounds

As with use in cement production, agricultural use requires a lesser purity than wallboard production. While wallboard manufacture requires approximately 90% $CaSO_4 \cdot 2H_2O$, 50 to 70% is adequate for use in agriculture. Therefore, oxidation can be less complete. However, such sludges would be thixotropic and difficult to apply unless mixed with flyash.

There are two known instances in this country in which FGD scrubber sludges from non-regenerable systems have been used in commercial applications. Both of these examples demonstrate the manner in which local markets are likely to be utilized as outlets for FGD by-products.

Thirty tons/day of oxidized sludge was produced from the Chiyoda Thoroughbred 101 scrubber at the Scholz Electric Generating Station of Gulf Power Company. The dry gypsum product was sold to Florida Lime & Dolomite (FL&D) in Greenwood, Florida, for agricultural use. FL&D obtained 60 to 70 tons every other day from the Scholz stockpile and trucked the material to their stockpile several miles away. After drying

and grinding, the finished product was sold to a local company, which contracted with local peanut farmers for on-land spreading. Similar utilization of the by-product gypsum from the Chiyoda 121 scrubber should be possible.

The 3 MW equivalent dual-alkali FMC scrubber at Firestone Tire and Rubber Comapny, Pottstown, Pennsylvania, produces a sulfite filter cake which is utilized in agricultural applications, augmenting calcium values in deficient soils (11). Local farmers haul this material from the Firestone stockpile as they need it. This application is under permit from Pennsylvania's Department of Environmental Resources.

In agriculture, the substitution of abatement gypsum for natural gypsum is expected to continue to increase. However, agricultural use of natural gypsum represents a minor part of the total gypsum market and is limited to certain geographical areas. Therefore, this market for utilization is not expected to have widespread application for large quantities across the United States. Agricultural use will probably be limited to local markets available to a limited number of utilities.

UTILIZATION OF FIXATED SLUDGE

Untreated or unprocessed FGD sludges have very poor structural properties. Even after dewatering, sulfite-containing sludge has a high moisture content, exhibits thixotropic properties and structurally is relatively unstable. As a result, unprocessed sludges have very limited value for construction purposes.

On the other hand, treated sludges produced as a dry product, such as that from the IUCS process, can be used effectively as fill material. Having properties similar to soil and having cementitious properties, fixed sludges make excellent fill. In general, fixed sludges can be used as a substitute fill for natural earth. As such, the sludge can be a versatile fill material for power station use. Conceivably, it could be used for road fill, dikes, berms, general fill, and similar local construction uses. In addition, fixated sludge has been demonstrated to be of beneficial use as a base for paving material, as a wastewater pond liner and as building blocks for artificial ocean reefs.

Structural Fill

Utilizing fixated sludge for structural purposes can be viewed from two perspectives: (1) post-closure utilization of the disposal site and (2) utilization of a portion of the fixated sludge for specific construction purposes. In view of the large acreage required, post-closure use of the fill area should be considered both in selecting the site and in determining the sludge processing requirements.

Proper planning and design of the disposal area for fixated sludge may allow for residential, recreational, or light industrial development. Such utilization of the site should be achievable as a result of the increased stability of a fill comprised of fixated sludge.

The potential of utilizing a fill for structural purposes is a function of the structural integrity of the fill. The compressive strength should be at least one ton/sq.ft. and the permeability should be less than $5x10^{-5}$ cm/sec. Experiments have indicated that these standards are achievable and that most landfills can be expected to develop the structural integrity which significantly exceeds these minimum standards.

In addition to the benefits obtained from using portions of the sludge produced for structural purposes, this use will extend the design life of the disposal area. In addition to the previously mentioned uses for light structural developments, fixated sludge could be used in a variety of construction projects requiring stable fill material, such as roadways. In utilizing fixated sludge as borrow material in construction, similar requirements for structural integrity would apply. Use would be limited to developments within a reasonable proximity to the plant or to the fill from which the material could be produced or excavated.

Paving Materials

Dry, fixed sludges have been demonstrated to be suitable as a base for airport paving, roads, parking lots, and similar paving uses. These sludges can be used for on-site construction. As noted previously, except in isolated cases, these uses are not expected to be large enough to provide an outlet for all the waste produced at a plant, but they could extend the useful life of the primary disposal area.

Most of the experience with dry, fixed scrubber sludge comes from IU Conversion Systems, Inc. (IUCS). The first recorded utilization of treated scrubber sludges was made by the G. & W. H. Corson Company, Inc., now IUCS, in 1969 in the construction of 20 parking pads at a small airport.

IUCS Poz-O-Tec^{R} from the Mohave Generating Station of Southern California Edison, Inc., was employed as a parking lot base and as road base for several sections of public highway in Arizona. Fixed sludge and ash from Duquesne Light Company's Elrama Power Station has also been employed as a base material for a municipal parking lot and for driveways at a commercial warehouse facility in the Pittsburgh area (see Figure

15-2). More recently, fixed sludge from the same station has been used in the construction of an ash-haul road at that company's Cheswick Power Station (see Figure 15-3). No long-term evaluation of the various application has yet been made (12,13).

Wastewater Basin Lining

Because of the low permeability of fixated sludge, it offers the potential for use in lining wastewater basins. IUCS field studies of Poz-O-Tec indicate that in situ permeabilities of 10^{-6} to 10^{-7} cm/sec are achievable. These studies also demonstrated a trend of decreasing permeability with time (14). In view of such permeabilities, consideration appears merited for utilizing Poz-O-Tec as a liner material. However, it must also be pointed out that this is a relatively rigid material and, as such, appropriate precautions must be taken in such applications.

Poz-O-Tec, processed with sludge from the experimental Weir scrubber at Four Corners Station of Arizona Public Service Company, was used to line a 70-ft. diameter evaporation pond at the plant. Several freeze-thaw cycles were reported to have had no effect.

Artificial Reefs

Ocean disposal of fixed scrubber sludge is an apparently attractive alternative if the environmental consequences can be minimized. To explore the feasibility of this alternative, EPRI, in conjunction with the New York State Energy Research and Development Authority, and the federal government, is sponsoring the Coal Waste Artificial Reef Program. This investigation is being conducted by a project team led by the Marine Sciences Research Center of the State University of New York at Stony Brook.

Phase I of this program has involved both laboratory research and in situ experiments at the site of the proposed reef. The study thus far has indicated that sludge blocks of sufficient strength and stability can be produced. These blocks are expected to retain their integrity and possibly become stronger from immersion in seawater. Furthermore, the blocks are not expected to cause any adverse effects on the marine environment (15). Further research in this area is anticipated.

Other Potential Uses

Through research activities and small scale applications a number of other potential uses of sludge have been explored. These have included: aggregate, brick, concrete block and land reclamation.



Figure 15-2. Using POZ-O-TEC as a Base Material in Construction of a Parking Area for a Warehouse Site Near Pittsburgh, PA.



Figure 15-3. Placing POZ-O-TEC as a Base for an Ash Haul Road at Cheswick Power Station, Duquesne Light Company

Interest in alternate sources of aggregate has been spurred by the increasing demand and diminishing supply. Recent investigations into the production of aggregate using FGD sludge has shown promise for future uses. An experimental road construction project using aggregate, which had been chemically stabilized by the addition of sludge, produced encouraging results. However, the feasibility of sintering sludge to produce a light weight aggregate is yet to be demonstrated. Major problems include softening of the product from the heat and controlling SO_2 emissions (16).

Producing brick from sintered sludge encounters the same problems as producing aggregate - the material does not achieve the necessary hardness and SO_2 is evolved in the sintering process. Because of these problems, producing brick from FGD sludge using a sintering process does not appear to be currently feasible. However, brick production from a mixture of FGD sludge, silica sand and lime may be viable. Experiments have indicated that autoclaving this mixture can result in a product of satisfactory quality. FGD sludge can also be used as a cementing agent in producing concrete blocks, which are lighter than conventional block. Promising uses for such building materials, which incorporate FGD sludge, would be as low cost construction materials; e.g., interior walls, decorative walls, patios, thermal and acoustic insulating walls (17).

Land recovery, especially strip mine reclamation, may be a promising concept for selected plants. As discussed in Section 6 - SITE SELECTION, the prospect of mine disposal is especially attractive for those power stations which are located near their source of coal. The Milton R. Young Station of the Minnkota Power Cooperative exemplifies the benefits of scrubber sludge disposal in an adjacent surface mine. At this station, sludge as well as bottom ash and flyash are disposed of in the mined-out strip pits prior to backfilling, replacing the topsoil and revegetating. In addition to the advantages associated with disposal, utilizing FGD sludge in surface mine reclamation is reasonable from an environmental perspective. It provides a means of returning scarred land to a more natural condition without consuming otherwise usable land. Such utilization has been considered by several utilities, but actual experience has been limited. Some fixed scrubber sludge from Commonwealth Edison Company's Will County Station was used by a local developer to reclaim land, which included old strip pits, for a golf course.

MARKET POTENTIAL EVALUATION

Prior to determining whether or not utilization will be included in the overall disposal strategy of a particular plant, the short-term and long-term viability of

utilization should be assessed. An important consideration in this assessment is the marketability of the sludge by-product. Using FGD sludge is generally dependent on replacing currently-used materials by successfully competing in the marketplace (e.g., using abatement gypsum rather than natural gypsum in cement production). To attempt to predict the position of sludge by-products in the marketplace, a survey of the available markets from a regional perspective is required. The major activities of a market survey include:

- Determining the marketable by-products which could be produced at the selected power plant given available sludge processing technology
- Identifying potential markets for these products
- Investigating markets to evaluate utilization potential In particular, conditions of supply and demand and quality requirements should be noted.
- Ranking markets based on relevant characteristics (e.g., demand potential, level of interest, long-term stability, proximity to power station)
- Evaluating technologies required to produce sludge in utilizable form. Considerations include reliability, developmental and operating costs, and ability to generate a by-product of required specifications.
- Selecting most feasible markets for sludge by-products

After identifying the most feasible markets for FGD sludge by-products, the economic appraisal of disposal strategies, including utilization, can be performed. This appraisal would include consideration of the revenue from by-product sale, comparative transportation costs, and the extended useful life of the disposal area for the sludge which is not utilized.

In the final analysis, for recovery of FGD by-products to be viable, the market must be sufficiently stable to enable amortizing any additional costs of producing the by-products over a reasonable projected life. Furthermore, the total cost (capital and operational) of producing the recoverable by-product should be offset by the anticipated revenues and by the extended useful life of the disposal site.

SUMMARY AND CONCLUSIONS

In summary, the current prospect for large-scale by-product recovery from non-regenerable FGD systems appears small. In most instances, the economic incentives for utilizing sludge by-product materials are not sufficient to enable substitution of currently-used materials. Also, product specifications present obstacles in some cases. In considering the nationwide quantity of sludge produced as compared to the

limited markets presently available for recovered by-products, it becomes apparent that most sludge is destined for disposal. While utilization offers a limited potential to some utilities, it cannot be considered a large scale alternative to sludge disposal in the nationwide perspective.

In many respects, the utilization of FGD by-products is quite similar to the problem of flyash utilization which has plagued the electric utility industry for years. There are outlets (e.g., wallboard manufacture, mine reclamation, cement substitution, agricultural soil amendment) through which all the waste at some plants could be utilized. While no existing full-scale facilities have this option, it is likely that some plants will in the future. There are also outlets which could accommodate a portion of the waste produced at a plant (e.g., liners, roadway and parking lot base course, agricultural use). Some plants are already using waste for these purposes, although on a limited basis. The potential for by-product utilization at any given location is primarily a function of local markets; actual utilization depends on ingenuity and perseverence in identifying, pursuing, and capturing those markets.

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Section 16

GYPSUM STACKING

INTRODUCTION

The application of forced oxidation in FGD sludge processing and disposal has recently received increased attention for converting calcium sulfite sludge to calcium sulfate (FGD gypsum). As discussed in Section 3 - WASTE COMPOSITION, the mineralogy, crystal geometry, and particle size of FGD gypsum provides settling, dewatering, and structural characteristics potentially conducive to "stacking" methods of waste disposal.

Gypsum is also a waste product of the phosphate fertilizer industry, which produces in excess of 21 million tons of gypsum per year in Florida alone. Stacking methods of waste disposal have been economically utilized by the phosphate industry in Florida for gypsum disposal for more than 20 years. These gypsum stacks are typically large (50 to 300 acres), structurally stable stockpiles reaching heights of 100 feet. A gypsum stack located near Bartow, Florida is shown in Figure 16-1.

The potential for utilizing "stacking" methods of waste disposal for FGD gypsum was recognized during operation of the Chiyoda Thoroughbred 101 Scrubber at Plant Scholz of Gulf Power Company in Sneads, Florida (Scholz). This FGD system produced an essentially pure gypsum which could be dewatered by centrifuge to 80 to 88 percent solids.

During subsequent installation and operation of the Chiyoda Thoroughbred 121 (CT-121) Scrubber at Scholz, the unique opportunity was offered to construct and study the performance of a prototype FGD gypsum stack. The prototype stack was constructed and operated over a 9 month test period from October 1978 to June 1979. During this time, every effort was made to construct and operate the stack as typically accomplished in the phosphate fertilizer industry. Although the prototype stack was relatively small (i.e., one-half acre and 12 feet high), the study did allow a comparison of laboratory tests of geotechnical engineering properties relevant to stacking with actual field behavior and a comparison of the overall stacking performance of CT-121 FGD gypsum with gypsum produced in the phosphate fertilizer industry. Complete details of the study, conducted under RP 536-3, will be given in a separate report.



Figure 16-1. Phosphate Fertilizer Plant Gypsum Stack Near Bartow, FL.

This section presents: (1) specific information and techniques utilized in the design, construction, and operation of waste gypsum stacks in the phosphate fertilizer industry which can be adapted by utilities for stacking FGD gypsum, and (2) engineering properties of FGD waste gypsum relevant to stacking methods of waste disposal. Comments regarding the feasibility of stacking FGD gypsum and specific engineering properties of FGD gypsum presented herein were developed from and are specific to the results of research with FGD gypsum produced by the Chiyoda Thoroughbred 121 Flue Gas Desulfurization process as installed and operated at Scholz. This research was conducted by Ardaman & Associates, Inc., Orlando, Florida under EPRI Research Project RP536-3.

DESIGN CONSIDERATIONS

The most economical method for disposing of waste gypsum is by stacking using the upstream method of construction. In this method, illustrated in Figure 16-2, an earthen starter dike is first constructed to form a sedimentation pond and stacking area. Gypsum is then pumped to the sedimentation pond in slurry form, usually at 15 to 20 percent solids, and allowed to settle and drain. Process water is decanted and returned to the plant. Once sufficient gypsum sediments within the pond, gypsum is excavated with a dragline to raise the perimeter dikes of the stack. The draglines typically have a working reach of 60 feet and a 2-3 cubic yard bucket. The process of sedimentation, excavation, and raising of the perimeter dikes continues on a regular basis during the active life of the stack.

Using the upstream method of construction, some gypsum stacks have reached heights exceeding 100 feet with slopes of 1.5 Horizontal to 1.0 Vertical which is approximately the angle of repose of some gypsums. These steep slopes result from casting the gypsum with a dragline and allowing some gypsum to roll down the outside of the stack to eliminate shaping. Therefore, the gypsum perimeter dikes of some stacks have a factor of safety very close to unity and from a conventional geotechnical engineering point of view, failures of gypsum stacks do occur. Fortunately, gypsum is a very forgiving material and, unlike most mine tailings, gypsum does not readily flow. Therefore, the consequences of these failures are usually not dramatic. The most serious consequence of a failure is the loss of process water stored on the gypsum stack. If process water escapes the plant property, liabilities from pollution and environmental damage might result.

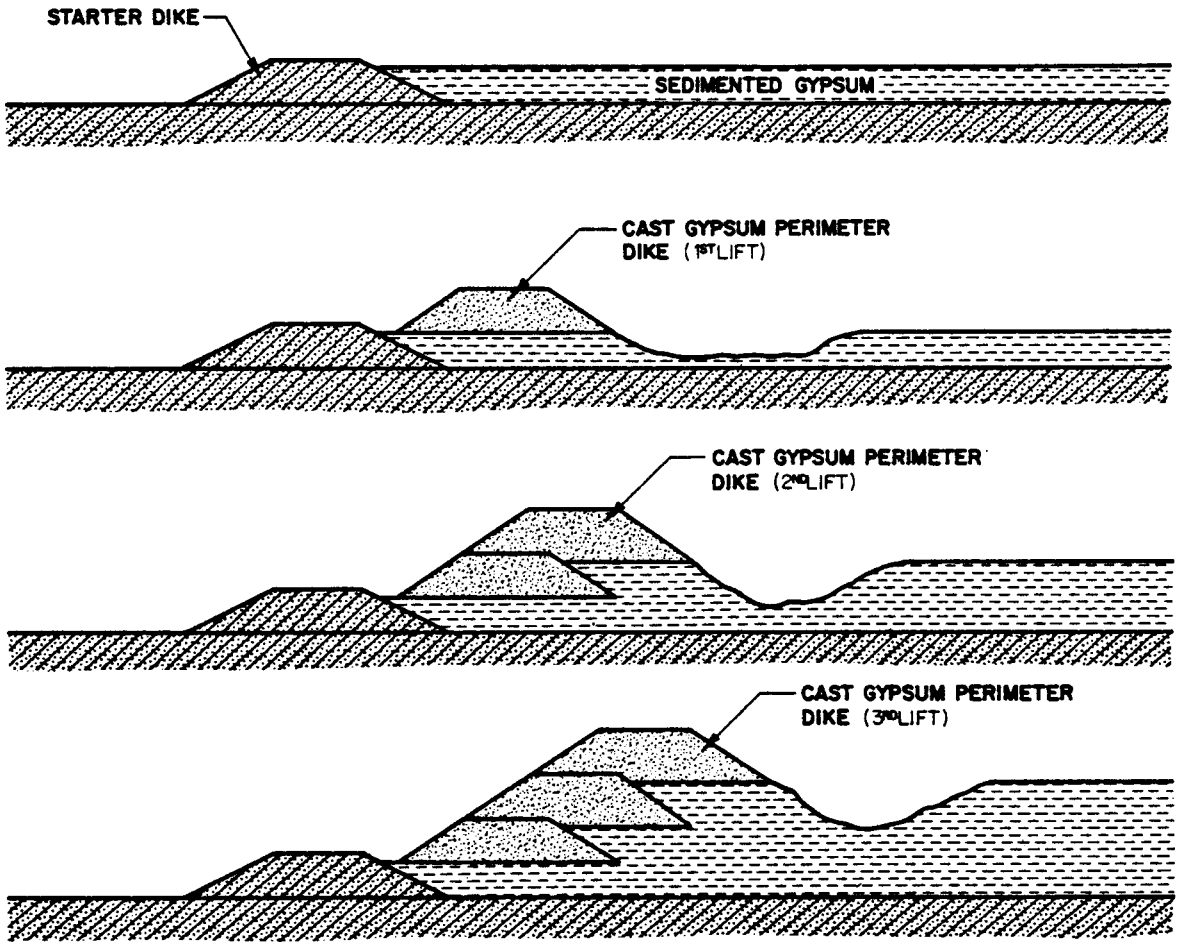


Figure 16-2. Upstream Method of Gypsum Stack Construction

Stack Layout

The experience gained from the operation and performance of phosphate gypsum stacks can be used in planning FGD gypsum stacks. An illustration of a typical stack design is shown in Figure 16-3. The specific features included in this stack are discussed below.

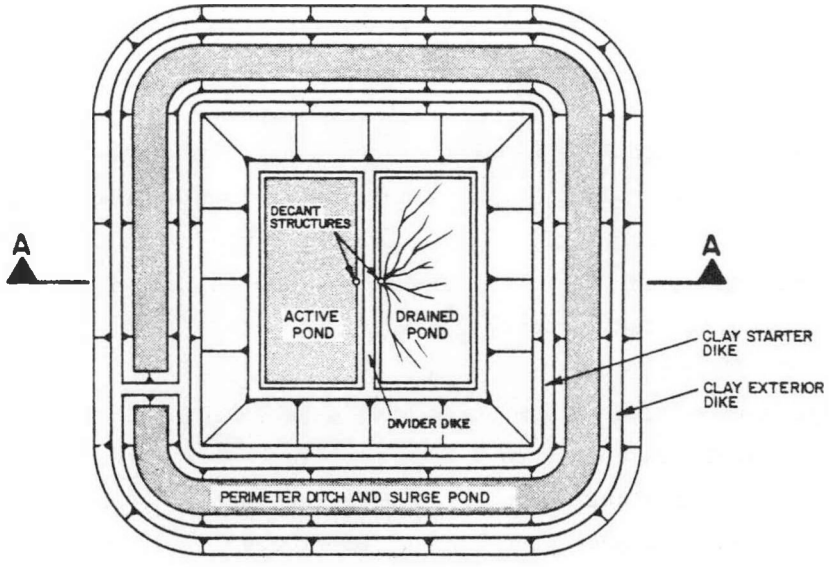
In plan, the gypsum stack is usually a square or a rectangle with a two to one length to width ratio. Ideally, a circular shape would give the minimum length of perimeter dike enclosing a given area. When a divider dike is included to separate the stack into two ponds, however, the difference in length of dike between a square and circular stack is only 7 percent.

The required area of the gypsum stack should be selected to allow raising the perimeter dikes approximately 5 to 8 feet per year. For a typical central Florida phosphate fertilizer plant where the production rate of gypsum is 2,700 to 5,500 tons per day, gypsum stacks have been proportioned for 11 to 170 tons per day per acre with an average from eleven plants of 55 tons per day per acre.

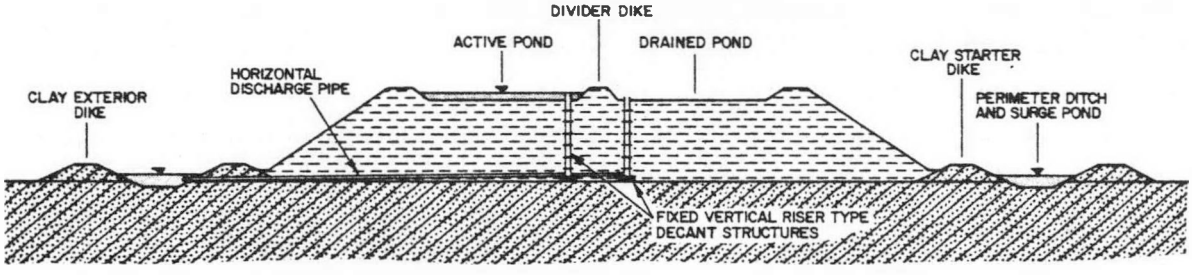
The gypsum stack is normally divided into at least two ponds. This allows one pond to drain while the other pond is in use. The dragline can then excavate gypsum from the drained pond for raising of the perimeter dike. The divider dike runs parallel to one side of the stack and divides the stack into ponds of approximately equal size.

The process water surge pond is built around the perimeter of the gypsum stack. The exterior dike forming the surge pond has sufficient freeboard to contain water stored on top of the gypsum stack in the event of accidental spillage. The surge capacity of the pond is typically designed to contain 1.5 times a 25 year, 24 hour storm on the watershed of the pond with no storage on the gypsum stack. Freeboard clearance above the maximum fluid level in the pond can vary from 3 to 5 feet and is normally governed by local regulations.

A clay starter dike is shown in the illustration and is preferred if suitable clay material is available. Sand dikes are commonly used in Florida, but must be protected against piping, erosion, and seepage. The starter dike should be constructed to a crest width of 20 feet to allow easy operation of construction equipment and should not be covered with gypsum when the stack is raised. The starter dike should be high enough to allow sufficient gypsum to sediment within the stacking area for



GYPSUM STACK SITE PLAN



SECTION A-A GYPSUM STACK CROSS SECTION

Figure 16-3. Typical Gypsum Stack Design

excavation and raising of the first lift of the perimeter dike. A minimum starter dike height of 8 feet allowing sedimentation of 5 feet of gypsum and 3 feet of freeboard is usually sufficient.

Fixed vertical riser type decant structures are shown in the center of the stack near the divider dike so that finer gypsum settles at the center of the stack and coarser gypsum around the perimeter of the stack. This is not an essential feature; however, it does eliminate the problems of trying to use soft, fine, and wet gypsum in construction of the perimeter dikes.

Stack Design

Planning Aspects. Planning of a gypsum stack and process water return system is as important as the engineering design. The process constraints and climatic constraints must be initially established. The process constraints may include an estimate of gypsum production, the planned life of the plant and stack, and inflow and out-flow process water quantities and water temperatures. Climatic conditions must be considered as they influence the process constraints. Both heat balance and water balance analyses are influenced by climatic conditions. If the plant is located in climates where severe cold winters occur, the effects of freezing on the design of the gypsum stack and process water return system, as well as the effect on limiting the construction season, must be considered.

Once the process constraints and climatic constraints have been established, sizing of the gypsum stack and process water system can be undertaken. The area required for the gypsum stack is related to the quantity of gypsum produced and design height of the stack. The height may be controlled by foundation conditions if a soft foundation underlies the stack. Otherwise, the height may be controlled by pumping considerations or even aesthetic considerations. Wind erosion and dusting may also become more severe as the stack height increases.

Stability. At least two modes of failure are normally considered in evaluating the stability of gypsum stacks:

- The deep seated bearing capacity type failure which is primarily controlled by the strength of the underlying foundation soils. This is illustrated in Figure 16-4 where the circular failure surface penetrates the foundation soils. Alternatively, the sliding wedge mode of failure along the interface of the gypsum stack and underlying foundation soils may prove more critical. In both analyses, the primary controlling factor is the strength of the foundation soils and not the strength of the gypsum. The

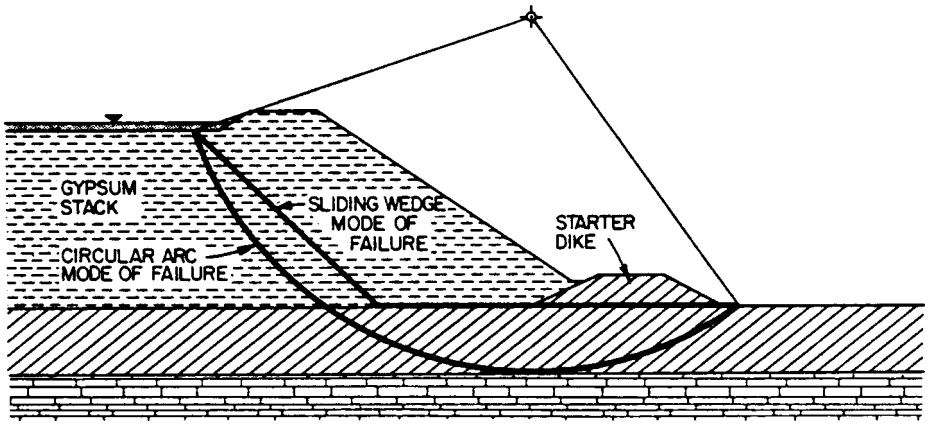


Figure 16-4. Bearing Capacity Type Foundation Failure

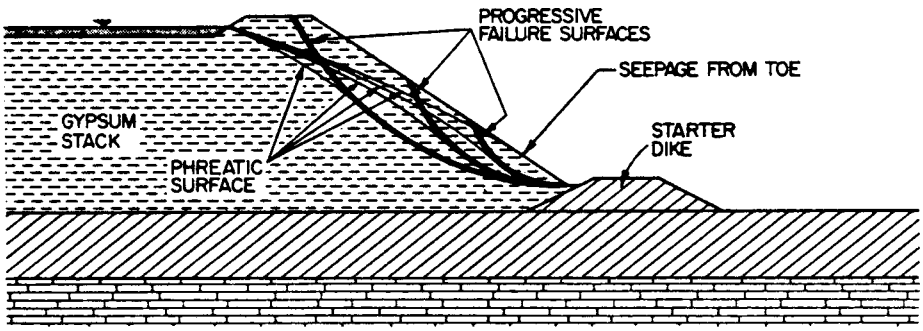


Figure 16-5. Progressive Type Slope Failure

most probable failure surface and critical mode of failure are found by trial and error procedure and represent conditions that yield the minimum factor of safety. In stability analysis, the factor of safety is defined as the summation of shear strength along the failure surface divided by the summation of shear stresses along the same surface. Flattening the outside slope of the gypsum stack and the use of berms increases the stability of the foundation and allows construction of a higher gypsum stack. For a given stacking area and height, however, these measures reduce the available storage capacity.

- Seepage instability and progressive failure of the gypsum stack slopes which is controlled by the strength properties of the gypsum and the seepage pattern through the gypsum stack. A progressive failure (Figure 16-5) may start by local instability at the toe of the slope below the springline where seepage is exiting the face of the stack. The failure starts by a small slide or slough, followed by a working back as progressive sloughing removes more of the support at the toe of the slope. Where progressive failure from seepage instability is a potential problem, flatter slopes (i.e., on the order of 3.0 Horizontal to 1.0 Vertical) must be used below the springline.

A small amount of cohesion from cementation of the gypsum has considerable influence on the factor of safety of the gypsum stack slopes, particularly with regard to seepage instability below the springline. Generally, the phosphate gypsum stacks in Florida have been constructed up to 100 feet high with slopes on the order of 2.0 Horizontal to 1.5 Vertical. These stacks, however, usually develop some cohesion from cementation.

In evaluating the stability of gypsum stacks, it must be assumed that sufficient water is available on top of the gypsum stack to develop the full seepage pattern. While this water should be kept to a minimum for safety reasons, it cannot be completely eliminated, because gypsum is continuously deposited hydraulically on top of the stack. Rain water can also keep the gypsum stack saturated.

Figure 16-6 shows a flow net constructed for a gypsum stack on a pervious foundation. Under these conditions, the flow is vertically downwards through the gypsum stack and, consequently, no seepage exits on the surface of the slope. From a stability point of view, this increases the factor of safety of the slope considerably with respect to potential sloughing and piping. However, because of cracking and solution cavities, concentrated downward seepage could develop through the stack causing the foundation sand to pipe at the toe because of high gradients in the sand which acts as a drain below the stack. Further, this downward flow could cause groundwater contamination. Under these conditions, the starter dike is not subjected to seepage and, therefore, could conceivably be constructed of any material with sufficient strength without consideration of piping.

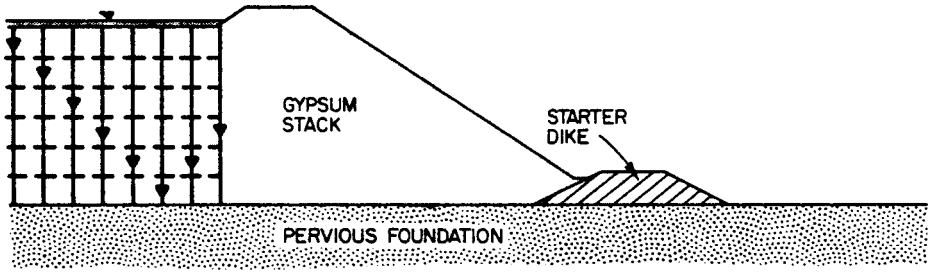


Figure 16-6. Seepage Pattern through a Gypsum Stack on a Pervious Foundation

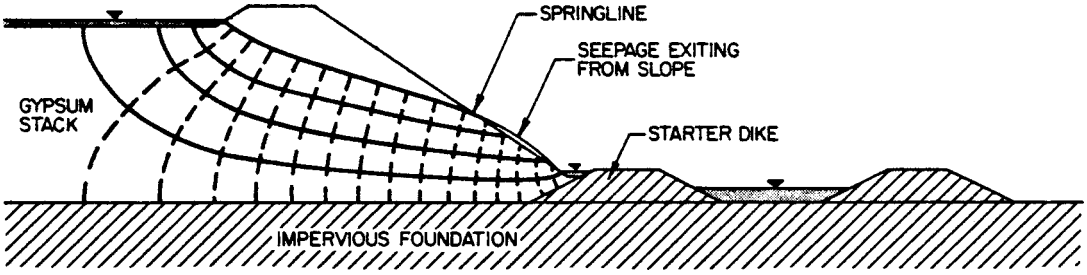


Figure 16-7. Seepage Pattern through a Gypsum Stack on an Impervious Foundation

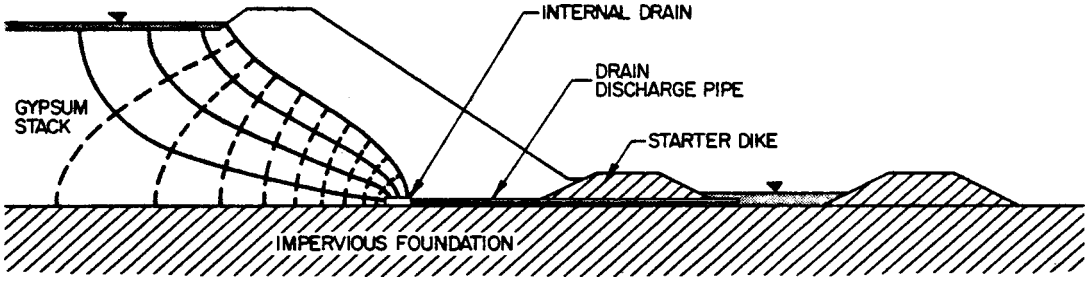


Figure 16-8. Effect of Internal Drain on Seepage Pattern through a Gypsum Stack on an Impervious Foundation

Figure 16-7 illustrates flow through a gypsum stack on an impervious foundation. Under these conditions, the starter dike and gypsum stack slope below the spring line are subjected to seepage. If the starter dike is not constructed of suitable material, problems associated with piping will result. Sloughing of the outside slope of the gypsum stack will also result unless the gypsum develops some cementation or relatively flat slopes are used.

Figure 16-8 illustrates the effect of an internal drain in eliminating the problems occurring with seepage through the gypsum stack slope and starter dike. In this case, seepage is collected in the drain, and neither the starter dike nor the outside slope of the gypsum stack is subjected to seepage. While the use of an internal drain is a satisfactory solution to many stability problems, it is generally expensive.

Process Water Return Systems. Process water pumped to the stacking area is normally decanted from the waste gypsum and returned to the plant for reuse. The type and location of the decant system used to return process water from the waste gypsum to the plant influences the quality and performance of the gypsum stack.

The location of the intake of the decant structure in relation to the point at which waste slurry is discharged into the pond influences the length of the flow path and retention time of the pond. The longer the flow path the longer the retention time, with all other factors being the same, and therefore the clearer the decanted water. The coarser fraction of gypsum settles close to the point of discharge and the finest fraction accumulates around the intake of the decant system. From seepage and stability considerations, it is desirable to have the coarse gypsum deposit along the perimeter of the pond and to have the finer gypsum settle in the center of the stack.

From solely geotechnical considerations having the intake of the decant system located away from the edges and preferably in the center of the pond is most desirable although it introduces several operational and maintenance problems. First, special provisions are necessary for access to the decant system for general maintenance. Access is also needed for the fixed vertical riser type decant system where spillway boards or collars must be added to the riser as the surface of the gypsum rises. Further, the cost of the decant system increases the farther in from the edge the spillway is located, because of the increased length of horizontal discharge pipe.

The fixed vertical riser type decant structure shown in Figure 16-9 is the most commonly employed system; it requires the least maintenance but must be continuously raised as the surface of the gypsum rises. Another disadvantage is that the horizontal discharge pipe is located at the bottom of the gypsum stack and therefore cannot be easily repaired or replaced and is subjected to increasing pressure as the surface of the pond rises. Piping of the starter dike soil around the discharge pipe may also occur if precautions and good construction procedures are not used.

To avoid some of the disadvantages of the fixed vertical riser type decant system a stage decant system can be used as illustrated in Figure 16-10. In this system, the intake spillway box and the horizontal section of the discharge pipe are removed and raised each time the spillway needs raising and an extension is added to the inclined section of the discharge pipe running down the gypsum stack slope. This system is feasible only when the intake spillway box is located close to the edge of the gypsum stack.

Groundwater Contamination

The process water from FGD scrubbers can be either acidic, basic or neutral, gypsum-saturated and contains high concentrations of calcium and sulfate. Depending on the process, the water may also contain high concentrations of chloride, magnesium, and sodium. The concentrations of all of these ions can be sufficiently high to pose a groundwater contamination problem. Trace elements of selenium, arsenic, chromium, lead, copper, zinc, and silver may also be present in the process water depending on fuel composition.

At sites where the foundation consists of clay strata of low permeability, the quantity of seepage is usually small, and the contribution of dissolved salts to the water supply source underlying the clay strata would most likely be insignificant. Further, highly plastic clays have large specific surface areas and consequently, up to the sorption capacity of the soil, are often effective in purifying the water that ultimately enters the underlying aquifers.

Frequently, gypsum stacks have been constructed directly on a relatively pervious sand stratum overlying relatively impervious clays. This has resulted in contamination of the shallow water table aquifer in the immediate vicinity of the gypsum stack. This seepage can usually be controlled by using impervious clay cutoffs or

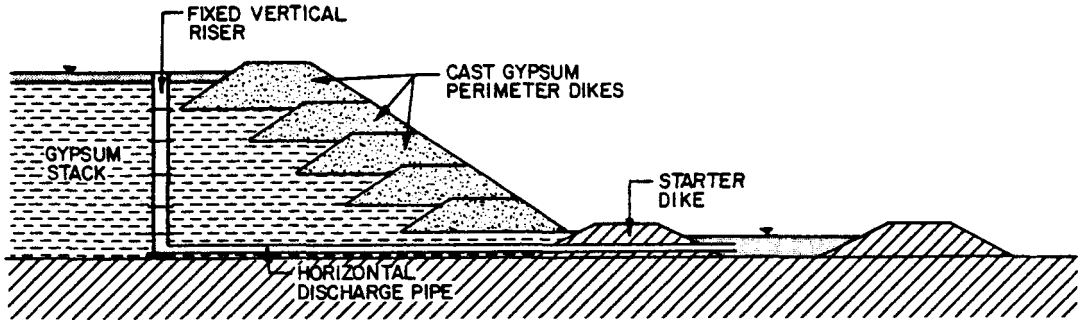


Figure 16-9. Fixed Vertical Riser Decant System

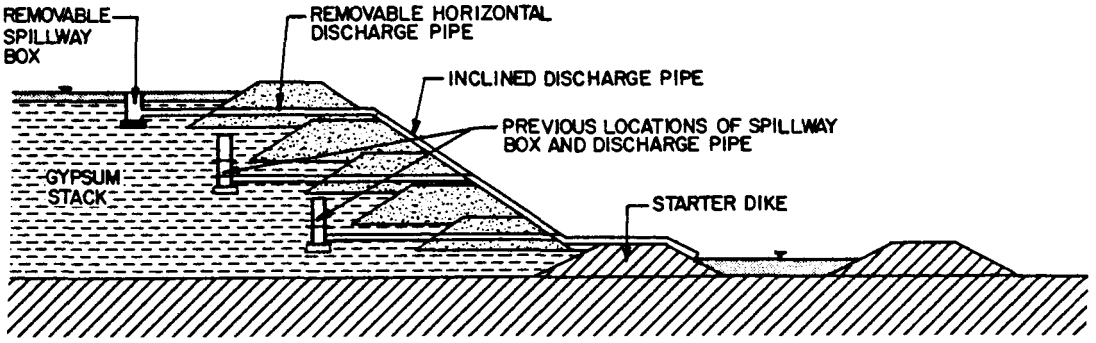


Figure 16-10. Stage Decant System

can be collected by seepage ditches or drains. Where possible, a cutoff is preferred because with a seepage collection ditch or drain, not only is process water seepage being collected, but also uncontaminated groundwater seepage and surface runoff. This can result in an unfavorable positive water balance requiring treatment of excess contaminated water.

The following examples are illustrations of methods that could be used to effectively control contamination from gypsum stacks.

- The illustrations in Figures 16-11 and 16-12 show how a seepage collection ditch around the perimeter of a gypsum stack can be effective in containing groundwater contamination. When the pervious foundation is relatively thick, the ditch is fully effective only if the water level in the ditch is kept below the level of the surrounding groundwater table (Figure 16-11). If the pervious layer is relatively shallow, the ditch need only be excavated to the underlying impervious stratum. The water level in the ditch needs to be kept at or slightly below the surface of the impervious stratum (Figure 16-12).

  The primary disadvantage of seepage collection ditches is that they add additional water to the system which must be stored and evaporated or treated before being released. On the other hand, where feasible, a seepage collection system is frequently the least expensive means of containing seepage especially around existing gypsum stacks.

- Where the pervious foundation is relatively shallow and a trench can be excavated to the underlying impervious stratum without major dewatering problems, a cutoff trench backfilled with low permeability soil can be effective in containing contamination from a gypsum stack (Figure 16-13). Impervious cutoffs are relatively expensive when compared with seepage collection ditches, but the initial construction cost may be more than offset by the cost of treating excess water that often results when seepage collection ditches are used.

- At some sites the subsurface soils may be effective in reducing the concentrations of some species within the leachate from gypsum stacks by soil sorption. An analysis of the textural, chemical, and mineralogical compositions of the foundation soils, supplemented by laboratory tests on the reactivity of the soils with the process water can help determine the purification potential at a given site. In Florida, for example, where the primary aquifer is a cavernous limestone formation, the confining bed, which is composed of calcareous clays and limestones often protects the aquifer from contamination by leachate from phosphate gypsum stacks.

- Where gypsum stacks must be placed on deep deposits of pervious sands adjacent to rivers or other bodies of fresh water which could become contaminated despite the groundwater controls described above, a liner should be used under the stack. (Figure 16-14). Where a good quality natural occurring clay is locally available it can be used to form the seepage barrier. In such cases an extensive study is required to determine the suitability of the

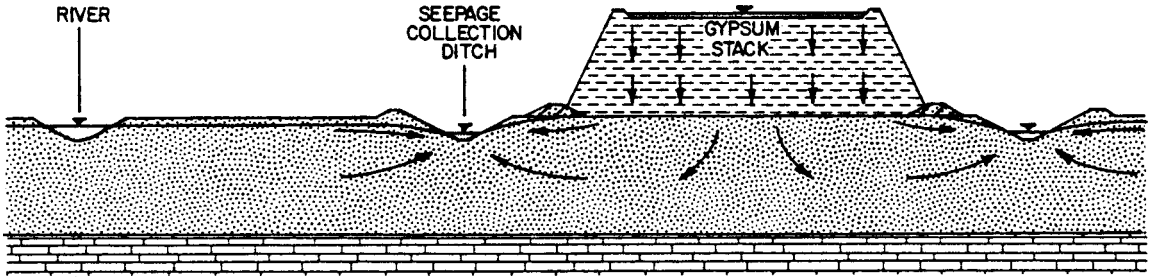


Figure 16-11. Perimeter Seepage Collection Ditch for Gypsum Stack on a Deep Sand Deposit Overlying an Impervious Foundation

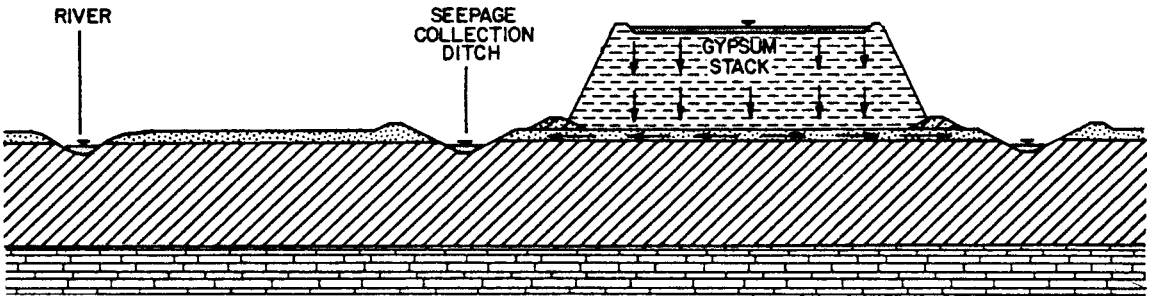


Figure 16-12. Perimeter Seepage Collection Ditch for Gypsum Stack on a Shallow Sand Foundation Overlying a Thick Clay Deposit

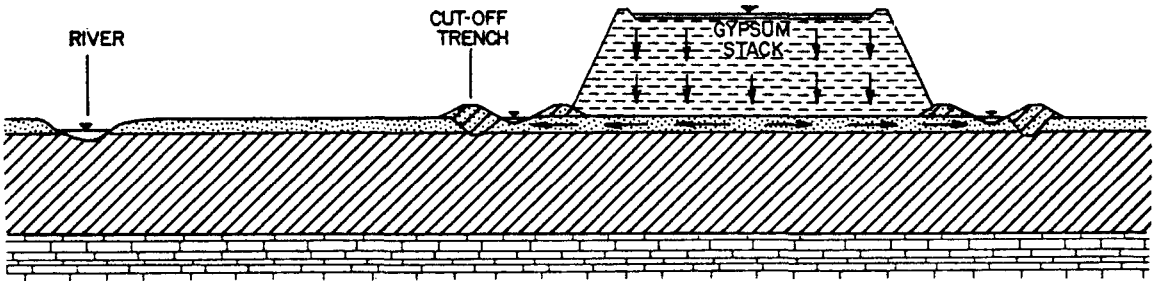


Figure 16-13. Use of Cut-Off Ditch to Control Seepage From a Gypsum Stack

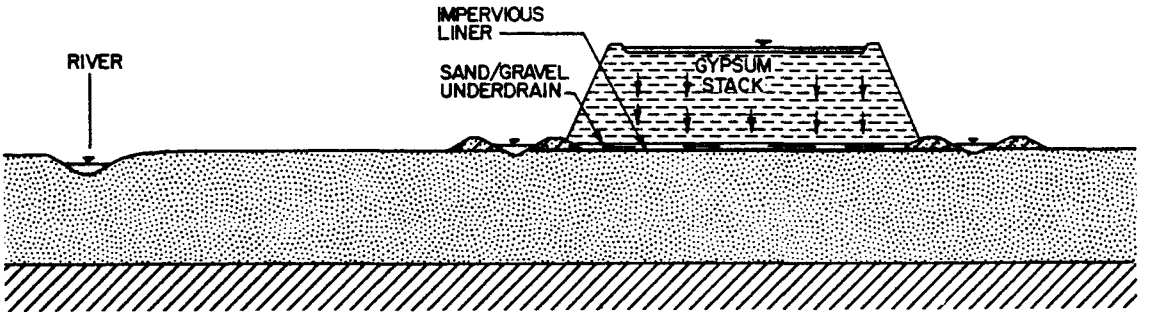


Figure 16-14. Use of an Impervious Liner and Underdrain to Control Seepage from a Gypsum Stack

clay as a liner. The effectiveness of a clay liner can be substantially increased by using a pervious sand/gravel layer above the clay liner. By properly designing the sand layer, any seepage flowing through the gypsum would be collected by the sand layer and drained through a grid of perforated pipes. With a fully effective sand drain the underlying clay blanket would be subjected to a relatively low hydraulic gradient and essentially all head loss would occur through the gypsum.

Another alternative is to use a reinforced plastic or rubber liner to replace the clay as the seepage barrier. Again, the use of a sand/gravel layer above the liner would give additional protection.

OPERATION OF GYPSUM STACKS

The two most important considerations in the operation of a gypsum stack are the retention of fine-grained gypsum within the stack and the characteristics of the gypsum deposited around the periphery of the stack.

If sufficient detention time is not provided within the ponded area on top of the stack, complete clarificarion will not occur and the finer particles of gypsum will discharge through the spillway and sediment within the surge pond. This problem has occurred at several phosphate gypsum stacks and required the dredging of fine-grained gypsum from the surge pond.

Although finer-grained gypsum can often be cast to raise the perimeter dikes, the lower permeability does not allow drainage to occur as quickly as with coarser-grained gypsum. Consequently, it is more difficult and time-consuming to use the finer material to raise the stack. For this reason, it is desirable to deposit the coarser material around the periphery of the stack.

It is possible to operate a gypsum stack so the coarser material is always deposited around the perimeter of the stack while simultaneously providing sufficient retention time for the finer particles to settle within the interior of the stack. This is accomplished by using an elevated ditch to carry the gypsum around the periphery of the stack and to create a ponded area within the interior of the stack. This concept is shown schematically in Figure 16-15. Note the decant structure is located within the ponded area and the elevated ditch passes over the discharge pipe.

Gypsum is generally cast to raise the perimeter dikes using a dragline. The cast gypsum is then shaped to form a road on the crest of the dike using a bulldozer.

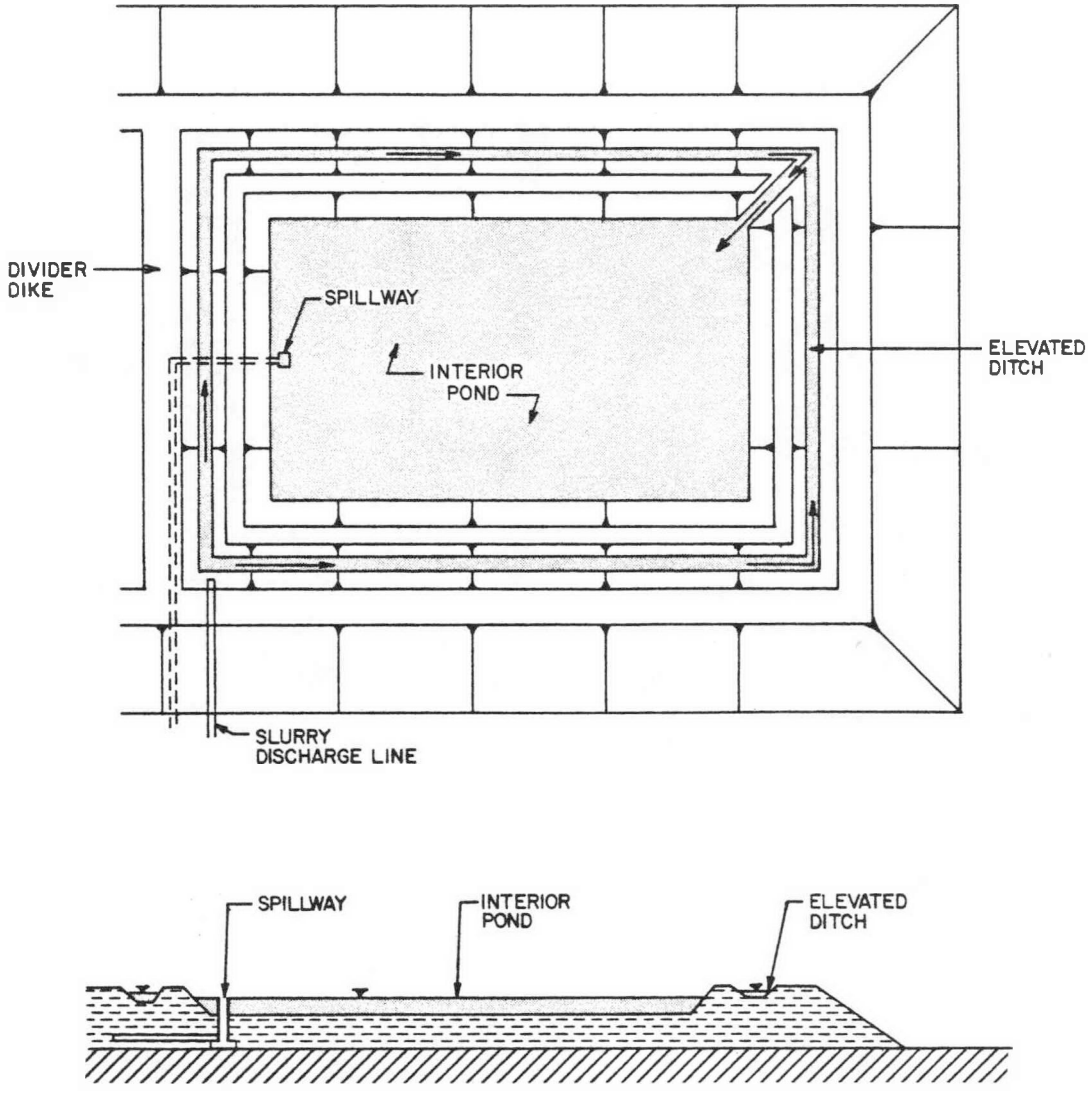


Figure 16-15. Use of Elevated Ditch to Sediment Coarse Gypsum Around Perimeter of Stack

In some cases, a bulldozer has been used to both raise and shape the perimeter dikes. In both cases, it is desirable to allow the elevated ditch to drain prior to raising the stack, although it is often possible, using the dragline, to raise the stack without draining the gypsum.

Gypsum stacks within the phosphate fertilizer industry are generally built as steeply as possible so that the retention capacity of the stack is maximized. If an average slope flatter than the angle of repose is required for stability, the perimeter dikes are generally offset from the outer perimeter as shown in Figure 16-16 to form benches in the slope. This eliminates the need for shaping the perimeter dike slopes which are simply cast and allowed to develop slopes corresponding to the angle of repose of gypsum.

It is not common to provide erosion protection on the outside slope of a gypsum stack. Experience indicates there is essentially no erosion of the slope from rainfall, and dusting has not been a significant problem. However, several grassing experiments with and without a topsoil dressing have been performed on phosphate gypsum stacks. The results of these experiments are not completed at this time, but initial results appear favorable even for relatively steep slopes (approximately 1.5 Horizontal : 1.0 Vertical). If long-term maintenance and reclamation require the slopes be grassed, it may be expedient to flatten the slopes to 2.5 Horizontal to 1.0 Vertical or flatter as the stack is raised. These flatter slopes will generally hold topsoil cover and can be maintained using conventional equipment.

Gypsum stacks in northern climates will be subject to freeze-thaw cycles. A number of phosphate fertilizer plants with gypsum stacks are located throughout the northern states and in Canada. Experience at these northern locations, where temperatures can drop below $-40^{\circ}F$, indicates no deleterious effects on the gypsum slopes from the freeze-thaw cycles. Earthen starter dikes, however, must be designed with due consideration for freeze-thaw effects.

PLANT SCHOLZ PROTOTYPE FGD GYPSUM STACK

During construction and operation of the FGD prototype gypsum stack at Scholz, all efforts were made to construct and operate the stack as typically accomplished in the phosphate industry. However, the relatively small size of the stack and the limited quantity of gypsum available for stacking required some departures from normal stacking procedures. Some aspects of the prototype stack construction are briefly discussed and illustrated in this section.

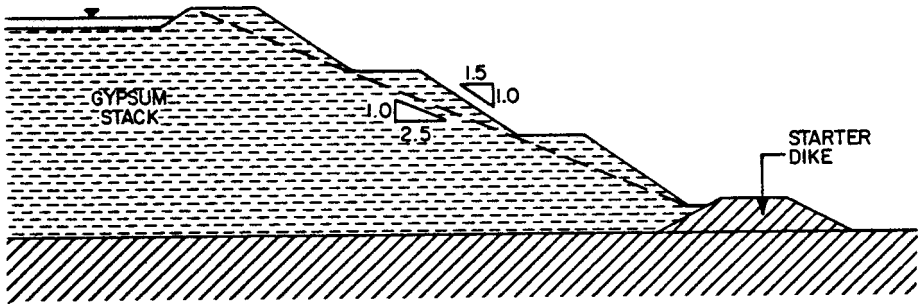


Figure 16-16. Flattening Gypsum Stack Slopes by Benching

Stack Construction

The disposal area and gypsum stack were proportioned for an estimated 9-month test period, gypsum production of 5,500 to 6,500 tons and a final stack height of 25 feet. Subsequent reductions in gypsum production during the test program, however, required a reduction in the final stack height. The stack geometry was also governed by the minimum dimensions required for: (1) safe operation of the dragline from the perimeter dike of the stack and (2) providing sufficient storage capacity within the center of the stack to sediment gypsum and allow clarification of the process water. For the small quantity of gypsum scheduled to be produced during the 9-month test program, the stack also had to be small in area to allow raising the stack to a sufficient height to observe the stacking behavior of FGD gypsum and slope stability of the cast gypsum dikes.

The gypsum stack was raised a total of four times by the upstream method of construction during the 9-month test program. Figure 16-17 presents photographs of the disposal area prior to raising the gypsum stack. As shown, the sedimented gypsum is easily walked upon.

Figure 16-18 presents photographs during one phase of construction of the north wall of the cast perimeter dike. As shown, the dragline first excavates gypsum from the containment area adjacent to the starter dike to form the perimeter ditch. The gypsum is then cast to form the perimeter dike of the gypsum stack. Photograph 16-18A shows the dragline excavating gypsum from the pond and casting the material to form the stack perimeter dike. Photograph 16-18B shows the perimeter ditch and cast dike shortly after construction. At this time, the gypsum was still too wet to cast more than 2 to 3 feet high without allowing some time for draining and drying. After drainage and drying from exposure to the sun, the gypsum was cast much easier and at steeper slopes as shown in Photograph 16-18C. After the crests of the dikes were sufficiently widened, the dragline could easily work from the cast dikes as shown by the photographs in Figure 16-19.

Photographs of the completed gypsum stack are shown in Figure 16-20. The average height of the stack above the invert of the perimeter ditch is approximately 12 feet. The perimeter dike crest width varies from 9 to 15 feet and the exterior slopes of the stack are generally 1.0 Vertical to 1.5 Horizontal. Photographs 16-20A and 16-20B show the entire stack and north wall approximately one month after the process shut-down. At this time, process water was being recirculated to the



Figure 16-17. Stacking Area Prior to Initial Dike Raising.



Figure 16-18. Raising North Wall of Cast Gypsum Dike.

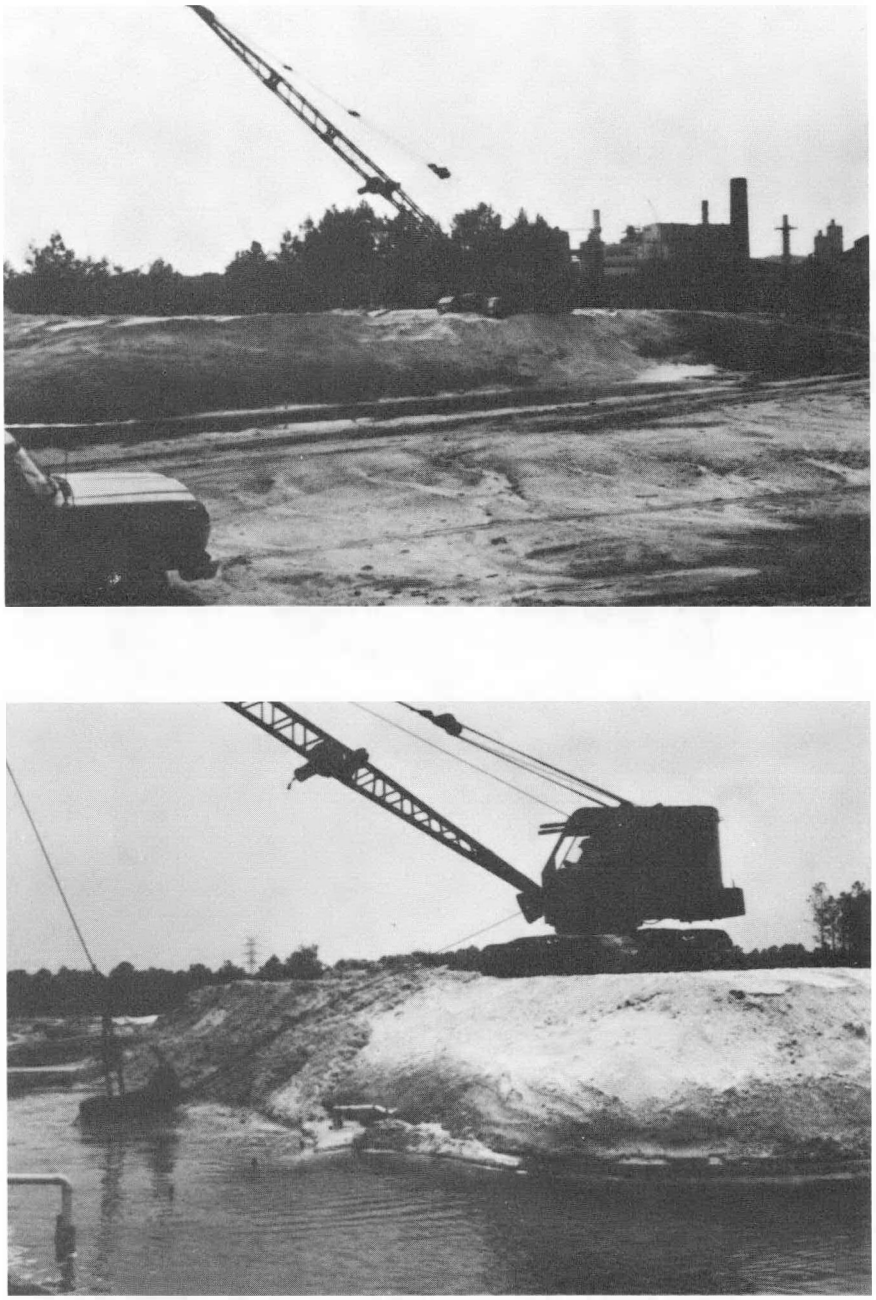
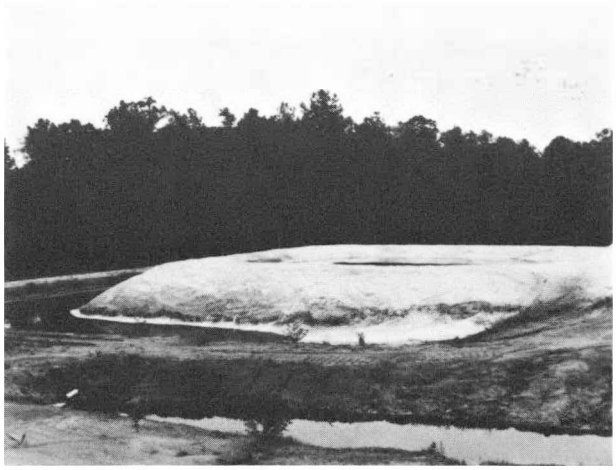
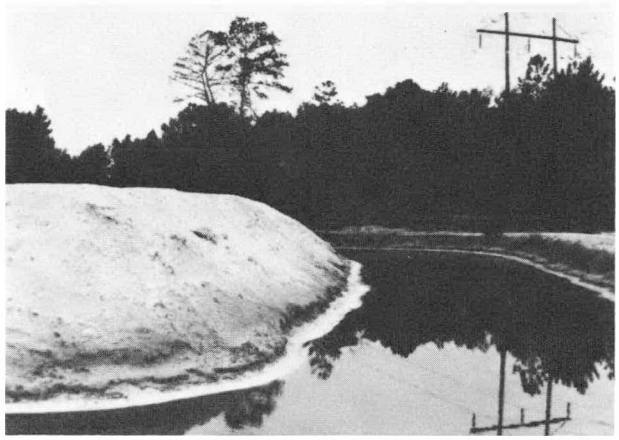


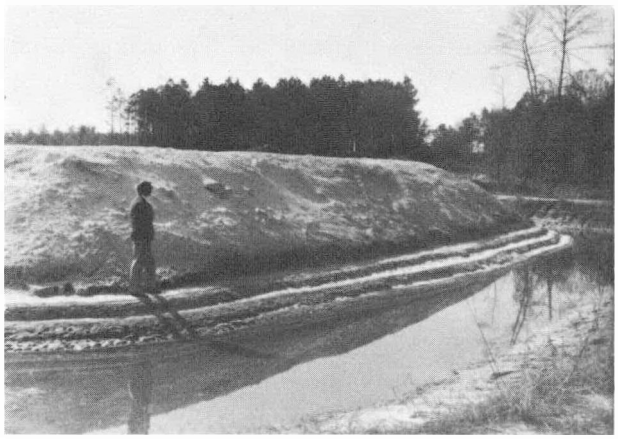
Figure 16-19. Dragline Operation from Crest of Cast Gypsum Dike.



(A) Overall View, July 1979



(B) North Wall, July 1979



(C) North Wall, November 1979

Figure 16-20. Completed Gypsum Stack.

stack to maintain steady-state-seepage through the stack. Photograph 16-20C, taken 5 months after the process shut-down, shows no significant change in the appearance of the north wall after several months of weathering and aging.

Stacking Performance

Stacking of saturated FGD gypsum from beneath the water surface of an undrained pond was possible provided the gypsum was cast upon a dry surface and sufficient time was allowed for water to drain from the cast material before attempting to pile the gypsum more than 2 to 3 feet high (Photographs 16-18A and 16-18B). Dry gypsum located above the water surface, which would be similar to gypsum within a drained pond, was excavated and cast easily and displayed acceptable stacking behavior.

Since no cohesion from cementation developed during the test program, sloughing often occurred below the spring line of the stack slope. In full-scale FGD gypsum stacks flat slopes below the spring line or internal drains may be required to control seepage instability and sloughing if some cohesion from cementation does not develop.

ENGINEERING PROPERTIES OF FGD WASTE GYPSUM

The following sections present the results of geotechnical laboratory testing of Chiyoda Thoroughbred 121 Flue Gas Desulfurization (FGD) waste gypsum. Emphasis is on presenting the physical and chemical properties, sedimentation-consolidation behavior, permeability characteristics, and shear strength characteristics of FGD gypsum relevant to stacking methods of waste disposal. Results are presented from FGD gypsum produced both at the Chiyoda pilot plant in Japan and at Scholz.

Mineralogical Analysis

X-ray diffraction data from a sample of pilot plant FGD gypsum indicate gypsum, $CaSO_4 \cdot 2H_2O$, as the only crystalline phase present. The X-ray diffraction trace of FGD gypsum is virtually identical to the trace of analytical reagent grade gypsum and also agrees with gypsum diffractometer data from the ASTM X-ray powder diffraction file.

The crystal habit and morphology of pilot plant FGD gypsum is illustrated by scanning electron photomicrographs in Figure 16-21. As shown, the gypsum crystals are generally elongate to tabular with sharp, regular edges.



Figure 16-21. Scanning Electron Photomicrographs of Chiyoda FGD Gypsum.

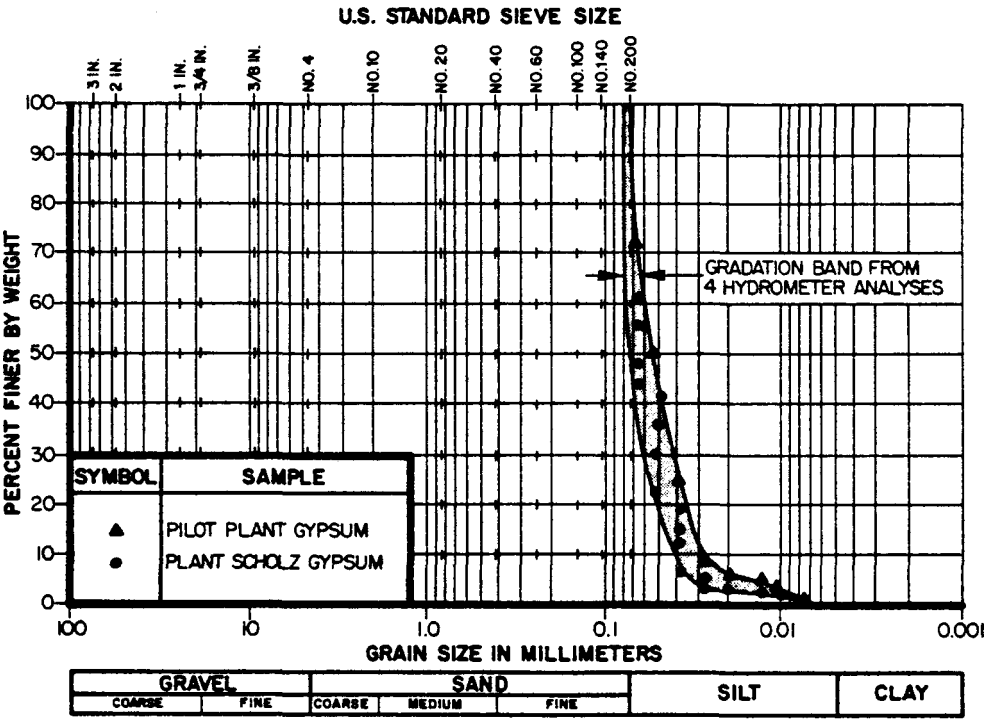


Figure 16-22. Grain Size Distribution

Grain Size Distribution

Results from sieve and hydrometer analyses indicate the particle size distribution of Chiyoda FGD gypsum as presented in Figure 16-22. As shown, FGD gypsum predominately consists of non-plastic, poorly-graded silt size particles with a fines content of 40 to 100 percent (i.e., percent by weight passing the U.S. No. 200 Sieve).

Specific Gravity

The specific gravity of FGD gypsum varies from 2.27 to 2.44 with an average of 2.34. Since gypsum was the only crystalline phase detected during X-ray diffraction analyses, this value is expected and agrees with the theoretical specific gravity of gypsum of 2.33.

Drying Curve Characteristics

Gypsum contains both chemically bonded and free water. The amount of chemically bonded water expelled during drying increases with increased drying temperature. To determine the correct drying temperature for evaluating gypsum moisture content and dry density, measurements of moisture content versus drying temperature were made for FGD gypsum and an analytical reagent grade gypsum (Figure 16-23).

During drying, gypsum converts to hemihydrate and then to anhydrite. Drying at the elevated temperature of 105°C commonly used for moisture content determinations of soils, therefore, is not appropriate. Drying samples of FGD gypsum over the temperature range of 35°C to 240°C indicates a drying curve behavior similar to that for reagent grade gypsum. At temperatures greater than 70°C, gypsum begins to expel chemically bonded water, yielding incorrect moisture contents. Accordingly, the moisture content of FGD gypsum should be evaluated at temperatures less than 70°C, with a temperature of 50°C normally selected.

Sedimentation and Consolidation

The typical sedimentation-consolidation behavior of Chiyoda pilot plant and Scholz FGD gypsum is summarized in Figure 16-24. As shown, the range in initial void ratio and dry density for FGD gypsum sedimented in gypsum saturated water at very low consolidation stresses of 0.001 to 0.01 kg/cm^2 is approximately 0.88 to 1.00 and 78.0 to 73.0 pcf, respectively.

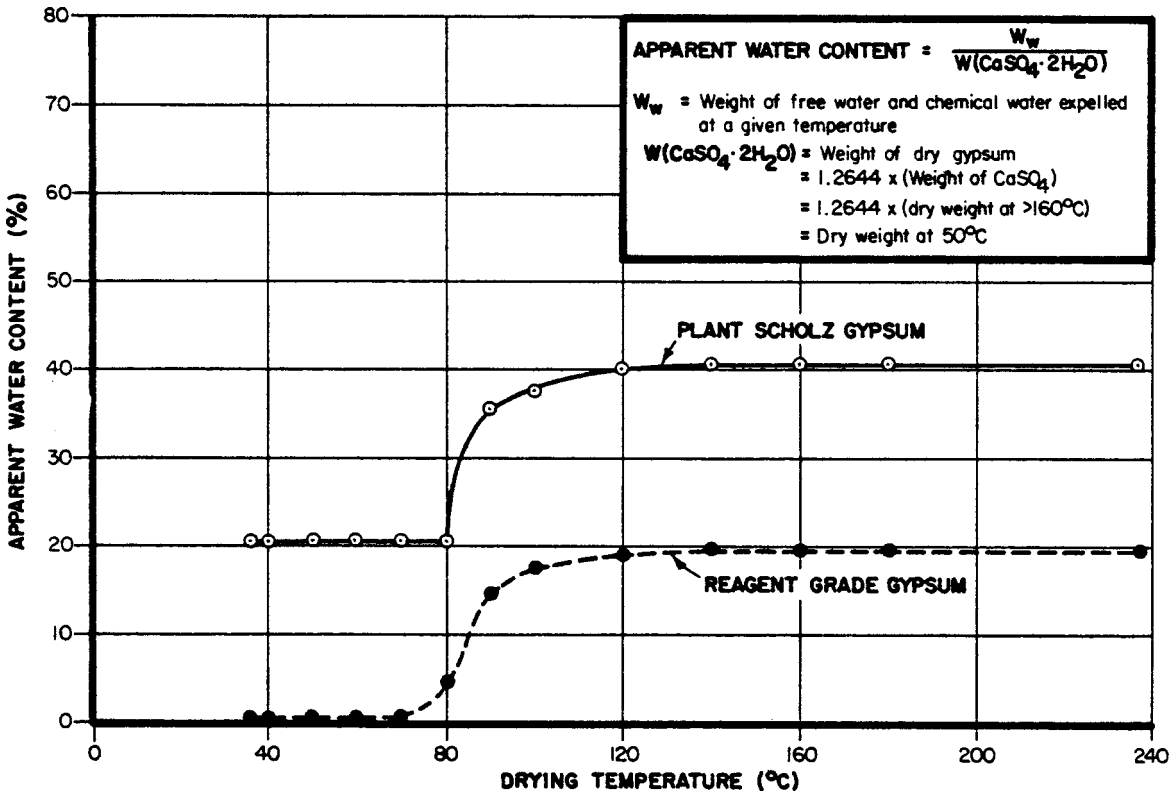


Figure 16-23. Drying Curve Characteristics

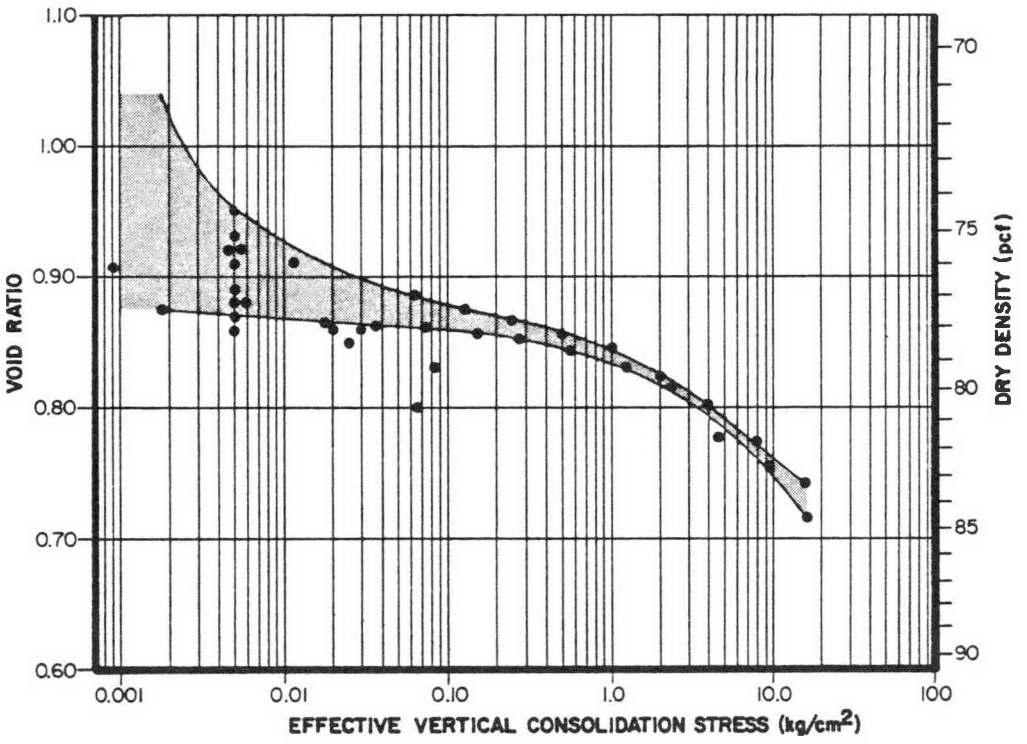


Figure 16-24. Sedimentation-Consolidation Behavior

Pore fluid pH has some effect on the initial sedimented void ratio and dry density. The initial void ratio of gypsum sedimented in pH 3.0 pore fluid was consistently 5 to 7 percent lower than the initial void ratio of gypsum sedimented in pH 6.5 pore fluid. The effect of pore fluid pH, however, is relatively small and can generally be neglected. The practical implication of the initial void ratio and dry density of sedimented gypsum at low consolidation stresses is that FGD gypsum will initially sediment to a dry density of 73 to 78 pcf (70 to 73 percent solids).

Primary consolidation for gypsum occurs quickly followed by drained creep deformations or secondary compression. Coefficients of consolidation calculated from compressibility and permeability parameters for each load increment indicate coefficients of consolidation ranging from 10 cm^2/sec at a stress level of 0.01 kg/cm^2 to greater than several hundred cm^2/sec at stress levels of 1.0 kg/cm^2 and higher. The practical conclusion from these data is that FGD gypsum has a rapid rate of primary consolidation, but exhibits one-dimensional secondary compression or drained creep deformations. The rate of secondary compression is small, however, and can generally be neglected in design.

Permeability

The effect of dry density and void ratio on the coefficient of permeability of sedimented FGD gypsum is illustrated in Figure 16-25. At consolidation stresses less than 2.0 kg/cm^2 and corresponding dry densities less than 80 pcf, the coefficient of permeability for intact sedimented gypsum ranges from 1.0×10^{-3} to 3.0×10^{-3} cm/sec. For consolidation stresses approaching 16.0 kg/cm^2 the dry density increases to 85 pcf and the average coefficient of permeability for sedimented gypsum decreases to 6.0×10^{-4} cm/sec. No measurable effect of pore fluid pH on the coefficient of permeability occurs for gypsum sedimented to the same void ratio.

Cast gypsum generally has a lower void ratio than sedimented gypsum and corresponding lower coefficient of permeability. The dry density of cast FGD gypsum from the laboratory tests varied in the range of 85 to 95 pcf with coefficients of permeability in the range of 2.0×10^{-4} to 5.0×10^{-4} cm/sec.

Shear Strength

Three types of samples were tested to evaluate the shear strength characteristics of Chiyoda FGD gypsum: (1) laboratory sedimented gypsum to simulate the sedimentation of gypsum within the gypsum stack, (2) laboratory cast gypsum to simulate

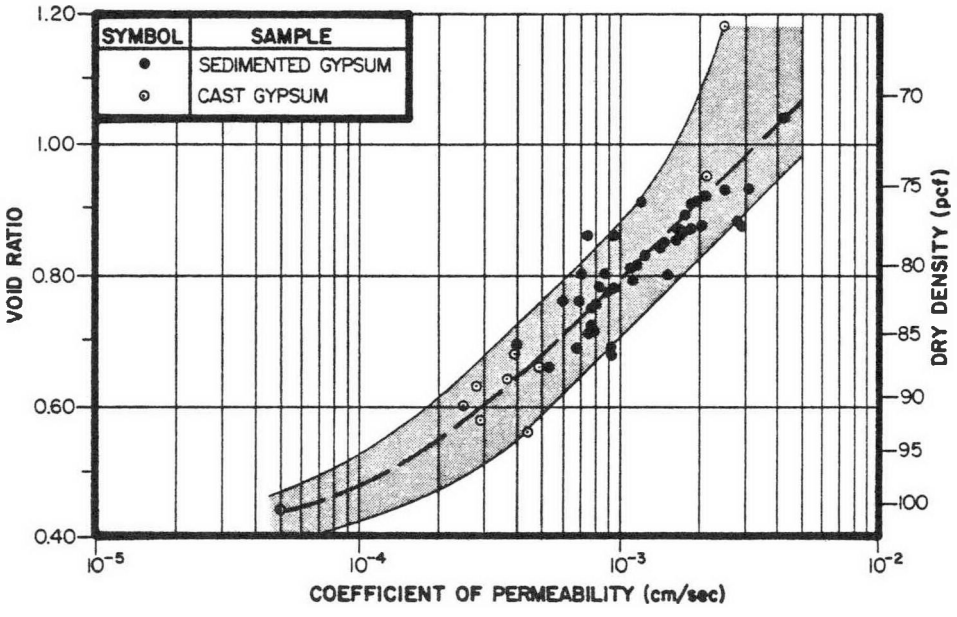


Figure 16-25. Void Ratio versus Coefficient of Permeability

the casting of gypsum by a dragline during construction of the stack perimeter dike, and (3) undisturbed samples of cast gypsum from the Scholz gypsum stack perimeter dike. The effect of pore fluid on shear strength was also investigated for pH 3.0 and 6.5 gypsum saturated water.

Typical Mohr-Coulomb effective stress paths and undrained stress-strain behavior for FGD gypsum in triaxial compression is shown in Figure 16-26. The full effective friction angle is mobilized early in the loading as indicated by the effective stress paths reaching the failure line (K_F line) early in the test. The shear resistance continues to increase, however, because the pore pressures become negative and lead to increased effective stresses. The negative pore pressures develop because although the sample is compressing during shear, there is a tendency for the sample to attempt to increase in volume to overcome particle interlocking.

Figure 16-27 summarizes the effective friction angle versus void ratio and dry density for cast and sedimented FGD gypsum. These data indicate an effective friction angle increasing from 40.5^{o} with zero cohesion at a dry density of 78 pcf to 46.5^{o} with zero cohesion at a dry density of 103 pcf. The range in dry density from 78 to 103 pcf covers most densities likely to occur in a gypsum stack except for loose, initially sedimented gypsum at very low consolidation stresses.

Pore fluid pH was found to have no measurable effect on the shear strength of cast or sedimented gypsum. At similar void ratios the shear strength of samples with pH 3.0 and pH 6.5 pore fluid displayed essentially identical stress-strain-strength behavior.

An important strength characteristic of typical phosphoric acid plant gypsums relevant to stacking is the development of true cohesion from cementation. The cementation is believed to develop because of the solubility of gypsum in acid or rain water allowing dissolution and subsequent recrystallization as a result of seepage and evapotranspiration. These field conditions causing cementation, however, cannot be readily simulated in the laboratory. Laboratory cast samples of pilot plant gypsum were allowed to dry under varying conditions in an attempt to simulate the drying which occurs in the perimeter dike. No true cohesion from cementation, however, was observed for any of these specimens upon resaturation and subsequent shearing in undrained triaxial compression tests.

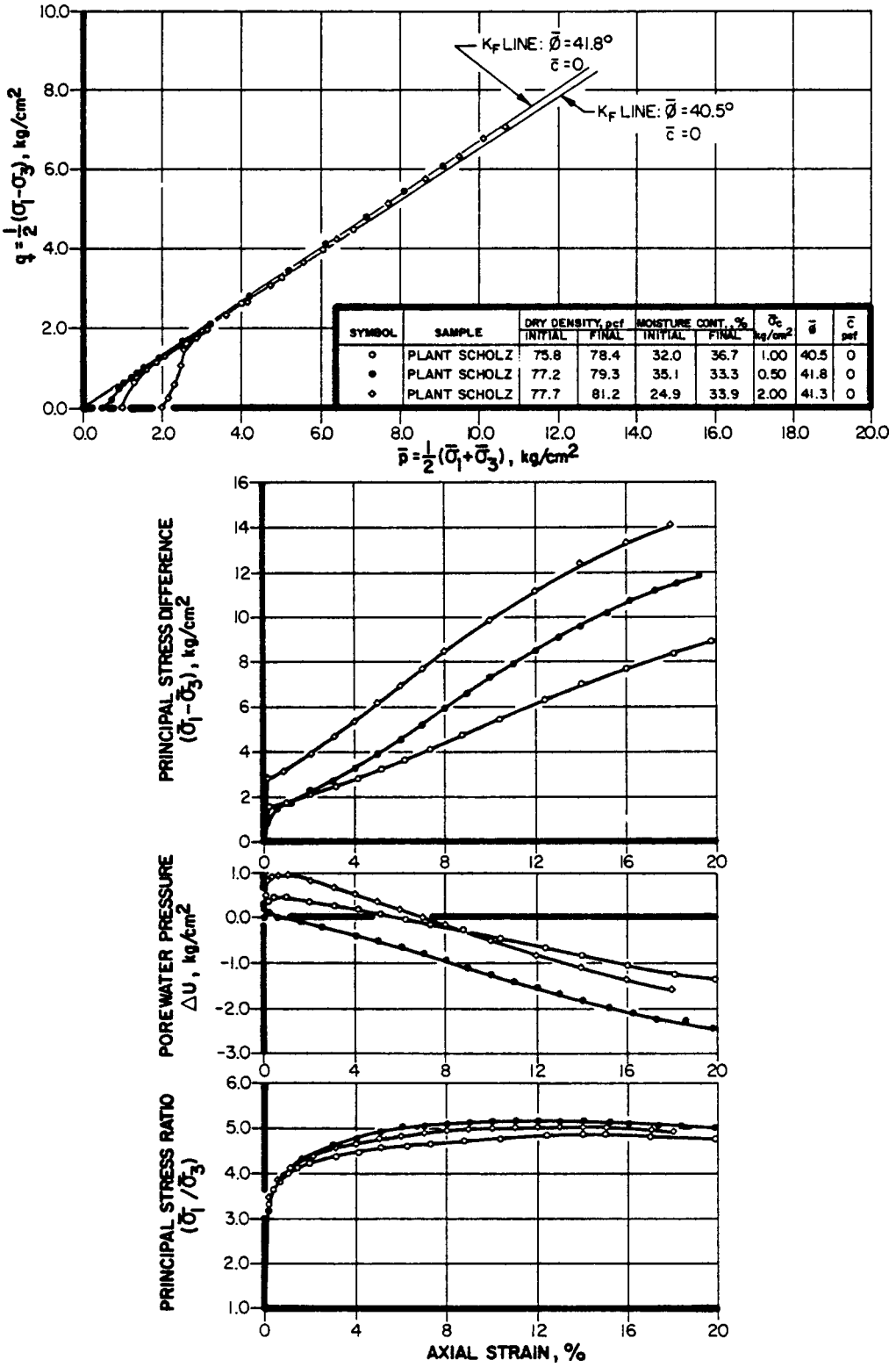


Figure 16-26. Typical Undrained Stress-Strain-Strength Behavior of FGD Gypsum.

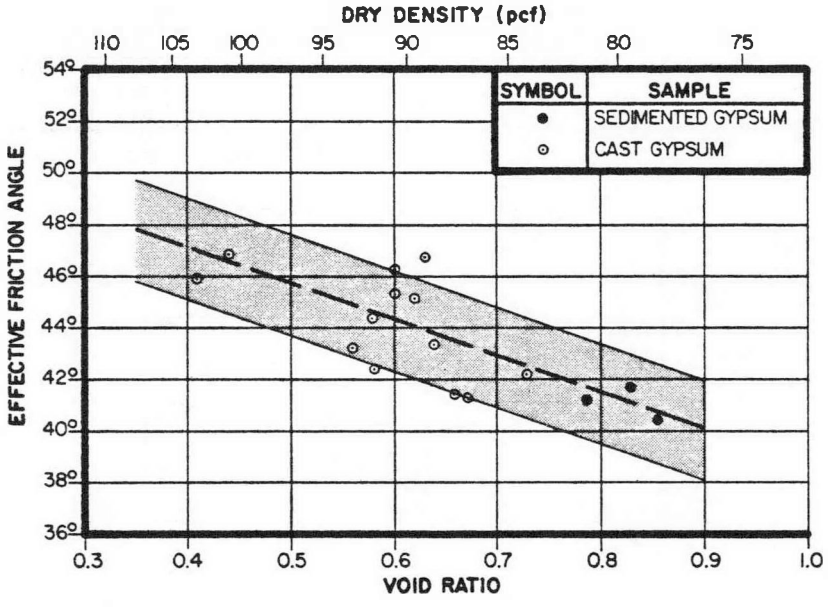


Figure 16-27. Void Ratio versus Effective Friction Angle

Phosphogypsums which develop cementation in the field often exhibit a true cohesion upon drying at elevated temperatures. Several samples of FGD gypsum were statically compacted to dry densities of 74 to 80 pcf and dried at 50°C for 48 hours. After drying, the samples were partially immersed in gypsum saturated water to check for cementation. All of the samples disintegrated and sloughed almost immediately after immersion indicating no true cohesion from cementation. Based upon laboratory triaxial strength tests, visual observation of laboratory test samples, and short-term observations of the gypsum stack at Scholz, no true cohesion from cementation has been found to develop for Chiyoda FGD gypsum.

SUMMARY AND CONCLUSIONS

Disposal of waste gypsum by stacking has been economically utilized by the phosphate fertilizer industry throughout the world for more than twenty years. Gypsum stacks over 100 feet high with average side slopes as steep as 1.5 Horizontal to 1.0 Vertical are not uncommon. The gypsum produced by FGD scrubbers has settling, dewatering, and structural characteristics similar to and, in some instances, more favorable than the phosphate gypsum making it an ideal candidate for stacking methods of waste disposal.

Engineering properties of FGD gypsum obtained from a prototype scrubber near Sneads, Florida have been summarized herein. The construction and performance of a small stack utilizing gypsum produced by this scrubber have also been discussed and illustrated.

The results of the stacking experiment indicate that FGD gypsum after a short drainage period could be easily excavated and cast up to construct the outer perimeter of the gypsum stack. Even saturated gypsum, excavated below the water surface of the pond, could be cast onto the outer perimeter, provided the cast-up material was allowed to drain for a short period before attempting to raise the perimeter gypsum more than a few feet high. Although only enough gypsum was produced to construct the stack to a maximum height of 12 feet, the experiment did show that FGD gypsum can be easily and economically disposed of through stacking.

Appendix A

REGULATORY REQUIREMENTS

NEW SOURCE PERFORMANCE STANDARDS (NSPS)

PERTINENT SECTIONS OF THE STANDARDS

On June 11, 1979, the Federal Register carried certain revisions/additions to Part 60 of CFR 40 which are relevant to the consideration of FGD sludge quantity (1). The portion of primary interest is Subpart D-a, which is titled "Standards of Performance for Electric Utility Steam Generating Units for Which Construction is Commenced After September 18, 1978."

Section 60.43a spells out the Standard for Sulfur Dioxide for solid fossil fuel burning plants, other than those using solvent refined coal or anthracite: no emissions are permitted to contain sulfur dioxide in excess of (1) 520 ng/J (1.20 lb/million Btu) heat input and 10% of the potential combustion concentration (90% reduction), or (2) 30% of the potential combustion concentration (70% reduction), when emissions are less than 260 ng/J (0.60 lb/million Btu) heat input. Section 60.43g goes on to state that compliance with the emission limitation and percent reduction requirements - - - are both determined on a 30-day rolling average basis. Section 60.48a, Compliance Determination Procedures and Methods, details the procedures and methods used to determine compliance with the sulfur dioxide standards. Included in that section is a discussion of the credits which may be taken for sulfur removed by coal cleaning, in the pulverizing process and by bottom ash and flyash interactions.

Credit for sulfur removal by pretreatment of the fuel is to be determined by a new reference Method 19 to Appendix A of Part 60. Procedures are given for determining overall reduction:

1. Sulfur is determined on fuel samples before and after pretreatment to determine the percent reduction by pretreatment. The sulfur thus removed may be credited toward meeting the SO_2 percentage reduction.
2. Sulfur dioxide and oxygen or carbon dioxide are determined on emissions upstream and downstream of sulfur dioxide removal devices and the results used to determine FGD removal efficiencies.

3. As an alternative to sampling upstream emissions, as-fired fuel samples can be analyzed for sulfur and heating value. Sulfur removal credits can thus be combined for removal by the pulverizers, adsorption by bottom ash and flyash and removal by the FGD system.

Conditions are given for the fuel sampling procedures, which are based on ASTM Standard Methods. The values obtained are used in equations given in the Standards of Performance for determining the sulfur credit that may be taken and the resultant emission rate and overall removal efficiency.

The concept of a sliding scale for sulfur dioxide reduction is included, but is termed "variable percent reduction" in the Rationale of the SO_2 Standards (page 33583). It is stated that under this approach, plants firing high-sulfur coals would be required to achieve a 90% reduction in potential emissions. Those using intermediate or low-sulfur content coals would be permitted to achieve between 70 and 90% reduction providing their emissions were less than 260 ng/J (0.6 lb/million Btu).

EFFECT OF STANDARDS

The requirements of the new NSPS have been incorporated into two sets of curves to enable the estimation of waste quantity. Figure A-1 shows the required SO_2 removal by classifying reduction requirements into four groups as governed by fuel sulfur content and heating value:

- 70% removal required
- 70 to 90% removal required
- 90% removal required
- More than 90% removal required

To illustrate the use of the curves, consider a 10,000 Btu/lb fuel with varying sulfur content:

- under 1% sulfur, 70% removal is required
- between 1 and 3% sulfur, 70 to 90% is required
- between 3 and 6% sulfur, 90% is required
- above 6% sulfur, more than 90% is required

The curves in Figure A-1 serve to classify fuels into four broad bands. To enable the determination of the exact degree of removal required for a fuel of a given sulfur and Btu, the same data obtained for Figure A-1 were used in plotting

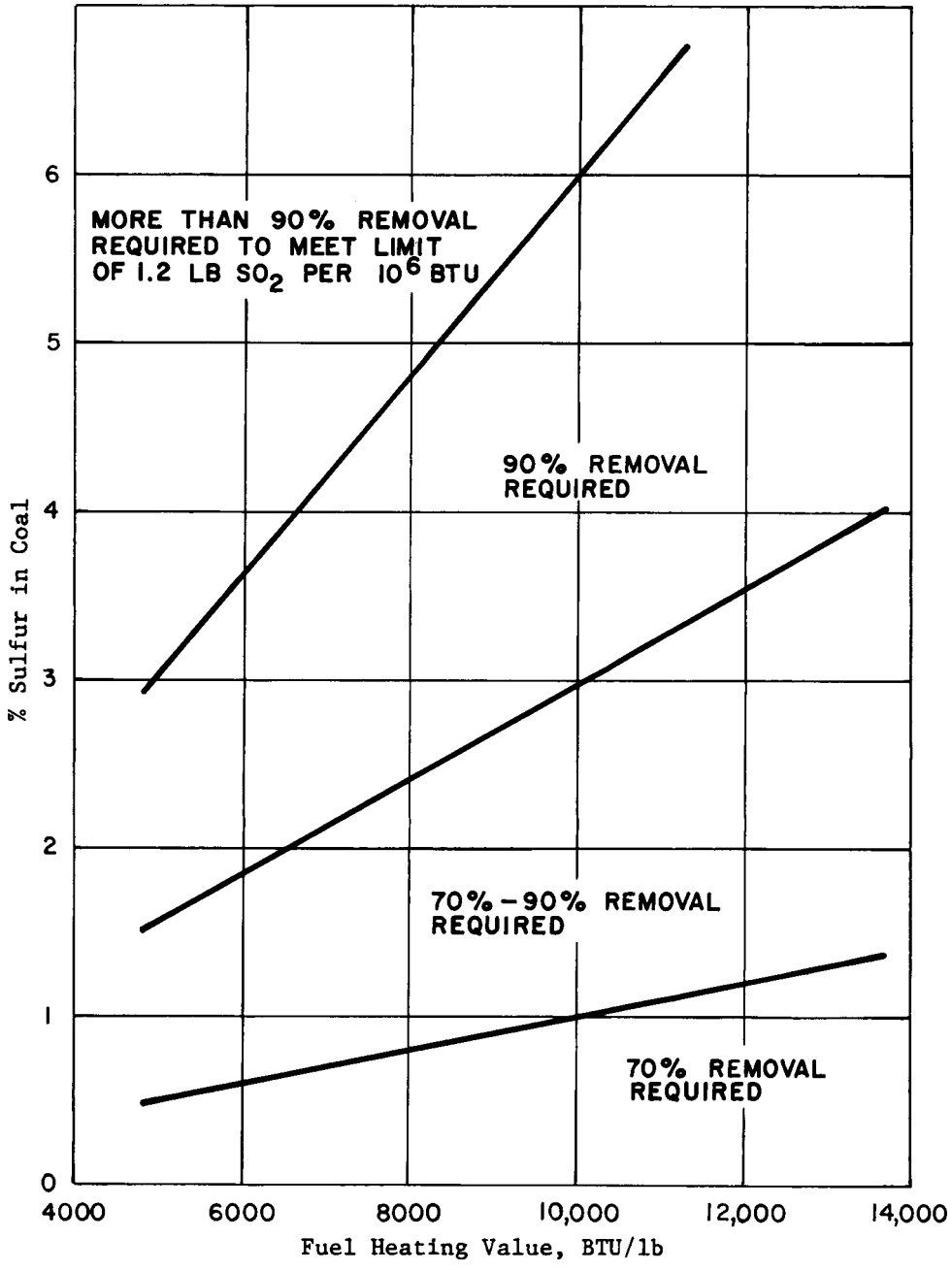


Figure A-1. SO_2 Removal Required to Meet 1979 NSPS Standards.

Figure A-2. Using this figure, it can be seen that the same 10,000 Btu fuel requires

- 75% removal with 1.2% sulfur
- 80% removal with 1.5% sulfur
- 85% removal with 2.0% sulfur

Note that no credit has been taken for sulfur removal by fuel pretreatment (cleaning), in the pulverizers or by interaction with ash in the boiler.

1. "New Stationary Sources Performance Standards: Electric Utility Steam Generating Units," Federal Register, Vol. 44, No. 113, Part II, June 11, 1979.

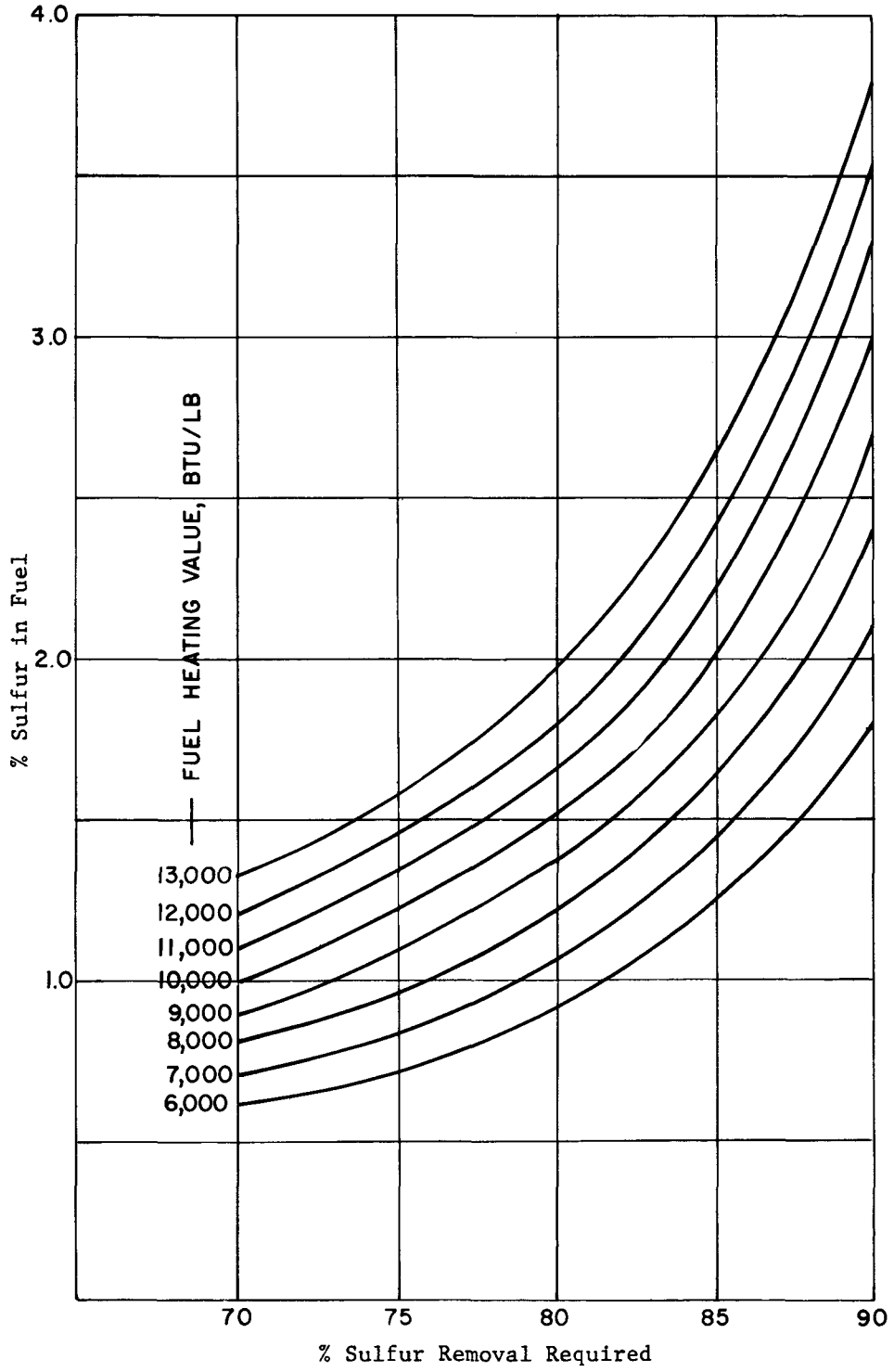


Figure A-2. SO_2 Removal Required to Meet 1979 NSPS Standards

APPENDIX B

DISPOSAL REGULATIONS

With the passage of the Resource Conservation and Recovery Act (RCRA of 1976, PL 94-580, Congress substantially modified the role of the federal government in solid waste management. Completely replacing the language of the Solid Waste Disposal Act of 1965, RCRA greatly expanded the role of the federal government in solid waste management. RCRA established the Office of Solid Waste within EPA to administer the Act and to coordinate related activities with the states. The purpose of this Act was twofold:

- To promote resource recovery and safe disposal of waste materials
- To regulate the management of hazardous waste

The regulation of both hazardous and non-hazardous wastes is provided for in Subtitle C and Subtitle D, respectively. FGD sludge is specifically addressed in Section 1004 of RCRA which defines solid waste as: "...any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant or air pollution control facility...". In EPA's proposed hazardous waste regulations (Federal Register, December 18, 1978), FGD sludge was included in the "Special Waste" subcategory of hazardous wastes. However, in the hazardous waste regulations promulgated on May 19, 1980, the EPA specifically excluded large volume utility wastes from regulation under Subtitle C. These regulations also have a provision which designates mixtures of hazardous and non-hazardous wastes as hazardous. There are a number of relatively low volume waste streams within power plants (e.g. metal cleaning wastes) which may be classified as hazardous by applying EPA's Extraction Procedure. Combining such waste streams with FGD sludges may result in a large volume waste subject to scrutiny as a hazardous waste. Exempting such waste mixtures from regulation as hazardous wastes may entail extensive testing in accordance with EPA procedures.

The exemption of FGD sludge from regulation under Subtitle C is subject to change as a result of an EPA sponsored study. Utilizing the results of this study, it is anticipated that the EPA will propose and eventually promulgate regulations which

define standards for the management of FGD sludge, bottom ash and flyash. Such regulations may not be in effect for four or five years. In the interim period, FGD sludge will be regulated as a non-hazardous waste.

NON-HAZARDOUS WASTE MANAGEMENT

EPA's role in the regulation of non-hazardous waste is not expected to be as active as in the regulation of hazardous waste. Wastes excluded from regulation as hazardous wastes will be subject to state enforcement of the requirements for non-hazardous wastes under Subtitle D of RCRA. This Subtitle prohibits open dumping and requires that environmentally acceptable practices be utilized.

FINAL REGULATIONS

As provided for in the Act, the EPA has developed Criteria for Classification of Solid Waste Disposal Facilities. These Criteria have been promulgated as regulations (Federal Register, September 13, 1979). Facilities which fail to satisfy the Criteria will be considered "open dumps" which are illegal. These Criteria are primarily oriented toward disposal of municipal solid waste. The criteria which are most pertinent to FGD sludge disposal are as follows:

Site Location. Disposal facilities are prohibited from restricting the flow of the 100-year flood and from disrupting critical habitats of endangered or threatened species.

Groundwater Protection. A disposal facility must not contaminate an underground drinking water source beyond the solid waste boundary or an alternate boundary set by the State. Contamination is defined as the introduction of a substance that would cause either:

- The concentration of that substance in the groundwater to exceed the maximum contaminant level specified in the primary drinking water standards, or
- An increase in the concentration of that substance in the groundwater where the existing concentration of that substance exceeds the maximum contaminant level specified in the primary drinking water standards.

In these regulations, the EPA has defined an underground drinking water source as an aquifer currently supplying drinking water for human consumption or an aquifer in which the concentration of total dissolved solids is less than 10,000 mg/l.

In defining the unacceptable effects of solid waste disposal on groundwater, the EPA has concluded that solid waste activities should not degrade groundwater beyond the levels established to protect human health. At this time, the EPA is relying on the primary drinking water standards. However, the EPA has proposed to include the maximum contaminant levels of the Proposed Secondary Drinking Water Regulations to the definition of groundwater contamination. This could have an important impact on FGD sludge disposal practices since some of the parameters which are usually found in high concentrations in sludge liquors (e.g. total dissolved solids, sulfate, and chloride) are included in these proposed regulations.

Surface Water Protection. The Criteria make reference to the requirements of the Clean Water Act with regard to point source discharges, disposal of fill material in waterways, and non-point source discharges. Point source discharges must comply with the requirements of the National Pollutant Discharge Elimination System (NPDES) under Section 402 of the Act. Disposal in certain waterways requires the authorization of the Army Corps of Engineers in accordance with Section 404 of the Act. Non-point source discharges must be in accordance with water quality management plans developed under Section 208 of the Act.

Controlled Access. The Criteria stipulate that public access be controlled to prevent the exposure of the public to potential health or safety hazards.

Proposed Guidelines

EPA has also proposed guidelines for the Landfill Disposal of Solid Waste (Federal Register, March 26, 1979). These Guidelines represent EPA's recommendations for the location, design, construction, operation and maintenance of solid waste landfill disposal facilities. EPA suggests that in many cases compliance with the aforementioned Criteria can be achieved by applying practices outlined in the Guidelines. As with the Criteria, these Guidelines are oriented toward the disposal of municipal solid waste. However, the Guidelines are more detailed than the Criteria. These Guidelines discuss specific measures for surface water control and groundwater monitoring. Of particular relevance are the various measures which may be acceptable for groundwater protection. The degree of protection required should be related to the hydrogeologic characteristics of the disposal area. Theoretically, acceptable methods may entail the use of natural mechanisms, such as soil attenuation and diffusion in the aquifer, in reducing the potential of polluting underground drinking water sources. However, in applying for the necessary permits,

the owner/operator of a waste disposal facility will likely be required to demonstrate that the facility does not pose an unacceptable risk to existing or potential underground drinking water sources. In many cases, this may entail the installation of impermeable liners.

STATE PROGRAMS FOR REGULATING FGD SLUDGE UNDER RCRA

The expansion of the federal role in solid waste management under RCRA has a direct impact on existing state programs. Regulation of non-hazardous wastes will continue to be the domain of the states. However, in promoting nationwide consistency, the EPA is developing federal standards and guidelines to be implemented by the states. Asserting greater control of hazardous wastes, the EPA will not authorize states to carry out Subtitle C regulatory programs unless the states' programs are demonstrated to be equivalent to and consistent with the EPA program.

As previously mentioned, FGD sludge has been classified as a non-hazardous waste. With the increasing federal role in setting disposal standards and authorizing state regulatory programs, state requirements and permitting procedures for FGD sludge disposal will likely change.

Most states are in the process of revising their programs to be consistent with RCRA. The states with the greatest coal-fired generating capacity are at various stages in pursuing authorization under RCRA. The progress which has been made and the anticipated changes are described in the following pages for Ohio, Pennsylvania, Illinois, Indiana, West Virginia, Kentucky, Tennessee, North Carolina, Missouri and Alabama.

Ohio

Solid waste disposal practices in this state are governed by Chapter 3734 of the Ohio Revised Code. As authorized by this legislation, the Ohio Environmental Protection Agency (OEPA) has promulgated solid waste disposal regulations. While these regulations do not specifically address FGD sludge, it does fall within the general definition of solid wastes subject to state regulation. Currently, utility sludge is evaluated on a case-by-case basis to determine its nature and appropriate disposal requirements. This determination will be made according to criteria set by the U.S. EPA pursuant to RCRA. In accordance with the U.S. EPA's exemption, scrubber sludge will be classified as a non-hazardous substance. Sludge disposal will be governed by OEPA's solid waste disposal regulations which specify the required contents of a license application (i.e. detailed plans and specifications, subsurface information, waste characteristics). Prior to licensing a sludge disposal facility, the OEPA requires a Permit to Install (PTI). Information required to obtain a PTI

includes a chemical analysis of the utility sludge along with the results of an extraction test and descriptive information on the process generating the sludge. Site plan approval and the PTI are applied for simultaneously to the district office of the OEPA. Following district office approval, OEPA's central office, after additional review and acceptance, will issue the required approvals.

In 1978, Ohio amended its solid waste disposal act to include hazardous waste provisions required by RCRA. This law states that the regulations to be promulgated should be consistent with but no more stringent than those promulgated by the U.S. EPA pursuant to RCRA. In turn, the Ohio EPA must amend its current solid waste disposal regulations to include provisions for management of hazardous solid waste according to RCRA. However, the effect that the hazardous waste regulations will have on FGD sludge disposal is expected to be minimal, since FGD sludge has been classified as a non-hazardous waste.

Pennsylvania

The Pennsylvania Solid Waste Management Act of 1968 provides the legal basis for control of solid waste in this state. The Department of Environmental Resources (DER), Bureau of Solid Waste Management, is responsible for the regulation of solid waste in accordance with this Act.

Current regulations governing solid waste disposal are found in Chapter 75 of DER's Rules and Regulations. As specified in Section 75.37, Standards for Flyash, Bottom Ash and Slag Disposal Areas, FGD sludge may be incorporated with flyash, if approved by the DER. Design standards for ash disposal sites include specifications on landfill slopes, surface runoff, and groundwater monitoring. The permitting procedure involves a two-step process. Approval of the proposed disposal site can be obtained by submitting a Phase I application, which provides information on waste quality and quantity and on the geology, hydrology and land use of the site. Subsequent approval of the design plan can be obtained by submitting a Phase II application, which includes detailed design and operational plans.

As required to receive EPA's authorization under RCRA, the Pennsylvania legislature is currently in the process of amending the Solid Waste Management Act. This amendment would probably not significantly alter the current regulation of FGD sludge in the state. Any changes to the current state regulatory standards for FGD sludge disposal will not be promulgated until the state law is amended.

Illinois

The Environmental Protection Act of 1970 governs solid waste disposal in the State of Illinois. This act, a broad spectrum law, was designed to protect the environment from all types of pollution including air, water, noise and solid waste. The act empowered the Illinois Pollution Control Board to promulgate rules known as the Illinois Pollution Control Board Rules and Regulations, Chapter 7, Solid Waste, which confer responsibility for permit issuance and enforcement to the Illinois Environmental Protection Agency.

No special provisions for the disposal of FGD sludge are contained in the current solid waste regulations. The current procedure utilized by the Illinois EPA is to classify FGD sludge as hazardous or non-hazardous according to the results of a toxicant extraction procedure. To construct a new disposal site, a Development Permit must be acquired from the Illinois Environmental Protection Agency. The application for a Development Permit must include plans for site development and hydrologic and geologic information prepared by a professional engineer.

Following issuance of the development permit, the next step in the permitting procedure is to apply for an Operating Permit. The Agency will issue this permit if the constructed site is found to be in compliance with all criteria specified in the Development Permit. An application for an Operating Permit will be considered filed with the Agency if no notification of an incomplete application is received within a 30 day period. The applicant may assume that his Operating Permit is granted if he receives no notification within 45 days of the date the application was received by the Agency.

The recent exemption of FGD sludge from the hazardous classification may simplify the permitting process. Since there are no state regulations governing hazardous waste disposal, the Agency currently develops appropriate hazardous waste disposal criteria during the permitting process on a case-by-case basis. It is expected that permitting the disposal of FGD sludge as a non-hazardous waste will be in accordance with established procedures which should be less complex.

Amending the state regulations to be consistent with RCRA entails obtaining approval of the state legislature. The Agency is currently drafting an amendment to Chapter 7 of its regulations concerning hazardous wastes and will present the proposed regulatory amendment to the legislature for approval when the draft amendment is finalized. It is anticipated that these draft regulations will be consistent with existing EPA regulations.

Indiana

The State of Indiana's solid waste management program is based on two laws, both of which became effective in 1971: the Refuse Disposal Act, Indiana Code (IC) 19-2-1; and the Environmental Management Act, IC 13-7. The Refuse Disposal Act outlawed open dumping in the State. Designed to prevent water and air pollution, the Environmental Management Act empowered the Indiana Stream Pollution Control Board (SPCB) to regulate solid waste disposal activities. The SPCB authorized the Solid Waste Management Section of the Indiana State Board of Health to draft regulations concerning solid waste disposal. These regulations, SPC-18, define permitting procedures and standards of operation for sanitary landfills, refuse processing facilities and hazardous waste disposal.

Evaluation of a potentially hazardous waste is performed on a case-by-base basis by the Solid Waste Management Section in conjunction with the Water Pollution Control and Air Pollution Control Divisions of the Indiana State Board of Health. The Solid Waste Management Section will classify FGD sludge according to criteria established in SPC-18. The definition of hazardous waste as listed in SPC-18 states that any solid or liquid waste with inherent dangers including, but not limited to, toxic chemicals will be classified as a hazardous substance. Also, any sludge containing less than 30 percent solids is classified as hazardous. In view of the moisture content and the possible heavy metal content of FGD sludge, some may be classified as hazardous under this current state procedure.

If determined to be non-hazardous, a permit for an FGD sludge disposal site can be obtained by following the standard three-phase procedure. First, following approval of the local zoning authority, a request should be made to the Solid Waste Management Section for a preliminary site approval and recommendations for soil boring locations. Second, an application for a construction permit should be submitted. This application includes site construction plans and operating procedures which must be in accordance with specifications outlined in SPC-18. Third, following construction, an operating permit application should be submitted. After inspecting the facility to ensure construction in accordance with the approved plans, the Solid Waste Section will issue the operating permit. However, this permit must be renewed every two years.

This procedure is also followed in approving hazardous waste disposal sites. However, more detailed information (particularly on the quality and quantity of the waste) and the written approval of the SPCB are required.

The State of Indiana plans to apply to the EPA for interim and final authorization of its program to regulate hazardous wastes. To this end, the SPCB is drafting an amendment to the Environmental Management Act. Passage of this amendment is anticipated in 1980 with the development of the associated regulations to follow shortly thereafter.

West Virginia

The Code of West Virginia does not specifically address the regulation of industrial solid waste. The State Board of Health has had primary jurisdiction over solid waste management. However, the regulation of industrial solid wastes, including FGD sludge, has recently been transferred to the Department of Natural Resources (DNR). While existing state regulations do not specifically address FGD sludge, a state permit is required for its disposal. DNR's review does not entail an evaluation of the detailed design of the disposal site. However, a public notice is required and a site investigation is usually conducted by DNR personnel.

West Virginia is seeking authorization to enforce the waste management programs under RCRA. It is anticipated that the DNR will maintain jurisdiction over non-hazardous as well as hazardous industrial wastes. The DNR is awaiting EPA's final regulations before drafting state regulations to administer the RCRA programs.

Kentucky

In 1968, the State of Kentucky enacted its original solid waste act, Kentucky Regulatory Statute (KRS) 224, which empowers the Kentucky Department for Natural Resources and Environmental Protection to manage solid waste disposal. In order to carry out its responsibilities under this law, the Department promulgated regulations in 1975 which define disposal methods and permitting procedures for non-hazardous waste disposal facilities. Within the Department, the Division of Solid Waste administers and regulates all phases of solid waste disposal including plan and specification approval, operational techniques, design criteria and permitting procedures.

KRS 224 was amended in 1978 to include provisions for the proper disposal of hazardous wastes, although the associated regulations have not yet been promulgated. The recent amendment (Section 855 of KRS 224) states that no solid waste disposal site in the State of Kentucky can be permitted to accept hazardous wastes without the consent and approval of the majority of the State Congress and the Governor of Kentucky. Before an application to locate such a facility can be submitted before the Senate, it must be approved by the Secretary of the Department of Natural Resources and Environmental Protection. Departmental approval can be gained only by submission of a

comprehensive environmental impact statement and public hearings must be held in the county where the proposed facility is to be located. Currently, there are no landfill facilities in Kentucky which are permitted to dispose hazardous wastes.

The Department regulates solid waste by authority of existing regulations and new sections of the revised law (KRS 224) relating to hazardous wastes. Various solid wastes are evaluated on a case-by-case basis to determine if the material is hazardous or non-hazardous according to the results of a leach test. Section 855 of KRS 224 will govern those materials classified as hazardous. Since FGD sludge has been classified by EPA as non-hazardous, the material will be considered suitable for disposal in accordance with existing state regulations. In order to permit a new FGD sludge disposal facility, an application to construct and/or operate a landfill must be submitted to the Division of Solid Waste.

A preliminary application to construct and/or operate a landfill must include all appropriate information (geological, hydrogeological, operational details and specific location). If the information is sufficient, the Division will review the preliminary application and decide if the facility is necessary. Upon this decision, the Division will request a full application including an engineering plan according to design criteria listed in the State regulations. The applicant must demonstrate financial responsibility by posting a fully prepaid bond for the operating life of the landfill and at least two years. If favorably reviewed by the Division, a permit to construct will be issued. Following a satisfactory inspection by a Department representative, the permit to construct automatically becomes a permit to operate. Permits are valid for one year and application for renewal of the permit should be made not less than six weeks prior to its expiration date.

As previously mentioned, KRS 224 was amended to cover the disposal of hazardous wastes. The regulations have been completed in draft form and the Kentucky Department for Natural Resources and Environmental Protection plans to submit these regulations to the State Senate for emergency promulgation. These draft regulations are equivalent to and no more stringent than those developed under RCRA. No modification of these draft regulations is anticipated unless induced by further changes in EPA regulations.

Tennessee

Solid waste disposal in this State is regulated by the Tennessee Solid Waste Disposal Act adopted in 1969. This law provides for the safe and sanitary processing and dis-

posal of solid wastes and the development of long range plans to coordinate a statewide program of efficient solid waste disposal. Tennessee Solid Waste Disposal Regulations, which were promulgated in 1971, describe methods for planning, constructing, operating and maintaining solid waste processing and disposal systems. Hazardous waste control was authorized by the Tennessee Hazardous Waste Management Act of 1977. This law provides for safe storage, transportation, treatment and disposal of hazardous wastes and the development of long range plans coordinating a statewide hazardous waste management program. Responsibilities for enforcing and controlling solid and hazardous wastes have been delegated to the Division of Solid Waste Management, Tennessee Department of Public Health. In 1978, this Division published draft hazardous waste regulations to implement a program of hazardous waste management controlling the waste from the point of generation to the point of ultimate disposal. These proposed regulations parallel EPA's regulations in many respects, but in general, are not as detailed or rigid.

As with most states, it is anticipated that Tennessee will classify FGD sludge as non-hazardous. The current authority of the Division does not extend to non-hazardous waste disposal operations conducted on the waste generator's property. Therefore, on-site disposal of FGD sludge which has been classified as non-hazardous is not currently subject to state regulation. However, a clause expanding State jurisdiction over on-site waste disposal is planned for amending the Solid Waste Disposal Act in the next session of the State Congress. The proposed disposal site must be evaluated by the governing zoning board and the controlling transportation authority. Approval must be granted from both authorities and authentication of approval must be supplied with the application to the Division of Solid Waste Management. After receiving approval from these authorities, application for registration to operate a solid waste disposal facility can be made in writing to the Department of Public Health. This application will include specific design, construction, operation and closure information. Written approval must be granted by the Department before operation of the facility can commence.

Specific regulations are currently proposed concerning hazardous waste disposal. While not expected to affect FGD sludge disposal, these proposed regulations will require a lengthy approval process for hazardous waste disposal facilities. Successive approvals are required for the following steps: (1) a preliminary site application, (2) an engineering report, (3) construction and operation plans, and (4) certification of construction in accordance with approved plans. The proposed regulations are in the process of being revised to address public comments. Follow-

ing this revision, the State intends to promulgate their draft hazardous waste regulations even though all federal regulations have not been finalized. The Division anticipates that additional changes to be consistent with federal requirements, if necessary, can be incorporated into the proposed state regulatory program.

North Carolina

The Solid Waste Management Act, Article 13B of Chapter 130, General Statutes of North Carolina authorized the North Carolina Department of Human Resources to promote sanitary processing, treatment, disposal, and overall management of solid waste. Originally passed in 1969, this act has been subsequently revised to provide for regulation of hazardous wastes in accordance with RCRA. Current state regulations promulgated under the act are known as the Solid Waste Management Rules of the North Carolina Administrative Code which define the specific procedure necessary to obtain permits for solid waste disposal sites. However, regulations concerning hazardous wastes have not yet been drafted.

Within the Department of Human Resources, the Solid Waste and Vector Control Branch of the Division of Health Services administers the solid waste regulations. In obtaining a permit for FGD sludge disposal, this material may require testing using the EPA extraction procedure. Assuming that the sludge is classified as non-hazardous, a site approval and operational plan approval will be required. The application for site approval must contain hydrologic and geologic information. The subsequent application for operational plan approval must contain explicit operational plans with provisions for controlling runoff and erosion. These applications should be accompanied by a report which describes types of wastes to be disposed, anticipated lifetime and projected uses for the site. Prior to permit issuance, a written approval of the sedimentation control plan for the proposed site is required from the North Carolina Sediment Control Commission.

Wastes classified as hazardous will be subject to a more complicated permitting process. While State regulations concerning hazardous wastes have not yet been promulgated, it is anticipated that they will be modeled after the federal regulations. While these regulations are not complete, the permitting procedure for non-hazardous wastes will be utilized. Provisions dictated by the specific nature of the waste will be addressed on a case-by-case review of the required applications.

Missouri

The Missouri Solid Waste Management Law of the Revised Statutes of Missouri was originally enacted in 1973 and was superseded by a similar law in 1975. This law established procedures for obtaining permits and operational procedures for solid waste disposal facilities. Regulations pertaining to this law, known as the Missouri Solid Waste Rules and Regulations, became effective in 1973 and were amended in 1976. The Missouri Department of Natural Resources has been authorized to implement and enforce these regulations which describe the specific methods for obtaining permission to conduct solid waste disposal operations. Since the Solid Waste Management Law preceded the Resource Conservation and Recovery Act (RCRA), changes in this legislation were required to be consistent with RCRA. To this end, the Missouri Hazardous Waste Management Law was passed in 1977. This law controls all phases of hazardous waste disposal, from generation to ultimate disposal. Regulations pursuant to the hazardous waste law have recently been adopted by the State but have not yet been published for circulation to the general public.

The State of Missouri has taken a firm stand on the disposal procedures for FGD sludge. Fly ash and FGD sludge were specifically exempted from the definition of hazardous waste since the newly adopted regulations were deemed to be unnecessarily complex for the voluminous quantities of FGD sludge. Therefore, FGD sludge disposal will be governed by the Missouri solid waste laws and regulations. According to state regulations, FGD sludge would be categorized as a special waste which requires handling procedures other than those normally used for municipal wastes. However, EPA's elimination of the special waste category may, in turn, result in changes in the state's categorization of these wastes.

To permit the disposal of FGD sludge, a written request should be submitted to the Department requesting permission to apply for a special operating permit. The request should explain in detail the characteristics of the waste and a justification for proposing design and operating procedures other than those provided for in the solid waste regulations. If the site meets Department criteria, detailed plans and data for the design and operation of the facility should be submitted to the Department for approval, along with an application for a permit to operate a special waste facility. These plans should include a section describing methods used in maintaining records and monitoring the environmental effects of the facility. Approval to locate a special waste disposal facility should be obtained from the local zoning authority. Once all procedures necessary to obtain a permit are fulfilled, the permit

will be granted by the Department. In issuing the permit, the Department may specify certain restrictions or may require alterations to the design and operation plans if it is deemed necessary to protect public health and minimize environmental damage.

Alabama

Solid waste disposal in the State of Alabama is governed by the Solid Wastes Disposal Act, which was adopted in 1969 and amended in 1971. The Alabama Rules and Regulations for Solid Waste Management, which were promulgated under the Solid Wastes Disposal Act, provide for proper storage, collection, transportation, treatment and disposal of solid wastes. Responsibility for enforcing the solid waste rules and regulations was assigned to the Division of Solid Waste and Vector Control of the Alabama Department of Public Health. In 1978, the State of Alabama adopted its Hazardous Wastes Management Act which endowed the Division of Solid Waste and Vector Control with the regulatory authority to manage the disposal of hazardous wastes. Regulations pursuant to the hazardous waste law have been drafted and presented to the general public for review and comment, but have not yet been adopted.

The definitions of solid waste and hazardous waste, as presented in the respective laws, do not explicitly classify FGD sludge as a hazardous or non-hazardous waste. Therefore, a toxicant extraction procedure may be required to allow classification. In view of EPA's classification of these wastes as non-hazardous, Alabama will likely follow suit. As such, the portion of the Solid Waste Management Regulations pertaining to semi-solid wastes would govern their handling in special landfills and treatment lagoons. These special disposal methods must be capable of fulfilling the basic requirements of proper and safe landfill disposal as approved by the Division of Solid Waste and Vector Control.

To request approval of the Division to develop a disposal site, an applicant must submit a study of the proposed site prepared by the local Soil Conservation Service, a location map with pertinent information, and an identification of types of waste to be disposed. Upon receipt of this information, the Division will request the State Geologic Survey to assist in determining the geological and hydrological suitability of the site. If the Geologic Survey and the Division approve the site, operational plans must be submitted to the Division for approval. Before operation of the facility can proceed, the Division inspects the site to insure compliance with the operational plan. If compliance is indicated by the inspection, a license to operate will be granted by the Division of Solid Waste and Vector Control.

Since State hazardous waste regulations are not yet in effect, the Division of Solid Waste and Vector Control currently can regulate hazardous waste disposal by authority of the Hazardous Wastes Management Act. This State law requires that a permit to construct and a permit to operate a hazardous waste facility must be obtained from the Division and a prepaid bond to ensure proper perpetual care must be submitted to the Division. The completed construction site will be investigated by Division personnel to ensure that the facility complies with the permitted construction plan.

The Division of Solid Waste and Vector Control will submit the draft hazardous waste regulations to the State Congress for approval. If this approval is granted prior to promulgation of the federal RCRA regulations, the Division will make the necessary changes to their regulations as dictated by the final EPA rules.

Appendix C

CASE HISTORIES
SITE SELECTION AND PERMITTING

OVERVIEW

A review of the experience of eight utilities in selecting disposal sites and obtaining the required permits is presented in the following case histories. Supplementing the general guidance provided in Section 6 - SITE SELECTION, these case histories describe the actual procedures used and the associated problems encountered by utilities in selecting and permitting disposal sites. By relating these various case histories, it is hoped that the experience of the selected utilities in resolving site specific concerns will prove to be useful to other utilities faced with similar situations. Furthermore, certain aspects, which are generally consistent nationwide (e.g., applying for discharge permits under the National Pollutant Discharge Elimination System), should provide guidance to many utilities.

The time requirements for selecting and permitting the disposal sites of these utilities varied from approximately six months to three years. Factors affecting the time period included delays in permit review by government agencies (permitting agencies as well as commenting agencies) and opposition from local citizens.

In recognition of the diversity of utility waste disposal practices, the case histories were selected in consideration of the following influential factors:

- Geographical regions (arid or non-arid)
- Disposal methods (pond, landfill or mine)
- Waste characteristics (fixed or unfixed)

These factors as represented by the following case histories are depicted in Table C-1.

CHOLLA STATION, ARIZONA PUBLIC SERVICE COMPANY

The Cholla Station is located in a relatively flat desert region near Joseph City, Arizona. Unit 1, rated at 116 MW, began commercial operation in 1962 and was retrofitted with a two-stage limestone scrubber in 1973. Units 2 and 3 are both rated at 250 MW. Unit 2, which began producing power in 1978, is also equipped with a limestone scrubber, while Unit 3, scheduled for operation in 1980, will control flyash

Table C-1

PERTINENT CHARACTERISTICS OF SELECTED CASE HISTORIES

UTILITY	STATION	GEOGRAPHIC REGION		DISPOSAL METHOD			WASTE CHARACTERISTICS	
		Arid	Non-Arid	Pond	Landfill	Mine	Fixed	Unfixed
Arizona Public Service	Cholla	X		X				X
Northern States Power	Sherburne		X	X				X(1)
Minnkota Power Cooperative	Milton R. Young	X				X		X
Alabama Electric Cooperative	Tombigbee		X	X				X
Pennsylvania Power	Bruce Mansfield		X	X			X	
Duquesne Light	Elrama		X		X		X	
Indianapolis Power & Light	Petersburg		X		X		X	
Springfield City Utilities	Southwest		X		X			X(2)

(1) Oxidized Sludge

(2) Stabilized with flyash

with electrostatic precipitators. Units 4 and 5, which are due for operation in 1983 and 1985, respectively, are planned to have a capacity of 350 MW and are to be equipped for SO_2 and flyash emissions control.

Scrubber sludge is pumped without processing to the disposal pond in a common pipeline with flyash. The selection of this disposal area was simplified by the availability of open land around the plant. The selected site was chosen from four candidate sites based on criteria which included regulatory constraints.

The light rainfall and high potential evaporation of the area preclude the need for a discharge from the disposal site. Since there is no discharge, an NPDES permit was not required. However, a number of permits were required from various state agencies. The Arizona State Health Department required a permit for the station's sewage treatment plant, which discharges to the sludge pond, and a permit for the solid waste disposal site. The Arizona Water Commission required a permit for the impoundment structure to ensure its safety. Also, the Arizona Department of Highways required a permit for the pipeline which crosses under the interstate highway located between the power plant and the disposal area.

A certificate of Environmental Compatibility on Units 2, 3, 4, and 5 was required from the State Siting Committee, a multi-agency group of approximately 18 persons. The certificate for Units 2 and 3 covered the entire plant, and specifically addressed issues relating to proposed and existing solid waste practices. Units 4 and 5 will use the common ash facilities. In issuing this certificate, the Committee imposed the following conditions:

- The disposal area should not be located within the 100-year floodplain.
- The disposal area should be located within a reasonable proximity to the plant to enable service for all the solid waste disposal needs of the plant.

SHERBURNE STATION, NORTHERN STATES POWER COMPANY

Sherburne Station, located in a relatively flat, rural area of Minnesota, has a generating capacity of 1480 MW. Units 1 and 2, which came on-line in 1976, are equipped with two-stage scrubbers for flyash and SO_2 removal. Following mechanical thickening, sludge generated by the scrubbers is impounded in a nearby 60-acre pond which was lined with locally available clay.

Because of the availability of land at the selected plant site, the selection of the disposal site was not a particular problem. An evaluation of numerous sites was not necessary, since the selected site, being adjacent to the plant site, was the obvious choice. However, since the existing disposal area has an expected design life of only eight to ten years, planning for a new site will have to begin within the next few years.

The company employed a relatively novel approach in selecting the plant site - a citizens' advisory task force was organized prior to the determination of an exact location. Overall, the input from this group was found to be helpful and may have been instrumental in averting any delays due to public opposition. The public hearing, sponsored by the Minnesota Pollution Control Agency (MPCA), addressed the overall power plant project and the permits governing various aspects of this project. This coordinated approach was maintained by the MPCA in issuing the required permits.

MPCA was the primary permitting authority governing the waste disposal site. Among the most complex applications was the one submitted for a solid waste disposal permit. This application had to be accompanied by detailed design information. The MPCA also issued the NPDES permit which covers the wastewater discharges from the plant including the blowdown from the scrubber system. However, since all of the supernatant from the pond is recycled to the scrubbers, no discharge from this system has been required. An air quality installation permit was also required from the MPCA. This permit briefly addresses the sludge disposal system.

Obtaining these and other power plant permits required approximately nine months. While this time period may appear short by today's standards, it accounted for a construction delay of approximately three months. However, this delay was made up during the construction period and initial operation was on schedule.

MILTON R. YOUNG STATION, MINNKOTA POWER COOPERATIVE, INC.

This station, a mine-mouth plant located near Bismarck, North Dakota, is comprised of two units which burn lignite from the nearby surface mines. Unit 1, which began commercial operation in 1970, is rated at 235 MW and is equipped with an electrostatic precipitator (ESP). Unit 2, which began commercial operation in 1977, is rated at 439 MW. This unit is equipped with an ESP and scrubbers which utilize the alkaline flyash collected by the ESPs. Solids in the two scrubber modules are controlled by bleeding to a thickener. The thickener underflow is pumped to two rotary

vacuum filters. Off-road trucks haul dewatered sludge, as well as bottom ash and excess flyash, to the mine pits where the lignite has been removed. After disposal of the sludge and ash, reclamation of the mined-out areas continues, with replacement of the overburden, followed by subsoil, topsoil, mulching and seeding. Large tracts of previously mined land have been restored to productive agricultural use.

Since the heat content of lignite is considerably lower than that of most coals, a larger volume must be burned for an equivalent output of power. In view of this, proximity to the lignite reserves was an important criteria in the selection of a site for the Milton R. Young Station. Since a mine-mouth plant site was selected, the obvious and preferred method of waste disposal was to return the sludge and ash to the point of origin of the lignite. Since this method was found to be viable and acceptable, no further evaluation of disposal sites was necessary.

In order to obtain government approval of the disposal operation, Minnkota Power Cooperative, Inc. submitted a permit application to the North Dakota State Department of Health, Division of Solid Waste Management. Because disposal was to be in a mine, the North Dakota Public Service Commission, which administers and enforces state mining reclamation laws, became involved in the review process as a commenting agency. In accordance with the State's Solid Waste Management Regulations, a permit to construct and operate was issued approximately three months after application submittal. The permitting procedure was simplified to a degree because minimal site development was required for disposal and because of the lack of a discharge from the disposal area. As required by the North Dakota Solid Waste Management and Land Protection Act, the permit was re-evaluated and re-issued two years after the original approval. Future re-evaluations are anticipated.

TOMBIGBEE STATION, ALABAMA ELECTRIC COOPERATIVE, INC.
Located in a rural area near Leroy, Alabama, this station consists of three units. Unit 1, which was constructed in the late 1960's, is rated at 75 MW. Units 2 and 3, rated at 255 MW each, began operation in 1979 and 1980, respectively. Sulfur dioxide emissions from these new units are controlled by limestone scrubbers. Following mechanical thickening, the scrubber sludge is pumped to an on-site disposal pond.

In the development of the 200-acre power plant site, future expansion was anticipated. However, since the need for disposal of scrubber sludge was not envisioned, land availability became a concern. While an alternate site approximately one mile from the plant was considered, a disposal site adjacent to the plant was selected.

Development of this site entailed acquiring additional property and overcoming certain regulatory constraints.

Since part of the disposal area was to be located in a wetlands area, a 404 permit was required from the Army Corps of Engineers. In order to satisfy the U.S. Fish and Wildlife Service, an agency which comments on Corps permits, the Coop proposed mitigating measures. These measures included the purchase of a wetland area at another location for use by this agency. Public hearings were held as part of the permit review process. Since no public objections were voiced and since a negotiated settlement was achieved with the Fish and Wildlife Service, the permit was issued.

An NPDES permit covering all of the wastewater discharges from the plant was issued from the regional office of the EPA. Obtaining this permit entailed legal arbitration at an adjudicatory hearing. Following resolution of the contested issues, primarily monitoring requirements, the NPDES permit was issued.

The Alabama Pollution Control Commission required a permit for the air emissions. In this permit there was some discussion of the solid waste disposal area. However, this coverage was considered incidental.

The time period required for obtaining the various permits was approximately 15 months. Since this length of time was unanticipated in the overall project schedule, a delay in the construction schedule resulted.

BRUCE MANSFIELD PLANT, PENNSYLVANIA POWER COMPANY

The Bruce Mansfield Plant was constructed for the CAPCO Group at Shippingport, Pennsylvania. Operated by the Pennsylvania Power Company, this station consists of three 917 MW coal fired units. Unit 1 was fired in 1975, Unit 2 in 1977; Unit 3 is scheduled for commercial operation in 1980. Units 1 and 2 are equipped with two-stage wet scrubbers for flyash and SO_2 removal. Flyash will be controlled by electrostatic precipitators upstream of the wet scrubbers for Unit 3. The scrubber bleed stream from Units 1 and 2 is pumped to a thickener at the plant site. Calcilox , a fixating agent developed by Dravo Lime, is then added to the thickener underflow prior to pumping seven miles to the disposal site. In traversing part of this distance to the 1400 acre disposal site, the company utilized an abandoned railroad right-of-way. Site preparation included the construction of a 400-foot dam to provide storage capacity for approximately 25 years.

The process of selecting the disposal site, which was conducted by Dravo Lime, began after the power plant site had been determined. The selection criteria included the following: adequate capacity, low public visibility, obtainable property, and easy access. The selected site in the Little Blue Run Valley conformed to these criteria.

The coordinated permitting effort was initiated at a meeting with the Pennsylvania Department of Environmental Resources (DER). Attendance by representatives of various divisions of the Department was helpful in identifying the majority of the permits required. In addition to the State permits, federal and local approvals were required for the disposal site. Federal approval came from the U.S. Environmental Protection Agency which issued a permit under the National Pollutant Discharge Elimination System (NPDES) for the discharge of supernatant from the impoundment. A State permit for this discharge was also required from DER, which later received delegation of the NPDES program from the EPA.

Since the disposal site crossed the State boundary, solid waste disposal permits were required from both Pennsylvania and West Virginia. One notable aspect of the DER permit was the requirement for groundwater monitoring. The monitoring program, which entailed the construction of numerous wells around the site, was found to be satisfactory to both states. Also required from DER were permits for the dam and for soil erosion and sedimentation control. As part of the process of obtaining the State permits, legal notices concerning the proposed disposal operation were required in the Pennsylvania Bulletin (a State publication) and in local newspapers.

The location of the impoundment was such that a road and utility lines had to be relocated. The road relocation required a permit from the Pennsylvania Department of Transportation which stipulated that the new road be built according to State specifications. Approval from the Pennsylvania Public Utility Commission was required for the relocation of utility lines, which belonged to one of the CAPCO member utilities.

Obtaining the local approvals was not without obstacle. Upon disclosure of the plans for constructing the disposal site, local Township officials passed an ordinance restricting such disposal activities. At local public meetings for discussion of this project, residents expressed concern over the use of township roads. Following resolution of these concerns, the request for a zoning variance was approved and a building permit was issued.

As part of the public relations effort, an environmental evaluation of the selected site was performed by an independent consulting firm. While not required, the resulting report proved to be valuable in satisfying many questions raised by local interest groups and by the permitting agencies.

The total time required for obtaining the permits was approximately two years. However, at the time construction was scheduled to begin, all of the necessary approvals were not yet in hand. Therefore, in order to prevent the postponement of construction, preliminary approval for some of the construction work was obtained, while awaiting final permit issuance.

ELRAMA POWER STATION, DUQUESNE LIGHT COMPANY

The four units at this plant, which have a combined rating of 510 MW, were constructed in stages approximately thirty years ago. These units are individually equipped with mechanical collectors and electrostatic precipitators for flyash removal. Sulfur dioxide emissions are controlled by lime scrubbers, which were retrofitted to the power plant in 1975. The scrubber bleed is pumped to two thickeners which are operated in parallel by Duquesne Light Company. Processing of the sludge from this point on is the responsibility of IU Conversion Systems, Inc. (IUCS). The settled sludge from the thickeners is pumped to IUCS vacuum filters for dewatering. The filter cake is then mixed with flyash and lime, and stockpiled at the processing facility prior to transport by truck to the landfill. Final stabilization does not take place until the processed material is properly placed and cured in the landfill.

In addition to owning and operating the stabilization facility, IU Conversion Systems, Inc., was retained to provide total management and technical direction for site selection, permitting, design and operation. IUCS, through competitive bidding, selected a sub-contractor to transport and dispose of the treated materials to a Pennsylvania Department of Environmental Resources (DER) approved site. Located approximately 10 miles from the power station, this site is adjacent to an inactive surface mine. The site, which also receives the bottom ash from the plant, is expected to have a design life of ten years with expansion potential for additional capacity.

Two State permits were required from DER for the site. The solid waste disposal permit addressed the landfill design, the waste characteristics and the landfill operation, including a groundwater monitoring program. The water quality management permit

established effluent limitations and monitoring requirements for the sedimentation pond outfalls. Prior to issuing the permits, DER required that a bond be provided to insure final closure of the site. The bond is in the amount of $5,000/acre utilized.

Local approvals were not an obstacle in obtaining the permits, and disposal operations began in November, 1978. From the time of application submission until permit issuance, approximately one year had elapsed.

PETERSBURG STATION, INDIANAPOLIS POWER AND LIGHT COMPANY

Of the three units at this plant, only the third, a 532 MW unit which became operational in 1977, is equipped for flue gas desulfurization. Electrostatic precipitators are installed upstream of the limestone scrubber. The scrubber bleed stream is pumped approximately 3,000 feet to sludge thickeners. The thickener underflow is pumped to a sludge storage tank then to vacuum filters, which are contracted from IU Conversion Systems, Inc. and operated by station personnel. Employing the IUCS process, the sludge is mixed with flyash and lime. The fixed sludge is then transported by truck to the disposal area which is on the power plant site.

Selection of the disposal site was simplified by the availability of adequate land on the station site. The existing landfill area has sufficient capacity for seven to ten years. However, the company currently is planning to utilize additional on-site property for a second phase disposal area.

The Indiana Stream Pollution Control Board (SPCB) was the primary permitting authority governing this waste disposal project. In order to obtain approval of the SPCB, the company submitted a solid waste permit application which included a plot plan, conceptual design and waste characteristics information. The SPCB granted approval with the following conditions:

1. Drainage ditches and sedimentation basins shall be installed for runoff control.
2. If a leachate problem develops, corrective action shall be taken.
3. A plot plan of the final topography shall be submitted to the state.
4. At the completion of each phase of the disposal site, the fill shall be covered with a two foot layer of soil and revegetated.

The discharge of runoff from the disposal site requires a National Pollutant Discharge Elimination System (NPDES) permit which is required for the other power plant discharges as well.

SOUTHWEST POWER STATION, SPRINGFIELD CITY UTILITIES

This power station consists of one 194 MW unit which began commercial operation in late 1976. Flue gas from the unit is cleaned by limestone scrubbers with upstream high efficiency electrostatic precipitators. The scrubber bleed is diverted to a thickener in which a polymer is added to aid in solids separation. Upon reaching the proper solids concentration, the thickener underflow is pumped to a vacuum belt filter for further dewatering. The filter cake is then mixed with flyash prior to truck transport to the landfill.

The existing landfill, located approximately one-fourth mile from the power plant, was developed to serve the immediate, short-term needs of the power plant. The selection of this site, as well as future disposal areas, was a consideration in locating the power plant. Situated in a rural area, land availability was not anticipated to be a problem. The utility is currently conducting subsurface investigations at a potential long-term site approximately one half mile from the plant.

There are two permits, both issued by the Missouri Department of Natural Resources (DNR), associated with the disposal area. The solid waste disposal permit, issued by DNR's Solid Waste Commission, entailed the submission of information on waste characteristics and on the site - including subsurface data. Detailed design information also accompanied this application. In view of the site's limited capacity and of concerns over adequate groundwater protection, the DNR issued a temporary experimental permit for this site. During the initial years of operation, groundwater monitoring is being conducted to ascertain the adequacy of the site liner which is comprised of flyash, lime and soil. The results of this program will provide guidance for the development of the long-term disposal site.

The other permit of concern was the NPDES permit issued by DNR's Clean Water Commission. This permit covers the discharges from the sedimentation pond below the landfill as well as other discharges from the power plant. Effluent limitations and monitoring requirements are stipulated for each of the discharges in this permit.

These permits were among those required for the power plant project. Submitted by the utility's engineering consultant, the time required for issuance was approximately one year.