REPORT

VOLUME I

FINAL REPORT

Technical Support for

the Ohio Clean Coal

Technology Program

Volume I, Baseline of
Knowledge Concerning
By-Product Characteristics

To

Ohio Coal Development Office

AUGUST 1989

CDO/R-88-LRI

1

FINAL REPORT

on

TECHNICAL SUPPORT FOR THE OHIO CLEAN COAL TECHNOLOGY PROGRAM
VOLUME I, BASELINE OF KNOWLEDGE CONCERNING
BY-PRODUCT CHARACTERISTICS

to

OHIO COAL DEVELOPMENT OFFICE

August 28, 1989

by

Robert Olfenbuttel
Sandra Clark
Eleanor Helper
Robert Hinchee
Charles Kuntz
Jeffrey Means
Joseph Oxley
Mark Paisley
Connie Rogers
William Sheppard
Lisa Smolak

BATTELLE
505 King Avenue
Columbus, Ohio 43201-2693

MASTER

Battelle does not engage in research for advertising, sales promotion, or endorsement of our clients' interests including raising investment capital or recommending investment decisions, or other publicity purposes, or for any use in litigation.

Battelle endeavors at all times to produce work of the highest quality, consistent with our contract commitments. However, because of the research and/or experimental nature of this work the client undertakes the sole responsibility for the consequences of any use, misuse, or inability to use, any information, apparatus, process or result obtained from Battelle, and Battelle, its employees, officers, or Trustees have no legal liability for the accuracy, adequacy, or efficacy thereof.

FOREWORD

This report was prepared for the Ohio Coal Development Office (OCDO) under Grant Agreement No. CDO/R-88-LR1 and comprises two volumes. Volume I presents data on the chemical, physical, and leaching characteristics of by-products from a wide variety of clean coal combustion processes. Volume II consists of a discussion of (a) process modification waste minimization opportunities and stabilization considerations; (b) research and development needs and issues relating to clean coal combustion technologies and by-products; (c) the market potential for reusing or recycling by-product materials; and (d) regulatory considerations relating to by-product disposal or reuse.

EXECUTIVE SUMMARY

Objectives and Approach

This report is a compilation of information regarding clean coal combustion technologies for the Ohio Coal Development Office. The objective was to establish baseline data on several issues pertaining to existing and emerging clean coal combustion by-products. The issues were addressed in this study as five separate tasks:

- Task 1: By-product composition and characteristics
- Task 2: Potential for by-product minimization through process modification, and stabilization
- Task 3: Identification of data needs and research issues for possible future study
- Task 4: Market potential for recovering or reusing by-products
- Task 5: The effect of current and potential environmental regulations on by-product disposal or reuse.

The data and evaluations provided herein are based primarily upon a review of existing literature and consultation with a considerable number of experts and authorities. The latter category included conversations and interviews with managers, chemists, and process engineers involved with ongoing clean coal combustion demonstration projects, as well as regulatory authorities and policy makers, both in Ohio and other select areas.

A brief summary of the findings of each of the five tasks is provided below.

Task 1: By-product Composition and Characteristics

A number of clean coal combustion demonstration projects are currently being conducted in Ohio. However, data on the physical, chemical, and leaching characteristics from these newly started operations are sparse

and will not be adequately defined until site-specific data are available. It will be advantageous to decision makers at OCDO, OEPA, and the utilities to ensure that this type of data is generated from ongoing and planned desulfurization demonstrations in Ohio. These data can be used to support the determination of the environmental impact of the by-products and their associated land disposal and reuse control requirements, which is also a recommendation of this report. The effect of variable amounts of sulfite and sulfate seems to be an especially important parameter to be studied.

Because of the limited amount of such data, data from non-Ohio locations utilizing non-Ohio coals were used to produce approximate computations. Insufficient data prevented a comprehensive statistical analysis. Compositions of by-products from clean coal combustion processes are similar, generally consisting of unreacted sorbent, sorbent-sulfur reaction products, and fly ash. The principal differences relate to the types of sorbents used, which are either calcium-based, calcium- and magnesium-based, or sodium-based. However, historical experience has shown that coal sites are not located based on sorbent variations. Moreover, there is variability among by-products as a function of coal type and/or process utilized.

Two of the processes identified are capable of producing significantly less waste in the form of elemental sulfur. Sulfur is essentially a nonleachable solid. The leachabilities of the calcium- and magnesium-based by-products appear to be within 30 times the U.S. Environmental Protection Agency's (EPA) primary and secondary drinking water standards, thus meeting a proposed standard. The sodium-based by-products would likely not meet such a standard because of their higher leachabilities; however, there do not appear to be sodium-based systems planned or underway in Ohio. The leaching data also show low metal concentrations, generally much lower than the EPA Resource Conservation and Recovery Act (RCRA) threshold values for the eight metals considered in the extraction procedure (EP) tests. This result is attributed to the low fly ash (and therefore metal) contents of the combustion by-products and the fact that leachates are typically alkaline, in which most metals have low solubilities.

Based on the results of EP toxicity tests and other hazard-identifying characteristics, it appears that the by-products are not toxic

and need not be treated as such. Solubility, however, is an issue. Further research using Ohio-based facilities and coal is needed, as identified in Chapter 3.

Task 2: Process Modification Opportunities

Economic reasons have caused some combustors in Ohio previously operating on high-sulfur coals to switch to other lower-sulfur fuels which are less expensive to use than higher-sulfur coals with added sulfur controls, a fact that forcefully illustrates the magnitude of the problem facing the State. For this reason, research on a number of innovative new technologies is being supported in an attempt to find a lower cost means of meeting sulfur dioxide emission goals when burning Ohio coals.

A simple spreadsheet was developed for calculating the amounts of by-products that would be produced from the six innovative new technologies that are currently being demonstrated by the State. These calculations show that a large portion of the total solid by-product produced comes from two sources: the coal ash itself and the unreacted sorbent. From this simple analysis alone, it becomes evident that methods for reduction of coal ash prior to use can have a significant impact on the total quantity of by-product produced at the site of combustion. Technologies within this category were not included in the scope of this baseline study.

Similarly, technologies that can reduce the required calcium-to-sulfur stoichiometric ratio can obviously have a large impact on the quantity of solid by-product produced. Some process considerations, however, must be balanced against the overall economics of the various processes. For example, power plants that use coal have as their first objective the production of electricity, preferably cleanly and with the least environmental impact. If the quality of by-products is high, all the better; however, production of low-cost electricity remains the priority.

Currently, some process improvements to boost the utilization of the sorbent and reduce the amount of generated by-product solids are being tested and/or planned as part of the various Ohio clean coal demonstrations. The HALT process, for example, is to be tested to determine if recycling of solids and modifications to improve the humidification systems will lower

the Ca/S stoichiometries and the amounts of by-product solids. The LIMB project is expected to investigate the possibility of using a solid by-product recycle system for reinjection of the by-products collected in the electrostatic precipitator to obtain increased utilization of its alkali values.

Aside from these considerations, the primary focus and objectives in the demonstrations are on maximizing the efficiency of sulfur dioxide capture while also maximizing electrical production efficiency and minimizing capital investment and operating costs. Most of the engineering for these systems is the result of considerable study and it is difficult to predict the degree to which further process improvements will increase efficiency and reduce solid by-products until these tests are carried out. Some process improvement research ideas germane to individual processes are identified in the Chapter 2 technology discussions, as well as generic recommendations covering development of a means to increase reagent reactivity and recycling of the by-product solids after suitable activation. One limitation, to developing further concepts for process modifications that could reduce solid by-product generation, is the current lack of available detailed process information on process design and results from the developers and vendors.

There are relatively few processes that can be considered for coal by-product stabilization. Five stabilization technologies are described in the report that have an applicability to clean coal combustion by-products in general.

Task 3: Research and Development Needs and Issues

The objectives of this task were to identify and evaluate opportunities for research and development that may assist in fostering the safe reuse of, and/or increase the ease of disposal for, clean coal combustion by-products. Some of the principal, but not all, issues and research data needs include the following:

By-product Characteristics

- Site-specific data on the physical, chemical, and leaching characteristics of by-products from new clean coal combustion processes that burn Ohio coal

- Characterization of the by-products produced upon use of chelates in scrubbing systems
- Documentation of data quality and methodology
- Data on the variability of by-product composition as a function of source coal composition and process parameters
- By-product stability versus system efficiency and the need for by-product stabilization
- Long-term stability of by-products in the environment.

Process Modification Opportunities

- Feasibility of increasing reagent reactivity
- Recycle of the by-product solids after suitable activation
- Detailed process analyses for by-product minimization improvement.

By-product Reuse Potential

- Support of private, noncommercialized development of processes to produce higher-value by-products (such as sulfur or sulfuric acid) at lower processing costs
- Demonstration of a postscrubbing forced-oxidation process optimized for making calcium sulfate instead of calcium sulfite
- Determination of the desirable and/or detrimental properties of synthetic gypsum relative to its potential use in commercial wallboard processing
- Determination of agricultural use throughout Ohio.

Regulatory Considerations

- Quantification of fate and effect of by-products in the environment
- Encouragement of reuse policy through environmental impact studies of by-product applications

- Encourage by-product reuse legislation
- Development of level of performance disposal criteria.

Task 4: Market Potential for By-product Reuse

This task examined the possibility of utilizing by-products directly as useful products or indirectly as raw material for making such products. The approach involved screening the potential markets for technical fit with the chemical composition of the by-products being considered and the size of the market relative to the production expected from an 800-MW generating unit. A more extensive market study, which considered demand, supply, pricing, and other relevant factors, was then conducted for promising alternatives.

A number of markets appear promising, including sulfur, sulfuric acid, gypsum, agricultural liming, and road base material.

- The sulfur and sulfuric acid markets would be satisfied by about 1,000 MW of capacity, operating half the hours of the year.
- As many as four 800-MW generating units producing gypsum by the chelated lime process followed by forced oxidation can potentially be supported by the market in Ohio. This presumes that by-product gypsum would be of suitable quality for wallboard manufacture.
- Five of the clean coal processes examined yielded by-product that can be used for liming soil and could command a price (before transportation) of as much as two-thirds that of ground limestone, or about \$2.70 per ton.
- Calcium-based by-products containing fly ash should be suitable for road base and fill, but not for surfacing unpaved roads or for use as aggregate in concrete or asphalt paving. The potential demand is large, but the price of competing limestone is only about \$3.50 per ton.

Task 5: Regulatory Considerations

Results of tests to characterize waste from clean coal technology processes have largely shown the wastes to be nonhazardous, as defined by RCRA. Given this fact, regulatory concern, particularly at the State level,

is focused on the long-term potential for release of toxic constituents from the waste, and the rates at which leaching may occur in disposed or reused by-products.

The Ohio EPA considers clean coal combustion by-products to be a solid waste, with exemptions granted to date on a case-by-case basis. However, in the continued absence of a more substantial data base on by-product environmental impact from which to make scientifically based decisions, public pressure and regulatory policy will continue to support a conservative, high level of disposal protection, leading to a continued rise in disposal cost. By resolving the environmental impact of by-product disposal and developing an associated clear set of clean coal facility permitting guidelines, the state could facilitate decision making regarding large-scale commercial construction of new or modified Ohio coal-fired generating plants. These actions can take into consideration the surrounding states of Pennsylvania, Kentucky, and West Virginia which have established differing positions on the regulation of these by-products. The ease of facility permitting within these states and Ohio can be a factor in future siting decisions by industry for commercial-scale construction projects.

Beneficial use of clean coal combustion by-products can become a more viable option to land disposal, but environmental legislation is needed to provide a vehicle for increased market support of options for by-product reuse.

x

TABLE OF CONTENTS

Page

VOLUME I

1.0 TASK 1: BASELINE OF KNOWLEDGE CONCERNING THE CHARACTERISTICS AND PROPERTIES OF OHIO CLEAN COAL COMBUSTION BY-PRODUCTS	
1.1 SUMMARY.....	1-1
1.2 INTRODUCTION.....	1-5
1.3 ADVANCED WET FLUE GAS DESULFURIZATION BY-PRODUCTS.....	1-6
1.3.1 General Process and By-product Description.....	1-6
1.3.2 Ohio Perspectives on Advanced Wet FGD By-products.....	1-6
1.3.3 Chemical Composition of Wet FGD By-products.....	1-8
1.3.4 Physical Properties of Wet FGD By-products.....	1-9
1.3.5 Leaching Results of Wet FGD By-products.....	1-10
1.4 ADVANCED DRY FLUE GAS DESULFURIZATION BY-PRODUCTS.....	1-12
1.4.1 General Process and By-product Description	1-12
1.4.2 Ohio Perspectives on Advanced Dry FGD By-products.....	1-12
1.4.3 Calcium Spray Dryer By-products.....	1-13
1.4.3.1 Chemical Composition.....	1-13
1.4.3.2 Physical Characteristics.....	1-14
1.4.3.3 Leaching Results.....	1-15
1.4.4 Dry Sodium Injection By-products.....	1-16
1.4.4.1 Chemical Composition.....	1-17
1.4.4.2 Physical Properties.....	1-17
1.4.4.3 Leaching Results.....	1-17
1.4.5 Lime/Limestone Injection By-products.....	1-18
1.4.5.1 Dravo HALT Injection Process.....	1-18
1.4.5.2 Coolside Process.....	1-19
1.4.5.3 Pressure-Hydrated Lime Injection.....	1-20
1.5 FLUIDIZED BED COMBUSTION BY-PRODUCTS.....	1-21
1.5.1 General Process and By-product Description.....	1-21
1.5.2 Ohio Perspectives.....	1-21
1.5.3 AFBC By-products.....	1-22
1.5.3.1 Chemical Composition.....	1-22
1.5.3.2 Physical Properties.....	1-23
1.5.3.3 Leaching Results.....	1-24

CONTENTS (Continued)

	<u>Page</u>
1.6 LIMB BY-PRODUCTS.....	1-25
1.6.1 General Process and By-product Description.....	1-25
1.6.2 Ohio Perspectives.....	1-25
1.6.2.1 Chemical Composition.....	1-25
1.6.2.2 Physical Data.....	1-26
1.6.2.3 Leaching Results.....	1-26
1.7 BY-PRODUCTS FROM OTHER CLEAN COAL TECHNOLOGY PROCESSES.....	1-28
1.8 REFERENCES.....	1-29

APPENDICES

APPENDIX A. DATA TABLES PERTAINING TO ADVANCED WET FLUE GAS DESULFURIZATION BY-PRODUCTS	
APPENDIX B. DATA TABLES PERTAINING TO ADVANCED DRY FLUE GAS DESULFURIZATION BY-PRODUCTS	
APPENDIX C. DATA TABLES PERTAINING TO FLUIDIZED BED COMBUSTION BY-PRODUCTS	
APPENDIX D. DATA PERTAINING TO LIMB BY-PRODUCTS	

TABLES

Table 1-1. Summary of Ohio's Clean Coal Combustion Demonstration Projects.....	1-2
Table 1-2. Summary of Typical By-product Compositions for Different Clean Coal Combustion Processes.....	1-3
Table A-1. Chemical Composition of Coal Ash - Major and Minor Elements (weight percent).....	A-1
Table A-2. Chemical Analysis of Lime-Based FGD By-products.....	A-2
Table A-3. Chemical Analysis of Limestone-Based FGD By-products.....	A-3
Table A-4. Identification of Chemical Phases of FGD Sludge.....	A-4
Table A-5. Trace Element Composition of FGD Sludge Solids (Concentration in ppm).....	A-5

CONTENTS (Continued)

		<u>Page</u>
Table A-6.	Equilibrium Concentrations of Trace Elements in FGD Sludge Leachate (ppm).....	A-6
Table A-7.	Solubilization of Metals and Chloride from Plant C By-product for Three pH Values (Double Alkali Process/ Ohio Coal).....	A-7
Table B-1.	Solids Leachate Analysis: 5-MW DOE-HALT Toronto Pilot (Lab Report).....	B-1
Table B-2.	Major and Minor Species in Spray Dryer By-products.....	B-2
Table B-3.	Concentrations of Major and Minor Species in By-products from Spray Dryer Systems.....	B-3
Table B-4.	Typical Calcium Spray Dryer By-product Compositions....	B-4
Table B-5.	Chemical Characterization of Spray Dryer Solids (mg/kg except where noted).....	B-5
Table B-6.	Trace Element Analyses of Calcium Spray Dryer By-product.....	B-7
Table B-7.	Trace Element Concentrations Found in By-products from Spray Dryer Systems.....	B-8
Table B-8.	Summary of Elemental Concentration Ranges in Eight Spray Dryer By-products.....	B-9
Table B-9.	Crystalline Species Identified in By-products from Dry Scrubbing Systems.....	B-10
Table B-10.	Summary of Elemental Concentration Ranges in RCRA EP Leachates and ASTM Leachate for Spray Dryer By-products (in mg/L).....	B-11
Table B-11.	RCRA EP Chemical Characterization of Spray Dryer By-products (mg/L except where noted).....	B-13
Table B-12.	Neutral Spray Dryer Leachate Chemical Characterization (mg/L except where noted).....	B-15
Table B-13.	TCLP Chemical Characterization of Spray Dryer By-products (mg/L).....	B-17

CONTENTS (Continued)

	<u>Page</u>
Table B-14. Chemical Characteristics of Raw and Spent Nahcolite....	B-18
Table B-15. Chemical Constituents in Dry Sodium Injection By-products.....	B-19
Table B-16. Physical Data for Dry Sodium Injection By-products.....	B-20
Table B-17. Chemical Composition of Coolside By-products.....	B-21
Table B-18. Leachate Compositions of Coolside By-products Generated With and Without the NaOH Additive.....	B-22
Table B-19. The Effect of Curing On Coolside Sludge Leachate Composition.....	B-24
Table B-20. EPA-EP Leaching Test Results for Fly Ashes from Pressure-Hydrated Lime Injection Tests Using Pittsburgh No. 8 Bituminous Coal	B-26
Table B-21. Maximum Allowable Levels of Leachate Contaminants for RCRA Hazardous Waste Classification	B-26
Table B-22. ASTM Leaching Test Results for Fly Ashes from Pressure-Hydrated Lime Injection Tests Using Pittsburgh No. 8 Bituminous Coal	B-27
Table B-23. Elemental Compositions of Fly Ashes from Pressure-Hydrated Lime Injection Tests Using Pittsburgh No. 8 Bituminous Coal	B-28
Table B-24. Mineral Compositions of Fly Ashes from Pressure-Hydrated Lime Injection Tests Using Pittsburgh No. 8 Bituminous Coal	B-29
Table B-25. Physical Properties of Fly Ashes from Hydrated-Lime Injection Tests Using Pittsburgh No. 8 Bituminous Coal	B-30
Table C-1. Analysis of Conventional PCF Fly Ash and PFBC Ash (weight percent as oxides).....	C-1
Table C-2. Conventional PCF Fly Ash and PFBC Ash EPA EP Toxicity Test Results.....	C-2
Table C-3. Conventional PCF Fly Ash and PFBC Ash ASTM D-3987-81 Leachate Test Results.....	C-3

CONTENTS (Continued)

		<u>Page</u>
Table C-4.	Summary of Elemental Concentration Ranges in Four AFBC Wastes.....	C-4
Table C-5.	Major Chemical Contents of AFBC Bed By-products from Six Units.....	C-5
Table C-6.	Trace Element Composition of an AFBC Bed Waste.....	C-6
Table C-7.	Results of X-Ray Diffraction Analyses of Five AFBC Bed Wastes.....	C-7
Table C-8.	Major Chemical Element Composition of AFBC By-product.....	C-8
Table C-9.	Trace Chemical Analyses of AFBC By-Products from Three Sites.....	C-9
Table C-10.	Characterization of AFBC Solids Before Leaching.....	C-10
Table C-11.	Calcium Species Percent Composition in AFBC By-products.....	C-11
Table C-12.	Radiochemical Analyses of Three AFBC Solid Residues.....	C-11
Table C-13.	AFBC By-product Physical Characteristics.....	C-12
Table C-14.	Summary of Physical Property Ranges in Four AFBC By-products.....	C-13
Table C-15.	Physical Properties of Three AFBC By-products.....	C-14
Table C-16.	Summary of Elemental Concentration Ranges in RCRA EP Leachates for AFBC By-products (in mg/L).....	C-15
Table D-1.	Chemical Analyses of Ash/Sorbent Mixtures Produced in SRI Combustor (weight percent).....	D-1
Table D-2.	Permeability Data for Consolidated LIMB Ash.....	D-2
Table D-3.	Leachate Data for Simulated LIMB Demonstration By-products from SRI Combustor.....	D-3

CONTENTS (Continued)

Page

VOLUME II

2.0 TASK 2: BASELINE OF KNOWLEDGE CONCERNING TECHNOLOGY FOR BY-PRODUCT MINIMIZATION OR STABILIZATION

2.1 SUMMARY.....	2-1
2.2 COMPUTER SIMULATION OF BY-PRODUCT GENERATION.....	2-3
2.3 CONTROL TECHNOLOGIES.....	2-10
2.3.1 Pressurized Fluidized Bed Combustion.....	2-10
2.3.2 Hydrate Addition at Low Temperatures.....	2-15
2.3.3 Advanced Wet-Lime Scrubbing.....	2-18
2.3.4 Limestone Injection in Multistage Burner.....	2-24
2.3.5 Electrostatic Precipitation with Injection.....	2-28
2.3.6 Reductive Desulfurization and Denitrification.....	2-31
2.3.6.1 The BSR Hydrogenation Process.....	2-31
2.3.6.2 The FLEXSORB SE PLUS Process.....	2-33
2.3.6.3 The Recycle Selectox Process.....	2-33
2.3.6.4 Catalyst Development.....	2-33
2.3.7 Alkalyzed Aluminate Flue Gas Treatment.....	2-34
2.3.8 Slagging Combustor with Limestone Injection.....	2-38
2.4 STABILIZATION PROCESSES.....	2-43
2.4.1 Approach.....	2-43
2.4.2 Stabilization Technologies.....	2-44
2.4.2.1 Calcilox® Process.....	2-44
2.4.2.2 Poz-O-Tec Process.....	2-44
2.4.2.3 Enviroclean Process.....	2-46
2.4.2.4 Terra Crete Process.....	2-46
2.4.2.5 Ames Granulation/Sintering Process.....	2-47
2.5 BY-PRODUCT PRODUCTION.....	2-49
2.6 REFERENCES.....	2-52

3.0 TASK 3: BASELINE OF KNOWLEDGE CONCERNING RESEARCH AND DEVELOPMENT NEEDS/ISSUES PERTAINING TO THE DISPOSAL OR REUSE OF COMBUSTION BY-PRODUCTS

3.1. INTRODUCTION.....	3-1
------------------------	-----

CONTENTS (Continued)

	<u>Page</u>
3.2 TASK 1: BY-PRODUCT CHARACTERISTICS.....	3-3
3.2.1 Site-Specific Characterization Data.....	3-3
3.2.2 Characterization of the By-products Produced Upon Use of Chelates in Lime Scrubbing Systems.....	3-4
3.2.3 Documentation of Data Quality and Methodology.....	3-4
3.2.4 By-product Variability as a Function of Source Coal and Process Parameters.....	3-5
3.2.5 By-product Stability Versus System Efficiency and the Need for By-product Stabilization.....	3-5
3.2.6 Long-Term Stability of By-Products in the Environment.....	3-6
3.3 TASK 2: PROCESS MODIFICATION OPPORTUNITIES.....	3-7
3.3.1 Means to Increase Limestone Reactivity.....	3-7
3.3.2 Recycle of the By-product Solids After Suitable Activation	3-7
3.3.3 Process Optimization.....	3-8
3.4 TASK 4: BY-PRODUCT REUSE POTENTIAL.....	3-9
3.4.1 Processes to Produce High Value By-products.....	3-9
3.4.2 Forced Oxidation of Calcium Sulfite in Chelated Systems...	3-9
3.4.3 Definition of the Parameters Associated with Synthetic Gypsum for Wallboard Manufacture.....	3-10
3.4.4 Road Aggregate.....	3-11
3.4.5 Agricultural Use.....	3-11
3.4.6 Reclamation Applications.....	3-12
3.4.7 Concrete Products.....	3-12
3.4.8 Landfill Uses.....	3-13
3.5 TASK 5: REGULATIONS ON CLEAN COAL COMBUSTION BY-PRODUCTS.....	3-14
3.5.1 Quantification of Fate and Effect of By-products in the Environment.....	3-14
3.5.2 Encourage Reuse Policy.....	3-14
3.5.3 Develop Level of Performance Disposal Criteria.....	3-14
3.5.4 Encourage By-product Reuse Legislation.....	3-15
3.5.5 Sponsor Multistate Symposium.....	3-15
 4.0 TASK 4: BASELINE OF KNOWLEDGE CONCERNING THE MARKET POTENTIAL FOR RECOVERABLE COMBUSTION BY-PRODUCTS	
4.1 SUMMARY.....	4-1
4.1.1 Sulfur and Sulfuric Acid.....	4-3
4.1.2 Gypsum.....	4-3
4.1.3 Agricultural Lime.....	4-3
4.1.4 Road Base.....	4-4

CONTENTS (Continued)

	<u>Page</u>
4.2 INTRODUCTION.....	4-5
4.2.1 Scope.....	4-5
4.2.2 Approach.....	4-6
4.2.2.1 Initial Screening.....	4-7
4.2.2.2 Final Analysis.....	4-8
4.3 INITIAL SCREENING.....	4-9
4.3.1 Sulfur.....	4-9
4.3.2 Sulfuric Acid.....	4-13
4.3.3 Gypsum.....	4-13
4.3.4 Ammonium Sulfate.....	4-14
4.3.5 Alum.....	4-14
4.3.6 Sulfur Dioxide.....	4-15
4.3.7 Ferrous Sulfate.....	4-15
4.3.8 Other Opportunities.....	4-16
4.4 POTENTIAL OPPORTUNITIES.....	4-17
4.4.1 Sulfur.....	4-17
4.4.1.1 Demand.....	4-17
4.4.1.2 Supply.....	4-18
4.4.1.3 Pricing.....	4-19
4.4.1.4 Outlook.....	4-20
4.4.2 Sulfuric Acid.....	4-21
4.4.2.1 Demand.....	4-21
4.4.2.2 Supply.....	4-23
4.4.2.3 Pricing.....	4-23
4.4.2.4 Outlook.....	4-25
4.4.3 Gypsum.....	4-26
4.4.3.1 Demand.....	4-27
4.4.3.2 Supply.....	4-30
4.4.3.3 Pricing.....	4-32
4.4.3.4 Outlook.....	4-33
4.4.4 Agriculture.....	4-34
4.4.4.1 Demand.....	4-35
4.4.4.2 Supply.....	4-37
4.4.4.3 Pricing.....	4-37
4.4.4.4 Outlook.....	4-38
4.4.5 Construction - Road Base.....	4-39
4.4.5.1 Demand.....	4-40
4.4.5.2 Supply.....	4-42
4.4.5.3 Pricing.....	4-42
4.4.5.4 Outlook.....	4-43
4.4.6 Construction - Stabilization.....	4-44
4.5 REFERENCES.....	4-45

CONTENTS (Continued)

Page

5.0 TASK 5: BASELINE OF KNOWLEDGE CONCERNING STATE AND FEDERAL REGULATORY REQUIREMENTS FOR BY-PRODUCT DISPOSAL OR REUSE

5.1 SUMMARY.....	5-1
5.2 INTRODUCTION.....	5-3
5.2.1 Clean Coal Technologies.....	5-4
5.2.1.1 Advanced Wet Flue Gas Desulfurization.....	5-4
5.2.1.2 Advanced Dry Flue Gas Desulfurization.....	5-4
5.2.1.3 Fluidized Bed Combustion.....	5-4
5.2.1.4 Limestone Injection Multistage Burner.....	5-5
5.2.2 U.S. Department of Energy Waste Management Program.....	5-5
5.3 ENVIRONMENTAL REGULATIONS.....	5-7
5.3.1 Background for the Current Regulatory Environment.....	5-7
5.3.1.1 Federal Regulations.....	5-7
5.3.1.2 State of Ohio Regulations.....	5-9
5.3.1.3 Surrounding States' Regulations.....	5-11
5.3.2 Effects of Environmental Regulations On Ohio Clean Clean Technologies.....	5-13
5.4 FUTURE ENCOURAGEMENT OF BY-PRODUCT REUSE.....	5-14
5.4.1 States' Policies.....	5-16
5.5 CONCLUSIONS.....	5-18
5.6 REFERENCES.....	5-20

TABLES

Table 2-1.	Predicted By-product Generation Rate for the E-SO _x Process.....	2-4
Table 2-2.	Predicted By-product Generation Rate for the LIMB Process.....	2-4
Table 2-3.	Predicted By-product Generation Rate for the HALT Process.....	2-5
Table 2-4.	Predicted By-product Generation Rate for the Lime Chelate Process.....	2-5

CONTENTS (Continued)

		<u>Page</u>
Table 2-5.	Predicted By-product Generation Rate for the Pressurized Fluidized Bed Process.....	2-6
Table 2-6.	Predicted By-product Generation Rate for the TRW Slagging Combustor Process.....	2-6
Table 2-7.	Cost Reduction Objectives - Advanced Versus Conventional Wet Flue Gas Desulfurization System.....	2-22
Table 3-1.	Summary of R&D Needs/Issues Pertaining to Disposal or Reuse of Ohio Clean Coal Combustion Products.....	3-2
Table 4-1.	Match Between Processes and Uses.....	4-2
Table 4-2.	Typical By-product Yields Based on 15.0 Percent Ash, 3.5 Percent Sulfur and 12,500 BTU/LB Coal.....	4-10
Table 4-3.	Price of Sulfuric Acid in Various Locations.....	4-24
Table 4-4.	Sulfuric Acid Plants in Ohio and Nearby Areas.....	4-25
Table 4-5.	Commercial Grade Gypsum Specifications.....	4-28
Table 4-6.	Value of Gypsum, United States and Ohio.....	4-32
Table 4-7.	Agricultural Uses of Lime or Crushed Stone Sold or Used in the United States and Ohio, Million Short Tons, 1987.	4-36
Table 4-8.	Construction Uses of Lime or Crushed Stone or Sand and Gravel Sold or Used in the United States and Ohio, Million Short Tons, or Annual.....	4-41
Table 5-1.	Ohio Water Quality Standards for Metals.....	5-10

FIGURES

Figure 2-1.	Schematic Drawing of the Pressurized Fluidized Combustion Process for Operation at TIDD.....	2-12
Figure 2-2.	Schematic Drawing of the Dravo Halt Demonstration Facility at Toronto.....	2-17
Figure 2-3.	Simplified FGD System Schematic Diagram.....	2-20
Figure 2-4.	Schematic Drawing of the LIMB Technology at Edgewater..	2-25

CONTENTS (Continued)

	<u>Page</u>
Figure 2-5. Schematic Drawing of E-SO _x Pilot Plant at Ohio Edison Company's R.E. Burger Plant.....	2-29
Figure 2-6. Schematic Flowsheet of the Parsons Flue Gas Cleaning Process.....	2-32
Figure 2-7. Schematic Flowsheet for the NOXSO Alkalized Aluminate Process.....	2-35
Figure 2-8. Schematic Drawing of the TRW Slagging Combustor Burner.	2-39
Figure 2-9. Schematic Representation of TRW Process Development Plans.....	2-41
Figure 2-10. The Ames Granulation/Sintering Process.....	2-48
Figure 5-1. Incentives for By-product Reuse.....	5-15

LIST OF ACRONYMS

AEP	American Electric Power
AFBC	atmospheric fluidized bed combustion
ASTM	American Society of Testing and Materials
B&W	Babcock and Wilcox
BSR	Beavon Sulfur Recovery
CFR	Code of Federal Regulations
CG&E	Cincinnati Gas & Electric
DCCS	Delaware Center for Catalytic Science and Technology
DOE	U.S. Department of Energy
ECE	Economic Commission for Europe
EDTA	ethylenediaminetetraacetic acid
EP	extraction procedure
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	electrostatic precipitator
FBC	fluidized bed combustion
FGD	flue gas desulfurization
FGT	flue gas treatment
H.B.	House Bill
HMTA	hexamethylenetetraamine
HALT	hydrate addition at low temperature
LI	limestone injection
LIMB	limestone injection multistage burners
L/G	liquid to gas
NPDES	National Pollution Discharge Elimination System
OCDO	Ohio Coal Development Office
OEPA	Ohio Environmental Protection Agency
PCF	pulverized coal-fired
PETC	Pittsburgh Energy Technology Center
PFBC	pressurized fluidized bed combustion
PennDOT	Pennsylvania Department of Transportation
RCRA	Resource Conservation and Recovery Act
SRI	Southern Research Institute
TDS	total dissolved solids
TVA	Tennessee Valley Authority
UNDEMRC	University of North Dakota Energy and Mineral Research Center
UNDP	United Nations Development Program
WES	Waterways Experiment Station

1.0 TASK 1: BASELINE OF KNOWLEDGE CONCERNING THE CHARACTERISTICS AND PROPERTIES OF OHIO CLEAN COAL COMBUSTION BY-PRODUCTS

1.1 SUMMARY

Data on the composition and characteristics of by-products from clean coal combustion processes are summarized. These data include primarily chemical composition, physical characteristics, and the results of leaching studies.

There are a number of clean coal combustion demonstration projects currently being conducted in the State of Ohio (Table 1-1). Data from these are sparse because most of these projects are just being started. In lieu of the lack of site- or coal-specific data relating to Ohio demonstration projects, this report summarizes data mostly from related types of projects, regardless of location. Priority was given to reporting data on high-sulfur, bituminous coals, where available. (For example, see Appendix A, Tables A-3 through A-6, for compositional data on wet scrubbing operations.) While out-of-state results using non-Ohio coals and ash data are helpful, they do not provide detailed information indicative of Ohio operations; rather the data are generic in nature and yield only approximate computations. This lack of data prevented a comprehensive statistical analysis. Further research on Ohio coals is needed. Nonetheless, the information gathered under Task 1 is worth closer examination.

The dominant chemical constituents in by-products from the major groups of processes are summarized in Table 1-2. In general (with the exception of the NOXSO and Columbia Gas processes), compositions of by-products from the clean coal composition processes are similar, consisting of unreacted sorbent, sorbent-sulfur reaction products, and fly ash. The principal differences relate to the types of sorbent used, which are either calcium-based (lime, slaked lime, or limestone), calcium- and magnesium-based (dolomitic), or sodium-based. There is, however, some variability among by-products as a function of the coal type and/or process utilized; data were insufficient to address these variabilities in detail.

TABLE 1-1. SUMMARY OF OHIO'S CLEAN COAL COMBUSTION DEMONSTRATION PROJECTS

Process ¹	Location	By-product Generation Start-up Date	Contact Person for By-product or Process Data
<u>Wet FGD</u> Lime Chelate	CG&E's Miami Fort Station	1989	Bernie Huff with CG&E; Lew Benson with Dravo
<u>Dry FGD</u> HALT	Ohio Edison's Toronto Station	1986	Manny Babu with Dravo; Rita Bolli with Ohio Edison
E-SO _x	Ohio Edison's Burger Station	March 1989	Hank Majdeski with B&W; Rita Bolli with Ohio Edison
Coolside Injection	Ohio Edison's Edgewater Station	Early 1989	Bernie Koch with Consol; Rita Bolli with Ohio Edison
<u>FBC</u> PFBC	AEP's Tidd plant	Mid-1990	Mike Robida with AEP
<u>LIMB</u> LIMB	Ohio Edison's Edgewater Station	Material was generated in 1988	Tom Hurst with B&W; Dr. Robert Dahlin with SRI
<u>Other Processes</u> NOXSO	Ohio Edison's Toronto Station	Proof-of-concept contract awarded 8-88; by-product generation date not identified	J.L. Haslbeck with NOXSO Corp.; Dr. James Yeh with DOE; Rita Bolli with Ohio Edison
Columbia Gas	St. Mary's Facility	Spring 1989	David Price with Columbia Gas

¹ Background information on processes and by-products was also provided by Michael J. Miller of the Electric Power Research Institute and Jerry L. Harness of the U.S. Department of Energy

TABLE 1-2. SUMMARY OF DOMINANT BY-PRODUCT COMPOSITIONS FOR DIFFERENT CLEAN COAL COMBUSTION PROCESSES

Process	Dominant By-product Constituents
Wet FGD ¹	Unreacted sorbent (lime or limestone), calcium sulfate, calcium sulfite, calcium carbonate, fly ash
Calcium spray dryer	Unreacted sorbent (usually slaked lime or calcium hydroxide), calcium-sulfur reaction products (sulfate or sulfite), calcium carbonate, magnesium hydroxide, fly ash
Dry sodium injection	Unreacted sorbent (usually sodium bicarbonate and/or carbonate), sodium-sulfate reaction products (sulfites, sulfates, mixed carbonates-sulfates), silica, aluminum silicate, fly ash
Lime/Limestone injection	Unreacted sorbent (calcium hydroxide), calcium sulfite, calcium sulfate, fly ash. Also sodium sulfate, sodium sulfite, and calcium carbonate when sodium hydroxide is used as a sorbent additive
FBC	Unreacted sorbent (calcium oxide, also magnesium oxide if sorbent is dolomitic) calcium sulfate, silica, alumina, iron oxide, unburned coal, char (circulating systems only) material
NOXSO	Elemental sulfur and fly ash
Columbia Gas	Elemental sulfur and fly ash

¹ Denitrification version of process by-products may also contain organic chelating agents.

A number of leaching studies have been conducted, most using Extraction Procedure (EP) Toxicity Characteristic or related methodology. The calcium- and magnesium-based by-products are approximately 100 times less soluble than the sodium-based by-products, because of the lower solubilities of alkaline earth compounds. Leachabilities of major ions from the calcium-based by-products so far reported appear to be within 30 times of the U.S. Environmental Protection Agency (EPA) primary and secondary drinking water standards, thus meeting a proposed Ohio standard. The sodium-based by-products would likely not meet such a standard because of their higher leachabilities.

Based on the results of EP toxic tests and other hazard characteristics, it appears that the by-products are not toxic and need not be treated as such. Solubility, however, is an issue; ash by-products need to be dealt with in an appropriate manner.

The available leaching data also show low metal concentrations, generally much lower than the EP toxicity threshold values for the eight EP metals. This may be attributed to the generally low total metal contents of the combustion by-products and the fact that leachates are typically alkaline, where the solubilities of certain metals are low due to the formation of insoluble hydroxide phases. Leachate pH is almost always lower than the Resource Conservation and Recovery Act (RCRA) reactivity (corrosivity) limit of 12.5, but frequently exceeds the Ohio Water Quality standard of 9.0. Proposed standards and regulatory issues pertaining to disposal are addressed in Task 5 of this research project and are summarized in the Task 5 report.

1.2 INTRODUCTION

The purpose of Task 1 of this project entitled, "Technical Support for the Ohio Clean Coal Technology Program: Research on Combustion Products," is to provide a data base on the composition and characteristics of by-products from various clean coal combustion processes. Four groups of processes were specified for investigation, namely

- 1) Advanced wet flue gas desulfurization (FGD)
- 2) Advanced dry FGD
- 3) Fluidized bed combustion (FBC)
- 4) Limestone injection multi-stage burners (LIMB).

Characterization data include information on chemical composition, physical properties, and leaching results. Analytical data for by-products from each of these processes are compiled in Appendices A through D. Information was obtained by (a) utilizing Battelle staff knowledge of clean coal combustion processes; (b) consulting with utilities about their demonstration projects; (c) communicating with individuals in the state of Ohio responsible for the development and evaluation of new processes; (d) reviewing available Electric Power Research Institute (EPRI) literature; and (e) conducting a computerized literature search. A comprehensive reference list is compiled at the conclusion of this report, including all sources cited as well as sources consulted but not cited in the body of the report.

Characterization data are organized and discussed by process type below. The organizational structure chosen was for the convenience of this report and should not necessarily be viewed as indicating genetic differences between the major processes. It was not always possible to draw clear lines of distinction between process types, in that many are interrelated in different ways.

1.3 ADVANCED WET FLUE GAS DESULFURIZATION BY-PRODUCTS

1.3.1 General Process and By-product Description

Three variations of wet FGD are commonly used. These include

- A limestone tail-end scrubbing system which utilizes a limestone slurry
- A lime scrubber process which utilizes lime as a sorbent
- A double alkali system which involves the sorption of SO_2 in sodium-based solutions with subsequent precipitation of calcium sulfite and calcium sulfate salts.

The term "scrubber sludge" is frequently used to describe the solid by-product produced by the desulfurization processes. Fly ash that results from burning coal in wet FGD systems may be collected independently of the scrubber sludge; however, fly ash is most frequently either collected with or added to the scrubber sludge for disposal purposes.

No two scrubber-boiler systems produce identical sludges, in terms of composition. Sludge composition varies as a function of the properties of the flue gas entering the system and the FGD system design and operation. Specific factors that affect sludge composition include the sulfur content of the coal, the gas cleaning sorbent used in the system, and the mechanics of scrubbing, including the degree of oxidation obtained.

1.3.2 Ohio Perspectives on Advanced Wet FGD By-products

The Ohio Coal Development Office (OCDO) is sponsoring an advanced wet FGD and denitrification demonstration at the Miami Fort Station in North Bend, Ohio. The NO_x removal aspects of the process, developed by Argonne National Laboratory, involves using a metal chelate, either ethylenediaminetetraacetic acid (EDTA) or hexamethylenetetraamine (HMTA), for NO_x removal in combination with a wet SO_2 scrubber. Studies of the denitrification aspects of this process in the U.S. to date have been done

only on a bench-scale; therefore, no scrubber sludge analyses are currently available (Harkness, 1989). It should be noted, however, that by-products from such combined processes would be expected to contain chelating agents, which may increase heavy metal leaching and mobility in the environment and therefore complicate by-product disposal unless the chelating agents are recycled or removed prior to disposal.

Ohio also has been involved in demonstrating effective methods of stabilizing wet FGD sludge from full-scale systems. The Conesville Power Station of Columbus and Southern Ohio Electric Company was the site of the demonstration. This full-scale system utilized a stabilization process known as the Poz-O-Tec process which was developed by I.U. Conversion System. The FGD sludge originates as bleed from the FGD system recycle slurry. The slurry is composed of approximately 5 to 12 percent solids and is routed to a thickener where the bleed is concentrated to approximately 30 percent solids. The reported composition of solids is approximately 80 percent calcium sulfite and 20 percent calcium sulfate. The material is then thickened to 60 percent solids. Fly ash and lime are added as stabilizing agents (Hupe and Shoemaker, 1979).

Physical characteristics of the stabilized sludge are summarized below:

- Unconfined compressive strength: 30 to 60 lb/in.² (2.11 to 4.21 kg/cm²)
- Compressibility: very small to negligible
- Stability of 3:1 slope: factor of safety above 3.0
- Bearing capacity for shallow foundations: above 6,000 psf (29,000 kg/m²)
- Average density: 95 lb/ft³ (1,537 kg/m³).

In regard to ground water impacts, Hupe (1981) concluded that sludge fixation was more desirable than direct ponding of unfixed sludge or thickening followed by ponding. In general, stabilized FGD sludge performed satisfactorily with respect to EPA's Criteria for Classification of Solid Waste Disposal Facilities and Practices, the Guidelines for Land

Disposal of Solid Waste, and National Pollution Discharge Elimination System (NPDES) requirements.

1.3.3 Chemical Composition Of Wet FGD By-products

Elemental analysis of scrubber sludge indicates that calcium, magnesium, sulfur dioxide (sulfite), sulfur trioxide (sulfate), and carbon dioxide (carbonate) are the major components. In addition, the solid by-products frequently contain fly ash, which typically includes silica, alumina, and iron oxide. Fly ash levels vary widely from system to system. The fly ash content of FGD sludge ranges from 1 to 65 percent. Fly ashes are composed mainly of small, glassy spheres with some inclusion of crystalline materials such as silica (quartz), calcium sulfate (anhydrite), iron oxide (hematite and magnetite), and aluminum silicate (mullite). Table A-1 illustrates the typical chemical composition of some coal fly ashes. Tables A-2 and A-3 provide typical FGD sludge compositional data for both lime and limestone FGD systems.

The solid phases that have been conclusively identified in wet scrubber sludges include calcium sulfite hemihydrate ($\text{CaSO}_3 \cdot \frac{1}{2}\text{H}_2\text{O}$), calcium sulfate dihydrate or gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), calcium carbonate as calcite (CaCO_3), and a co-precipitate of calcium sulfite and calcium sulfate hemihydrate. Table A-4 provides weight percent data on the solid phases. Lime FGD sludges have been shown to contain rosette-type sulfite crystals which do not settle as well as the plate-type sulfite particles that are more common in many limestone systems.

The ratio of sulfate to sulfite in FGD systems is important because of the differences in crystal size and shape. As the relative quantity of sulfate increases, the solids content of the dewatered sludge also increases. The relative amounts of sulfite and sulfate will influence the mechanical stability of the solid by-product and may influence the chemical oxygen demand of the leachate.

In addition to the calcium-sulfur compounds discussed above, numerous trace elements are also usually present. Unlike the calcium-sulfur compounds that are a direct result of the desulfurization process, trace

elements originate primarily from the fly ash. Enrichment in the smaller fly ash particles is noted for the following trace elements: antimony, arsenic, beryllium, cadmium, fluorine, germanium, lead, selenium, and zinc. A typical example of trace element composition is provided by Table A-5 which lists trace element content of sludges from two power plants that burn high-sulfur coal (Holland et al., 1975, as cited in Coltharp et al., 1979). The trace element content of the FGD sludge will certainly depend in part upon the trace element content of the coal, which may vary significantly within the coal seam.

1.3.4 Physical Properties Of Wet FGD By-products

Groups that have performed physical testing on FGD sludge include the Tennessee Valley Authority (TVA), University of Louisville, Combustion Engineering, Aerospace Corporation, Dravo Corporation, the University of Pittsburgh, A.D. Little, Incorporated, and the U.S. Army Waterways Experiment Station. The following parameters have been measured on scrubber sludge (Coltharp et al., 1979):

- Particle size: <1 to 200 microns
- Permeabilities: 1×10^{-4} to 1×10^{-7} cm/sec
- Bulk density: untreated 45 to 90 lb/ft³
treated 50 to 100 lb/ft³
- Settleability: sulfite sludges settle to ~30 to 35
percent solids
sulfate sludges settle to ~60 to 65
percent solids
- Optimum dry density: ~70 to 85 lb/ft³
- Optimum moisture: 35 to 40 percent
- Shear strength: low, resembling inorganic silt or sand
- Unconfined compressive strength: near 100 psi for sludge/ash mixtures which have been allowed to cure.

Physical properties are greatly affected by the abundance of sulfite versus sulfate crystals present in the sludge. Sulfite crystals are

typically plates of 0.5 to 2.0 microns in thickness and 2 to 40 microns in length, whereas sulfate crystals are larger (often cubic in shape) with dimensions of 1 to 100 microns. Sludges high in sulfate crystals exhibit higher permeability and are more easily dewatered (Coltharp et al., 1979).

1.3.5 Leaching Results of Wet FGD By-products

Numerous institutions have investigated the leaching behavior of untreated and treated sludge and sludge-ash mixtures. Coltharp et al. (1979) mention the following major leaching studies in their report:

- EPA/Waterways Experiment Station (WES) evaluation of fixation processes
- EPRI/Radian ponded ash and sludge study
- EPA/Aerospace laboratory leaching
- EPA/Dugway study of migration of hazardous pollutants
- EPA Shawnee field evaluation.

The EPA/WES study indicated that untreated lime and limestone sludges produced leachates that were initially high in TDS but which gradually decreased over time and tended to approach stable values. TDS leached at a higher rate from untreated sludges from the double alkali system; however, the high leach rate continued throughout the year rather than leveling off. Lead leached at a higher rate from the untreated sludge from the double alkali system than it did from the untreated sludges from the lime and limestone systems. In addition to examining untreated sludge, EPA/WES evaluated various treatment processes and determined that no process consistently lowered the TDS values of the leachates. The cement-and-fly-ash-addition process, however, improved the sulfur content in leachates from double alkali sludge, but had no effect on the sulfate content of leachates from sludges from the lime and limestone systems.

The EPRI/Radian study demonstrated that the levels of the trace elements in scrubber sludge leachate are generally low with the exception of boron and selenium. Table A-6 summarizes the results of the sludge leaching experiments performed by EPRI/Radian. Sludge from Station 4 contained

primarily calcium sulfate-sulfite materials, while sludge from Station 5 contained high levels of fly ash.

The EPA/Aerospace experiments indicated that fixation did not improve the leachate quality with respect to trace metals. However, anaerobic leaching conditions inhibited the release of major constituents such as sulfate.

The EPA/Dugway study showed that metal concentrations generally increased as the pH decreased. Table A-7 shows data on the solubilization of trace metals in sludge produced by a double alkali process which utilized Ohio coal.

The EPA Shawnee field evaluation obtained data on untreated FGD sludge leachate that indicated the following:

- Levels of TDS progressively increased with time.
- Similarly, levels of chlorides progressively increased with time.
- Sulfates tended to remain stable.

Leachate from treated by-product, on the other hand, demonstrated a reduction in TDS and sulfate, but had a negligible effect on chlorides.

In conclusion, a number of leaching studies have been conducted, with a variety of different observations noted. In general the leaching data would appear to indicate a nonhazardous classification for wet FGD by-products.

1.4 ADVANCED DRY FLUE GAS DESULFURIZATION BY-PRODUCTS

1.4.1 General Process and By-product Description

Three variations of dry FGD are commonly used:

- SO₂ removal by contacting wet reagents and flue gases in a manner whereby the water is evaporated and the products are collected as dry solids
- SO₂ removal by dry injection of reactants after the furnace and before the final particulate control removal
- SO₂ removal by injecting pulverized sorbent (limestone or hydrated lime) into the furnace cavity above the burner zone.

By-products from these processes are composed of a combination of fly ash, unreacted sorbents, and calcium-sulfur reaction products. When compared with conventional fly ash, by-products from these processes are more alkaline, produce a more alkaline leachate, and have a fairly significant heat of hydration. Specific characterization data for each process are presented below.

1.4.2 Ohio Perspectives on Advanced Dry FGD By-products

Various demonstration projects involving advanced dry FGD processes are currently under way in Ohio. The first project involved the Dravo hydrate addition at low temperature (HALT) lime injection process as originally studied at Ohio Edison's Toronto Station pilot plant. The pilot plant became operational in 1986. A full report on the Dravo Halt demonstration at the Toronto Station will soon be released (Babu, 1989). Chemical constituent data are being collected but have not yet been published (Babu, 1989). Representative EP toxicity leachate data from this demonstration are provided in Table B-1.

A second project involves the demonstration of the E-SO_x post-combustion sulfur dioxide control process at Ohio Edison's Burger Station. The Burger station facility was expected to start generating FGD by-products

in early to mid-March, 1989 (Majdeski, 1989). By-products will be analyzed for a 7-month period following start-up. No preliminary studies have yet been done to characterize these by-products, because it is anticipated that they will be quite similar to those by-products produced by the LIMB process or other dry FGD processes (Majdeski, 1989).

A third project involved the LIMB demonstration program at Ohio Edison's Edgewater Station. The prime contractor is B&W and the program is now in its second year of study.

A fourth project involves demonstrating the Coolside lime injection process also at Ohio Edison's Edgewater Station and is scheduled to begin in early 1989. Preliminary Coolside by-product analyses have been conducted using by-products generated by Consol's pilot unit. Results of the studies on Consol's by-products are summarized in Section 1.4.5.2.

Ohio perspectives on by-products from these major systems are discussed in Section 1.5.2. There also are smaller efforts under way in the State of Ohio, but generally data on possible waste products are not yet available.

1.4.3 Calcium Spray Dryer By-products

The calcium spray-dryer process removes SO_2 from the flue gas by contacting reagents and flue gases in a spray dryer. Slaked lime (calcium hydroxide) is generally the reagent of choice to be used as the SO_2 sorbent in this process. Sodium-based sorbents have also been used, but the by-products produced by sodium-based sorbents are more water-soluble and do not always set up properly, which may lead to disposal problems (Boyd et al., 1985).

1.4.3.1 Chemical Composition

Calcium spray dryer by-products are composed of a combination of fly ash (primarily silicates), unreacted sorbent (predominantly calcium hydroxide, although a side reaction with carbon dioxide also forms calcium carbonate), and calcium-sulfur reaction products (calcium sulfite

hemihydrate and mixed hydrates of calcium sulfate). Generally, calcium spray dryer by-products are described as a combination of spherical, glassy, fly ash particles coated by and intermixed with fine crystals of calcium/sulfur reaction products (Golden, 1988). Table B-2 provides data on the concentrations of major and minor species collected from spray dryer systems. Note, however, that only low-sulfur coal was used in this study (Thompson et al., 1982). Similar data were reported in a study by Boyd et al. (1986) and in a study by Dawson et al. (1988b, see Table B-3). Table B-4 provides data on the major chemical constituents of calcium spray dryer by-products from both low-sulfur and high-sulfur systems (Dawson et al., 1987). The data demonstrate that the sulfur content of the coal has a significant effect on the composition of the by-products.

Trace element analyses of the calcium spray dryer by-products are available for systems burning low-sulfur coal (see Tables B-5 and B-6); however, data on by-products from high-sulfur coal were not found. Additional trace element data were reported by Boyd et al. (1986) for coals of unspecified sulfur content (Table B-7). Beryllium, cadmium, iron, nickel, and sulfate had ranges that exceeded the range for conventional fly ash. Aluminum, copper, molybdenum, and vanadium were lower than in conventional fly ash. Similar data are summarized in Table B-8, which represents compositional ranges from eight spray dryer systems examined by Eklund et al. (1986). Crystalline species in by-products produced by burning low-sulfur coal have been identified using X-ray diffraction analysis. Table B-9 lists the crystalline species found in by-products from dry scrubbing systems.

1.4.3.2 Physical Characteristics

Spray dryer by-product is composed of conventional fly ash particles that have been coated with calcium-sulfur compounds and separate smaller particles consisting of various calcium-sulfur compounds (Golden, 1988). The fly ash particles provide reaction sites for the nucleation of sulfur and, consequently, become coated with reaction products. The smaller (other than fly ash) particles are spherically shaped and finer than fly

ash, with mean sizes primarily in the 2 to 30 micron range, compared with 35 to 55 microns for fly ash. Spray dryer by-products have somewhat greater fineness (passing a 40 micron or 325 mesh sieve) than conventional fly ash (Dawson et al., 1987). Vuceta et al. (1980) found the highest percentage of particles in spray dryer by-product in the 4 to 10 μ range. Many particles, however, appeared to be agglomerates of smaller particles. Scanning electron micrographs have been used to examine particle size and shape of by-products produced by spray dryer systems utilizing low-sulfur coal. The particle size distribution of spray dryer by-product is also affected by the sulfur content of the coal being burned, in that the finest particles are comprised mainly of sulfur reaction products (Dawson et al., 1987).

Optimum moisture contents range from 18 to 54 percent (Boyd et al., 1986). Optimum moisture content increases with increasing sulfur content (Dawson et al., 1987). Density values at optimum moisture, on the other hand, diminish as sulfur content increases. Bulk densities range from 61 to 91 pounds per cubic foot (Boyd et al., 1986). Compressive strength usually ranges from 200 to 1,000 psi after 28 days of curing (Dawson et al., 1987). Permeability coefficients range from 10⁻⁴ to less than 10⁻¹⁰ cm/sec but generally fall in the range of 10⁻⁵ to 10⁻⁶ cm/sec (Thompson et al., 1982).

1.4.3.3 Leaching Results

Eklund et al. (1986) presented leachate data on eight different spray dryer by-products from unspecified coals (Table B-10). The conclusions from these spray dryer leachate analyses were as follows:

- Concentrations of the eight RCRA elements (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) in the EP extracts from all the spray dryer by-products were well below levels at which the by-products would be classified as toxic
- Spray dryer by-products produced basic leachate (pH values ~7.6 to 12.0).
- Calcium, sulfate, and TDS had the highest concentrations in EP extracts.

Dawson et al. (1988b) conducted leachate analyses on spray dryer by-products from the eight stations in the western United States. All systems operated on low-sulfur western subbituminous or northern Great Plains lignite coals. Their study indicated that the subject spray dryer by-products would be classified as nonhazardous. Tables B-11 through B-13 summarize their data on leachate from spray dryer by-products. Golden (1988) also stated that the results of leachate analyses indicate that spray dryer by-products would not be considered toxic under current federal regulations. However, no studies were found specifically on leachate from systems burning high-sulfur coal.

1.4.4 Dry Sodium Injection By-products

Desulfurization is sometimes accomplished by injecting a sodium-based alkali sorbent into a coal-fired electric utility boiler system. The sorbent injection location varies from system to system. Of the systems we studied, none involved dry sodium injection as such. However, numerous sodium compounds have been tested for dry injection, including commercial sodium bicarbonate, soda ash (sodium carbonate), trona (natural hydrous sodium carbonate and sodium bicarbonate), and nahcolite (natural sodium bicarbonate). Commercial sodium bicarbonate and nahcolite are usually the two most effective sorbents in terms of SO₂ removal efficiency (Dawson et al., 1987). All of the studies on dry sodium injection by-products identified have been done on systems that burn low-sulfur coal (Thompson et al., 1982).

The major difference between dry sodium injection by-products and calcium-based by-products from dry SO₂ removal technologies is that sodium compounds are approximately two order of magnitude more soluble in water than calcium compounds; therefore the potential for water quality problems from leaching is much greater with sodium injection by-products (Dawson et al., 1987).

1.4.4.1 Chemical Composition

The desulfurization reactions using nahcolite involve the conversion of NaHCO_3 to Na_2CO_3 , the reaction of the sodium carbonate with SO_2 to form Na_2SO_3 , and the subsequent oxidation of Na_2SO_3 to Na_2SO_4 . These reactions typically go to only 70 percent completion. Consequently all species (NaHCO_3 , Na_2CO_3 , Na_2SO_3 , and Na_2SO_4) are present in the resulting dry injection by-product (Vuceta et al., 1980). Table B-14 provides chemical characteristic data on raw and spent nahcolite. The by-products generated from dry injection systems that utilize nahcolite as sorbent contain approximately 40 percent spent nahcolite and 60 percent fly ash (Vuceta et al., 1980). Other dry injection by-products may consist of up to 70 percent fly ash and from 30 to 70 percent sodium sulfate depending on the sulfur content of the coal burned (Dawson et al., 1987). The main constituents in the fly ash portion of the dry injection by-product are silica, sodium, potassium, calcium, magnesium, barium, carbon, iron, sulfur, aluminum, titanium, and phosphorus (Vuceta et al., 1980). Data on the chemical constituents in dry sodium injection by-products are reported in Table B-15.

1.4.4.2 Physical Properties

Dry sodium injection by-products form fine-grained, spherically shaped particles, generally finer than 50 microns. Because dry sodium injection by-products are comprised of a high percentage of fly ash (up to 70 percent), these by-products appear and behave much like fly ash (Dawson et al., 1987). Data on various physical/engineering parameters are provided in Table B-16 (Boyd et al., 1986).

1.4.4.3 Leaching Results

Dry sodium injection by-products are approximately 100 times more soluble than calcium-based by-products. The solubility of the sodium salts

in the dry injection by-products could potentially raise the concentrations of TDS and sulfates in ground-water leachates to values in excess of water quality criteria (Dawson et al., 1987). Furthermore, sodium concentrations in leachates from sodium-based scrubbing systems have been found to be rather high, ranging from 19,000 to 33,000 ppm (Dawson et al., 1987). The EP extraction data for the eight EP Toxicity metals have been measured to be below RCRA toxicity limits (Dawson et al., 1987).

1.4.5 Lime/Limestone Injection By-products

Lime/limestone injection may be accomplished by using one of two techniques:

- In-furnace sorbent injection by means of limestone injection integral with multistage burners (LIMB process)
- Lime or limestone injection above the boiler zone or in downstream ducting.

The LIMB process has been reported to be more effective than the upper furnace sorbent injection process in controlling SO₂ emissions (Dawson et al., 1987). A separate section of the report has been created for LIMB processes because of the large volume of information. Data on by-products from three injection processes (the Dravo HALT injection process, the Coolside process, and the University of North Dakota Energy and Mineral Research Center's [UNDEMRC] pressure-hydrated lime injection process) are discussed below.

1.4.5.1 Dravo HALT Injection Process

A pilot plant at the Toronto Station of Ohio Edison began using the Dravo HALT lime injection process in 1986. Comprehensive chemical analyses of solid by-products generated by the HALT pilot test unit at the Toronto Station of Ohio Edison, as indicated in the "Ohio Perspectives" section above, have not yet been published. In general the by-products are composed primarily of lime, calcium, sulfate, calcium sulfate, and fly ash. Results of leachate analyses obtained using EPA test procedures are provided

in Table B-1 (Babu, 1989). The leaching data indicate relatively low concentrations of the EP metals.

1.4.5.2 Coolside Process

Coolside by-products differ from bituminous coal fly ash in that Coolside by-products have a high calcium content (25 to 40 weight percent determined as CaO) and may have an elevated sodium content (2 to 4 weight percent determined as Na_2O) when sodium hydroxide is added to the sorbent. As shown in the Consol Martinsville field tests, the major components of Coolside by-products, excluding fly ash, are $\text{Ca}(\text{OH})_2$, CaSO_3 , and CaSO_4 . Minor components include Na_2SO_3 , Na_2SO_4 , and CaCO_3 (Wu and Winschel, 1988). Compositional data on Coolside by-products are provided in Table B-17 (Wu and Winschel, 1988).

The optimum moisture content for Coolside by-products is 30 weight percent. Unconfined compressive strengths may be as high as 251 psi. Permeability coefficients range from 10^{-5} to 10^{-6} cm/sec. Furthermore, wetting of Coolside by-products results in only a minor ($\leq 10^\circ \text{F}$) increase in temperature.

Tables B-18 and B-19 summarize the Coolside by-product leachate data. Leachate toxicity was measured using the EP procedure and again by the same procedure using only deionized water instead of dilute aqueous acetic acid. By-products produced both with and without the sodium hydroxide additive were tested. The leachates were within RCRA limits, and the concentrations of trace elements, sulfate, and TDS in the leachates were less than 30 times the EPA primary and secondary drinking water standards (possible Ohio EPA requirements) on by-products produced both with and without the sodium hydroxide additive. Nitrate, fluoride, and chloride could not be determined on the standard EP leachates because of interferences from the acetate ion. However; their concentrations were well below Ohio standards in deionized water leachates. The leachates from the by-product produced without the sodium hydroxide additive have lower sodium, sulfate, and TDS concentrations, but are otherwise similar to those from the samples produced with the additive. One test using a sample that was first

cured for 28 days then ground and leached showed that curing did not significantly affect leachability.

1.4.5.3 Pressure-Hydrated Lime Injection Process

At UNDEMRC, by-products from a pressure-hydrated lime injection system have been generated. Data have been generated using Pittsburgh No. 8 coal which pertain to the chemical, physical, and leaching characteristics of the by-products (Moretti et al., 1988). The findings are summarized in Tables B-20 through B-25.

The characterization data generated for the lime-injection fly ashes indicate that no major regulatory problems should be encountered for the disposal of these materials. The results of the EPA-EP leaching tests clearly show that the wastes would not be classified as hazardous wastes based on trace metal content under the existing RCRA regulations. The baseline Pittsburgh No. 8 fly ash did produce an American Society of Testing and Materials (ASTM) leachate with an arsenic concentration that exceeded 10 percent of the RCRA limit; however, both of the lime-injection fly ashes had much lower arsenic concentrations.

One additional issue is the exothermal hydration behavior of the fly ash produced by lime injection, which, if the process is to be implemented, must be controlled on a commercial scale to avoid possible problems with waste handling.

1.5 FLUIDIZED BED COMBUSTION BY-PRODUCTS

1.5.1 General Process and By-product Description

Fluidized bed combustion (FBC) involves the burning of coal in a bed of high calcium or dolomitic limestone sorbent which is fluidized by upward jets of hot air under conditions that calcine the limestone to form oxides. In this form, the limestone acts as a reagent to capture the sulfur gases emitted during coal burning (Dawson et al., 1987).

By-products produced by FBC consist of spent sorbent (calcium sulfate), excess sorbent (lime), ash, and some unburned coal. The FBC systems generally produce at least two different types of solid by-products: (a) FBC fly ash (baghouse material); and (b) spent bed material. In circulating bed systems, a carryover or recycle material (char) is also produced and collected by a cyclone. Two major types of FBC processes are discussed below. The pressurized FBC (PFBC) process is currently being demonstrated in Ohio and is discussed under Section 1.5.2. Site- and coal-specific data are not available. By-products from the atmospheric FBC system (AFBC), a related process whose by-products are similar to those from the PFBC system, are described in Section 1.5.3.

1.5.2 Ohio Perspectives

The State of Ohio has, along with the U.S. Department of Energy (DOE), been involved in funding the design and operation of AEP's Tidd PFBC demonstration plant in Brilliant, Ohio. Construction at AEP's Tidd plant began in 1988, and start-up is currently scheduled for mid-1990. Preliminary chemical and leachate analyses of bed ash and fly ash from a different PFBC unit using Ohio coal and dolomite have been performed at the Component Test Facility in Malmö, Sweden (Tables C-1 through C-3). Results of the EP toxicity test were all within a factor of 10 of the drinking water standard for both PFBC bed ash and PFBC fly ash as indicated by Table C-2. Furthermore, comparing the PFBC ash and fly ash from a conventional

pulverized coal-fired (PCF) plant burning similar coal showed that the PFBC ash leachate is of better overall quality (Table C-2). The ASTM D-3987-81 leachate test produced similar results (Table C-3). The concentrations of all parameters for the leachates from both the PFBC bed ash and PFBC fly ash were within a factor of 2 of the drinking water standard (Robida et al., 1988).

1.5.3 AFBC By-products

1.5.3.1 Chemical Composition

AFBC by-products consist of spent sorbent (calcium sulfate), excess sorbent (calcium oxide), coal ash, and unburned coal (Eklund et al., 1986). All AFBC systems produce spent bed material and fly ash. Circulating systems also produce a char material.

A study at the TVA 20-MW bubbling bed AFBC pilot plant generated information on the major constituents in spent bed material, AFBC fly ash, and char (Golden, 1988). Spent bed material had the highest calcium content (45 percent as CaO). Recycled char also exhibited a high calcium content (31 percent CaO) and the highest sulfur content (20 percent as SO₃) of all the by-products tested. The baghouse AFBC fly ash was chemically similar to high calcium Type C fly ash except for higher SO₃ and lower SiO₂ content (Golden, 1988).

Eklund et al. (1986) investigated chemical constituents of by-products from four AFBC systems. The type of waste was a composite of bed, char, and baghouse material. The chemical constituents are summarized in Table C-4. Dawson et al. (1987) examined chemical compositional data on numerous AFBC systems. Their study indicated that spent bed material was comprised of 34 percent calcium oxide, 28 percent calcium sulfate, 26 percent silica, 4 percent alumina, 3 percent iron oxide, 2 percent magnesium oxide, and 3 percent other components including trace elements. Furthermore, AFBC fly ash generally had low percentages of calcium oxide (10 to 15 percent) and sulfate (5 to 10 percent) and moderate amounts of silica (10 to 25 percent) and combined alumina and iron (10 to 15 percent).

The Dearborn Environmental Consulting Services and the Wastewater Technology Centre (1985) conducted (1) a literature review on AFBC solid by-products and (2) laboratory studies on by-products that were generated during the combustion of Canadian high-sulfur coal and a mixture of high-sulfur coal and woodchips in a limestone bed at an AFBC test facility. Tables C-5 through C-9 summarize information regarding major chemical constituents, trace element composition, and principal crystalline phases on both spent bed material and carryover/fly ash material. Chemical characterization data were also reported on by-products that were generated during the combustion of Canadian high-sulfur coal (Tables C-10 through C-12). The by-products that were analyzed in the laboratory study consisted of (1) Minto bed material (Minto coal, wood chip waste, Havelock limestone, spent bed material); (2) Devco bed material (Devco Prince coal, Havelock limestone, spent bed material); and (3) Devco baghouse material (Devco Prince coal, Havelock limestone, and baghouse material). Both coals were classified as high-sulfur bituminous coals. Because of varying chemical compositions, generalizations about the similarities among the by-products cannot be made; however, the various compositions may be indicative of Ohio coals.

1.5.3.2. Physical Properties

Tables C-13 and C-14 summarize AFBC by-product physical characteristic data as reported by Golden (1988) and Eklund et al. (1986), respectively. Table 3-15 pertains to data generated by the Dearborn Environmental Consulting Services and the Wastewater Technology Centre (1985) on the physical characteristics of AFBC by-products generated by burning Canadian high-sulfur bituminous coal.

In general, spent bed materials have the consistency of coarse sand and a speckled (salt and pepper) appearance. Recycled char is a finer-grained material. AFBC baghouse material is the finest-grained of the three materials and may have a dark gray or black appearance, indicative of higher carbon content than those ordinarily found in bituminous coal fly ash from pulverized coal boilers (Dawson et al., 1987).

1.5.3.3 Leaching Results

Dawson et al. (1987) reported that a detailed investigation of the environmental impacts of AFBC by-product disposal was performed for EPA by Westinghouse Electric Company. The program involved several types of leaching tests conducted on more than 40 samples of spent bed and char recycle materials obtained from eight different experimental and pilot-scale FBC boiler units. Leachate testing was conducted under conditions considered more severe than anticipated for land disposal. Trace element concentrations in leachates from AFBC by-products were quite low and consistently less than drinking water standards. High pH, TDS, sulfates, and calcium were the water quality parameters of greatest concern. The authors concluded that AFBC by-products should be classified as nonhazardous and considered nontoxic.

Eklund et al. (1986) summarized leachate data on numerous metals and anions in AFBC by-products. Table C-16 provides data ranges for the water quality parameters evaluated.

Lastly, the Dearborn Environmental Consulting Services and Wastewater Technology Centre (1985) conducted a study on the leachate produced from AFBC by-products generated by burning Canadian high-sulfur bituminous coal. Its data base includes an extensive characterization of solids, leachates, and solids after leaching. Primary chemical constituents in the by-products were anhydrous calcium sulfate, calcium sulfate dihydrate, lime, and silica. Leachates contained primarily calcium and sulfate, with lesser amounts of sodium, chloride, potassium, and silica.

1.6 LIMB BY-PRODUCTS

1.6.1 General Process and By-product Description

The LIMB process combines sorbent injection for SO₂ control with the use of low-NO_x burners in which staged combustion is utilized for NO_x control. By-products from this process are composed of fly ash, unreacted sorbent, and calcium-sulfur reaction products. As with other dry FGD systems, the LIMB by-products are more alkaline, have a significantly higher heat of hydration, and produce a more alkaline leachate than conventional ash.

1.6.2 Ohio Perspectives

A full-scale demonstration of the LIMB process began in 1987, with the installation of a LIMB system to the 105-MW boiler at Ohio Edison's Edgewater Station in Lorain, Ohio. EPA is currently sharing the cost of the project with the major participants: the State of Ohio, Ohio Edison, and Babcock and Wilcox (B&W). Chemical analyses and leachate data have not been completed for by-products from the full-scale demonstration at Edgewater (Dahlin, 1989); however, Southern Research Institute (SRI) performed a variety of physical and chemical tests on LIMB by-products that are expected to be similar in composition. These by-products were produced by SRI's pilot plant fired with Pittsburgh No. 8 coal while using commercial hydrated lime as the sorbent. The by-product characterization data for the SRI pilot demonstration include leaching and chemical constituent data (Hurst, 1989). Chemical constituent and leaching data will be collected on by-products from the full-scale demonstration at Edgewater Station sometime in the future.

1.6.2.1 Chemical Composition

LIMB by-products differ from conventional fly ash in that they contain 15 to 30 percent by weight free lime (CaO) and 10 to 25 percent by

weight calcium sulfate. The free lime reacts exothermically with water and increases the pH of water that comes into contact with the LIMB by-products.

Table D-1 provides data on the major chemical constituents of LIMB by-products produced by SRI's pilot combustor. The analyses correspond to free lime contents of 29 to 32 percent, and CaSO_4 contents of 31 to 37 percent in the SRI LIMB by-products.

1.6.2.2 Physical Data

The combination of lime, calcium sulfate, and silicates in LIMB by-products results in cementitious behavior upon adding water. Table D-2 provides permeability data on the two different LIMB by-products produced in the SRI pilot demonstration using Pittsburgh No. 8 and hydrated lime. The only difference was the supplier of the hydrated lime. The permeability results indicate that the addition of cement to the LIMB by-product does not greatly decrease its permeability since the permeability coefficient for the consolidated LIMB ash is already in the 10^{-6} cm/sec range after curing.

As mentioned earlier, a significant heat of hydration is associated with LIMB by-product. The SRI pilot demonstration by-product exhibited a temperature change from 77 to 144 F within 12 minutes when the LIMB by-product was slaked in accordance with ASTM C110. Other SRI studies demonstrated that temperature rises were largely dependent upon water-to-LIMB by-product ratios. Furthermore, wetted LIMB by-product may need to be cooled before transport.

1.6.2.3 Leaching Results

LIMB by-products from the SRI pilot combustor have been analyzed using the EP Toxicity Test (Table D-3). Results were well below the RCRA allowable limits for the EP metals. The pHs were close to, but still below, the RCRA allowable limit of 12.5. Based on these results, the LIMB by-product would not be considered a hazardous waste; however, leachates may have to be neutralized somewhat in order to satisfy the Ohio Water Quality

Standard of 6.5 to 9.0, if this standard is found to be applicable to this type of by-product. Also, the runoff in an environmental setting may not be as basic as indicated by the EP Toxicity Test, because of the low permeability of the undisturbed by-product.

1.7 BY-PRODUCTS FROM OTHER CLEAN COAL COMBUSTION PROCESSES

Two demonstration processes that do not fall in any of the above categories were also identified, namely the NOXSO process developed by the NOXSO Corporation and a catalytic reduction process being developed by Columbia Gas. The processes are both unique in that the principal by-products produced are fly ash and elemental sulfur. Furthermore, the fly ash and elemental sulfur are removed separately, thus enabling the constituents to be recycled. Another significant advantage of these systems (as opposed to other clean coal combustion processes) is the minimal amount of by-products produced.

The NOXSO process is a dry, regenerable-sorbent system that can simultaneously remove 90 percent of the SO_2 and NO_x in flue gas. The sorbent consists of NaAlO_2 on a gamma alumina substrate. The solid by-products consist of sulfur and baghouse trace materials. The baghouse material contains fly ash with slight amounts of sorbent. In August 1988, NOXSO Corporation obtained a contract to build a proof-of-concept test unit at the Toronto Station of Ohio Edison. Characterization data on all products will soon be available (Yeh, 1989).

Columbia Gas is developing a catalytic reduction process for removing SO_2 and NO_x from flue gas, working with the Ralph M. Parson Company at the University of Delaware. Similar to the NOXSO process, the principal solid by-products generated are expected to be fly ash (which is removed by an electrostatic precipitator before the catalytic reduction reactor) and elemental sulfur (Price, 1989). Although work has been done only on a bench-scale, more field tests at the St. Mary's facility are planned in the spring of 1989. The St. Mary's field tests are expected to include analyses of the fly ash and a test of the durability of the catalyst to flue gas exposure.

REFERENCES

References cited in the text are marked with an asterisk. Other references were consulted but are not specifically cited.

Adams, D.F, and Farwell, S.O., "Sulfur Gas Emissions from Stored Flue Gas Desulfurization Solids," EA-2067, Electric Power Research Institute, Palo Alto, California, 1981.

American Coal Ash Association, Proceedings: Eight International Ash Utilization Symposium, Vol. 1, CS-5362, Research Project 2422, Washington, D.C., 1987.

Ayer, F.A., Proceedings: Symposium on Flue Gas Desulfurization-Holeston, Vol. 1, EPA-600/9-81-019B, Research Park Triangle, North Carolina, 1981.

Ayer, F.A., Proceedings: Symposium on Flue Gas Desulfurization-Holeston, Vol. 2, EPA-600/9-81-019B, Research Park Triangle, North Carolina, 1981.

*Babu, M., Personal communication regarding Dravo Lime Company's work with the HALT process, 1989.

Bahor, M.P., et al., "Coal Ash Disposal Manual," 2nd ed., CS-2049, Research Project 1685-3, Final Report, GAI Consultants, Inc., Monroeville, Pennsylvania, 1981.

Berger, D.A., "Clean Coal Technology-State of the Art Experience." Paper presented at the Twenty-Seventh Annual Kentucky Industrial Coal Conference. University of Kentucky, April 13-14, 1988.

Botoman, G., and Stith, D., "Analyses of Ohio Coals, 1979-1980." Ohio Department of Natural Resources, Columbus, Ohio, 1986. 26 pp.

*Boyd, R.H., Jr., et al., "Advanced SO2 Control Solid Waste Management Planning Study," CS-4402, Electric Power Research Institute, Palo Alto, California, 1986.

Collins, H.R., "Ohio," In 1980 Keystone Coal Industry.

*Coltharp, W.M., et al., "Review and Assessment of the Existing Data Base Regarding Flue Gas Cleaning Wastes," FP-671, Electric Power Research Institute, Palo Alto, California, 1979.

Coltharp, W.M., et al., "Chemical/Physical Stability of Flue Gas Cleaning Wastes," FP-671, Vol. 2, Research Projects 786-2, Radian Corporation, Austin, Texas, 1979.

Cooper, D.W., et al., "Evaluation of Eight Novel Fine Particle Collection Devices," EPA-600/2-76-035, GCA Corporation, Bedford, Massachusetts, 1976.

*Dahlin, R.S., et al., "Analysis of LIMB Waste Management Options." Paper presented at the 2nd Joint Symposium on Dry SO₂ and Simultaneous SO₂/NO_x Control Technologies. Raleigh, North Carolina, June 2-6, 1986.

Dahlin, R.S., et al., "Disposal, Recycle, and Utilization of Modified Fly Ash from Hydrated Lime Injection into Coal-Fired Utility Boilers." Paper presented at the 80th Annual Meeting of the Air Pollution Control Association. New York, New York, June 21-26, 1987.

*Dahlin, R., Personal communication regarding SRI's pilot facility and SRI's work on samples from the Edgewater station demonstration project, 1989.

Dawson, D.W., et al., "Laboratory Characterization of Advanced SO₂ Control By-products: Furnace Sorbent Injection Wastes," CS-5783, Electric Power Research Institute, Palo Alto, California, 1988a.

*Dawson, D.W., et al., "Laboratory Characterization of Advanced SO₂ Control By-products: Spray Dryer Waste," CS-5782, Electric Power Research Institute, Palo Alto, California, 1988b.

*Dawson, G., et al., "Utilization Potential of Advanced SO₂ Control By-products," CS-5269, Electric Power Research Institute, Palo Alto, California, 1987.

*Dearborn Environmental Consulting Services and the Wastewater Technology Centre, "Preliminary Evaluation of AFBC Solid Waste Properties, 1982/1983," Report EPS 3/PG/2, Environmental Protection Service, Environment Canada, Ottawa, Ontario, 1985.

Duval, W.A., Jr., "FGD Sludge Disposal Manual FP - 977 Research Project 786-1," Final Report, Michael Baker, Jr., Inc., Beaver, Pennsylvania, 1979.

*Eklund, A.G., et al., "Characteristics Affecting Design Considerations for Waste Management Systems for Advanced SO₂ Technologies." Paper presented at the 79th Annual Meeting of the Air Pollution Control Association. Minneapolis, Minnesota, June 22-27, 1986.

Electric Power Research Institute, EPRI Products Vol.5: Environmental Control Technology. EPRI Products 88-1-Vol 5(W), Palo Alto, California, 1988.

- Electric Power Research Institute, EPRI Research and Resources Flue Gas Desulfurization Systems and SO₂ Control. GS-6121 EPRI, Palo Alto, California, 1988. 38 pp.
- Electric Power Research Institute, EPRI Guide Technical Reports, published January 1982-August 1987, Technical Information Division, Palo Alto, California, 1987.
- Forsythe, R.C., et al., "Land Application Uses for Dry FGD By-products." Presented to the Ohio Coal Development Office, 1989. 120 pp.
- *Golden, D.M., "Design and Costs of Waste Management Systems for Advanced SO₂ Control Technologies." Paper presented at the Joint Power Generation Conference, September 1988.
- Golomb, A., and Nott, B.R., "Waste Characterization." Paper presented at EPRI's Conference on Effects of Coal Quality on Power Plants. Atlanta, Georgia, October 13-15, 1987.
- *Harkness, J., Personal communication regarding Argonne National Laboratories' studies which involved using a metal chelate to enhance wet FGD and denitrification, 1989.
- Haslbeck, J.L., Personal communication regarding innovative FGD process developed by the NOXSO Corporation, 1989.
- Hayward, J.C., et al., "Engineering Evaluation of Projected Solid Waste Disposal Practices," CS-2627, Vol. 1. Research Project 1728-1, Final Report, Michael Baker, Jr., Inc., Beaver, Pennsylvania, 1982.
- Heaton, R.L., et al., "Trace Element Characterization of Coal Wastes - Fifth Annual Progress Report," EPA-600/7-81-087, U.S. Environmental Protection Agency, Washington, D.C., 1981. 100 pp.
- Hendriks, R.V., and Nolan, P.S., "EPA's LIMB Development and Demonstration Program," Journal of the Air Pollution Control Association, Vol. 36, pp. 432-438, 1986.
- Horvath, M., Personal communication about Ohio Edison's involvement with the LIMB project at the Edgewater station, the E-SO_x process at the Burger station, and the HALT process at the Toronto station, 1989.
- Hudson, J.L., and Rochelle, G.T., Flue Gas Desulfurization, American Chemical Society Symposium Series 188, Washington, D.C., 1982
- *Hupe, D.W., and Shoemaker, S.H., "Monitoring the Fixed FGD Sludge Landfill, Conesville, Ohio - Phase I," FP-1172, Research Project 1406-2, Michael Baker, Jr., Inc., Beaver, Pennsylvania, 1979.

- *Hupe, D.W., "Monitoring the Fixed FGD Sludge Landfill, Conesville, Ohio - Phase II," CS-1984, Research Project 1406-2, Michael Baker, Jr., Inc., Beaver, Pennsylvania, 1981.
- *Hurst, T., Personal communication regarding Babcock and Wilcox's involvement with the LIMB project at Edgewater, 1989.
- Ifeadi, C.N., et al., "Topical Report on Characterization and Disposition of Flue Gas Desulfurization Sludges," Battelle Columbus Laboratories, Columbus, Ohio, 1975.
- Kresovich, N., et al., "Recycle of Modified Fly Ash from Furnace Sorbent Injection." Paper presented at the 81st Annual Meeting of APCA. Dallas, Texas, June 20-24, 1988.
- Long, W.H., Personal communication regarding the PEDCO Rotary Cascading Bed Boiler Project, 1989.
- Mahlock, J.L., "Chemical Fixation of FGD Sludges - Physical and Chemical Properties, Environmental Effects Laboratory," Vicksburg, Mississippi.
- *Majdeski, H., Personal communication regarding Babcock and Wilcox's involvement with Ohio Edison's E-SO_x post-combustion sulfur dioxide control demonstration at the Burger station, 1989.
- McElroy, M.W., et al., Proceedings: First Joint Symposium on Dry SO₂ and Simultaneous SO₂/NO_x Control Technologies, Vol. 2, Power Plant Integration, Economics, and Full-scale Experience. EPA/600/9-85/0206.
- Moretti, C., Personal communication regarding work done by the University of North Dakota Energy Management Research Center (UNDEMRC) on desulfurization of Pittsburgh # 8 coal using a pressure-hydrated lime injection above the boiler zone, 1989.
- *Moretti, C.J., and Henke, K.R., "Waste Management: Quarterly Technical Progress Report for the Period April-June 1988." University of North Dakota Energy and Mineral Research Center, 1988.
- Murarka, I.P., "Solid Waste Environmental Studies: The Needs and the Priorities," EA-2538-SR, Special Report, Electric Power Research Institute, Palo Alto, California, 1982.
- Murarka, I.P., "Leaching Chemistry of Combustion Residues," EPRI Journal, 1988.

- Muzio, L.J., et al., "Control of Nitrogen Oxides: Assessment of Needs and Options, Technical Support Document, Vol. 5: Emissions Control Technology for Combustion Sources," EA-2048, Vol. 5 Research Project 1375, Final Report, KBC Inc., Irvine, California, 1983.
- Newby, R.A., et al., "Effect of SO₂ Emission Requirements on Fluidized Bed Combustion Systems Preliminary Technical/Economic Assessment," Westinghouse Research and Development Center, Pittsburgh, Pennsylvania.
- OCDO (Ohio Coal Development Office), "LIMB Demonstration to Begin," ODCO Newsletter, Vol. II, Issue 4, Columbus, Ohio, June 1987.
- Persson, T., ed., "PFBC Combustor Erection Underway in Stockholm," PFBC Newsletter No. 1/89. Asea, Brown and Boveri (ABB) Carbon AB, Finspong, Sweden, 1989. 8 pp.
- *Price, D., Personal communication regarding an innovative FGD process developed by Columbia Gas which will be demonstrated at the St. Mary's facility in the Spring 1989.
- Rai, D., et al., "Inorganic Constituents in Fossil Fuel Combustion Residues," EA-5176. Electric Power Research Institute, Palo Alto, California, 1987.
- Reese, S., Personal communication regarding a rotary cascading bed boiler that will be used by the Scio Pottery Company, 1989.
- Robida, M., Personal communication regarding ash characteristics and PFBC ash regulations, 1989.
- Robida, M., Personal communication regarding the AEP's Tidd Pressurized Fluidized Bed Combustion project, 1989.
- Robida, M., Personal communication regarding in-duct scrubbing ash, 1989.
- *Robida, M.R., et al., "AEP's Tidd Pressurized Fluidized Bed Combustion Demonstration Plant - An Update and Review of Environmental Aspects." Paper presented at the EPRI/APCA/ASME Fourth Symposium on Integrated Environmental Control. Washington, D.C., March 2-4, 1988.
- Rose, J.G., et al., Product of Concrete Using Fluidized Bed Combustion Waste and Power Plant Fly Ash., Commonwealth of Kentucky, Kentucky Energy Cabinet, 1986.
- Rosenburg, H.S., et al., "Status of Stack Gas Technology for SO₂ Control," Research Project 209, Final Report Part I, Battelle Columbus Laboratories, 1975.

- Rosenburg, H.S., et al., "Status of Stack Gas Technology for SO₂ Control," Research Project 209, Final Report Part II, Battelle Columbus Laboratories, 1975.
- Rosenburg, H.S., By-product Gypsum from Flue Gas Desulfurization Processes, I&EC Product Research & Development, Vol. 25, pp. 348, 1986.
- Santhanum, C.J., and Ulbrich, C.R., "Characterization of Flue Gas Cleaning (FGC) Waste From Coal Combustion." Paper presented at Fifth International Ash Utilities Symposium, 1979.
- Smith, E.O., et al., "Full Scale Scrubber Characterization of Conesville Unit 5," CS-2525, Research Project 1410-3, Final Report, Black & Veatch Consulting Engineers, Kansas City, Missouri, 1982.
- Stansel, J., Personal communication regarding control of SO₂ emissions from the TRW Slagging Combustor in Cleveland by limestone additions to the coal, 1989.
- Stout, W.L., et al., Manual for Applying Fluidized Bed Combustion Residue to Agricultural Lands. ARS-74. U.S. Department of Agriculture, Agricultural Research Service, 1988. 15 pp.
- Sun, D.C., and Peterson, D.H., "Fluidized Bed Combustion Residue Disposal: Environmental Impact and Utilization," EPA 600/1-80-015c.
- *Thompson, C.M., et al., "Characteristics of Waste Products From Dry Scrubbing Systems," CS-2766, Electric Power Research Institute, Palo Alto, California, 1982.
- Turner, R.R., et al., "Leachability and Aqueous Speciation of Selected Trace Constituents of Coal Fly Ash," EA-2588 Final Report, Electric Power Research Institute, Palo Alto, California, 1982.
- United Nations Development Program (UNDP) and Economic Commission for Europe (ECE), "Low-emission Combustion Processes and Their By-products." Paper presented at the Task Force on Low Emission Combustion Processes, First Meeting, Sarajevo, Yugoslavia, March 15-17, 1989, and at the Task Force on Utilization and Disposal of By-products, First Meeting, Rabat, Malta, February 13-14, 1989.
- Venditti, F.P., et al., Symposium on the Transfer and Utilization of Particulate Control Technology: Vol 3. Scrubbers, Advanced Technology, and HTP Applications, EPA-600/7-79-044c, U.S. Environmental Protection Agency, Washington, D.C., 1979.
- *Vuceta, J., et al., "Characteristics and Disposal of Solid By-Products from Dry Flue Gas Desulfurization Systems." Paper presented at the 73rd Annual Meeting of the Air Pollution Control Association. Montreal, Quebec, June 22-27, 1980.

Wilhelm, J.H., et al., "Sludge Dewatering for FGD Products FP-937 Research Project 786-3," Final Report, Envirotech Corporation, Salt Lake City, Utah, 1979.

*Wu, M.M., and Winschel, R.A., "Coolside Waste Management Studies - Final Report," DOE Cooperative Agreement No. DE-FC22-87PC79798, Consol Consolidation Coal Company, Liberty, Pennsylvania, 1988.

*Yeh, J., Personal communication regarding analyses of baghouse waste produced by the NOXSO process, 1989.

APPENDIX A

DATA TABLES PERTAINING TO ADVANCED
WET FLUE GAS DESULFURIZATION BY-PRODUCTS

TABLE A-1. CHEMICAL COMPOSITION OF COAL ASH - MAJOR AND MINOR ELEMENTS

Sample Content Identification	Composition (weight percent)										Sulfur of Coal
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	TiO ₂	P ₂ O ₅	SO ₃	
Eastern bituminous fly ash	50.8	20.6	16.9	2.0	1.0	2.6	0.4	2.5	--	2.4	--
Bituminous	49.1	16.25	22.31	4.48	1.00	1.42	0.05	1.69	--	0.73	--
Illinois	36.0	20.5	35.4	1.8	0.8	1.8	0.6	1.0	0.11	--	2.7
Kentucky	39.3	20.6	31.3	2.5	0.5	2.3	0.3	1.1	0.17	--	3.3
Ohio	49.7	22.7	21.2	1.8	1.7	2.0	0.3	1.0	0.08	--	3.7

Reference: Coltharp et al., 1979.

TABLE A-2. CHEMICAL ANALYSIS OF LIME-BASED FGD BY-PRODUCTS

Plant	Composition of Sludge Solids (weight percent)										
	Fly ash	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₂	SO ₃	CO ₂
TVA-Shawnee Pond A	42.5	--	--	--	25.9	--	--	--	23.0	5.5	1.5
	46.9	--	--	--	27.0	--	--	--	19.1	6.6	1.7
TVA-Shawnee Pond C	25.1	--	--	--	23.8	--	--	--	20.2	5.8	1.6
	22.2	--	--	--	23.9	--	--	--			
Plant A	--	31.6	18.3	4.3	18.1	2.4	--	--	12.1	2.9	3.2
Plant A	--	4.9	3.4	0.6	43.2	0.2	--	--	33.0	5.9	6.7
Mitsui Aluminum	5	3.76	1.71	0.86	40.7	--	--	--	32.9	4.8	2.3
Plant E (naturally oxidized)	--	1.2	0.2	0.8	45.7	0.4	0.2	0.1	38.8	6.4	--

Reference: Coltharp et al., 1979

TABLE A-3. CHEMICAL ANALYSIS OF LIMESTONE-BASED FGD BY-PRODUCTS

Plant	Composition of Sludge Solids (weight percent)										
	Fly ash	SiO2	Al2O3	Fe2O3	CaO	MgO	Na2O	K2O	SO2	SO3	CO2
TVA-Shawnee Pond D	37.9	-	-	-	30.1	-	-	-	15.1	6.7	9.5
	34.7	-	-	-	31.2	-	-	-	16.4	8.2	8.7
	38.3	-	-	-	29.3	-	-	-	15.3	7.1	7.4
TVA-Shawnee Pond B1	35.5	-	-	-	30.5	-	-	-	15.2	9.1	8.5
	34.0	-	-	-	32.5	-	-	-	16.3	8.1	9.9
TVA-Shawnee Pond E1	34.2	-	-	-	25.4	-	-	-	13.8	4.4	8.1
Plant E	15.0	-	-	0.19	37.1	0.14	Negl.	-	30.0	4.4	5.1
LG&E Paddy's Run Station (naturally oxidized)	-	4.3	2.0	2.2	41.2	1.4	0.2	0.3	26.0	14.1	6.4
LG&E Paddy's Run Station (forced oxidation)	-	7.1	3.3	2.6	39.3	1.7	0.2	0.5	0.2	33.7	8.7

1 Sample of untreated sludge before chemical fixation

Reference: Coltharp et al., 1979.

TABLE A-4. IDENTIFICATION OF CHEMICAL PHASES OF FGD SLUDGE

Facility	Weight Percent of Chemical Phase					
	Absorbent	CaSO ₃ · $\frac{1}{2}$ H ₂ O	CaSO ₄ ·2H ₂ O	CaCO ₃	Fly Ash	Other
Kansas City Power & Light Hawthorn 4	Limestone	17	23	15	45	
Commonwealth Edison Will County 1	Limestone	50	15	20	15	
City of Key West Stock Island	Limestone	20	5	74	1	
Kansas City Power & Light LaCygne	Limestone	40	15	30	15	
Tennessee Valley Authority Shawnee - Turbulent Contact Absorber 3 dates	Limestone Limestone Limestone	18.5 21.4 21.8	21.9 15.4 31.2	38.7 20.2 4.5	20.1 40.9 40.1	4.6 MgSO ₄ ·6H ₂ O 3.7 MgSO ₄ ·6H ₂ O 1.9 MgSO ₄ ·6H ₂ O
Louisville Gas and Electric Paddy's Run 6	Lime	94	2	0	4	
Tennessee Valley Authority Shawnee	Lime	48.8	6.3	2.5	40.5	1.9 MgSO ₄ ·6H ₂ O
Duquesne Light Company Phillips	Lime	12.9	19.0	0.2	59.7	9.8 CaS ₃ O ₁₀
General Motors Parma	Double Alkali	12.9	48.3	7.7	7.4	19.2 CaSO ₄ · $\frac{1}{2}$ H ₂ O 6.9 Na ₂ SO ₄ ·7H ₂ O
Schools	Double	65-90	5-25	2-10	Nil	

Reference: Coltharp et al., 1979

TABLE A-5. TRACE ELEMENT COMPOSITION OF FGD SLUDGE SOLIDS
(Concentration in ppm)

Identification: Coal Type: Sorbent:	Station 4 Eastern High Sulfur Limestone	Station 5 Eastern High Sulfur Limestone
Antimony	7.5	6.7
Arsenic	12	6.7
Barium	4400	< 20
Beryllium	1.0	1.8
Boron	211	41.8
Cadmium	1.1	25
Chromium	4.0	5.2
Copper	104	65
Fluorine	950	266
Germanium	2.4	5.9
Lead	2.4	190
Manganese	147	340
Mercury	0.46	0.101
Molybdenum	8.0	9.6
Nickel	26.0	75.2
Selenium	3.8	2.1
Vanadium	< 100	< 100
Zinc	169	2050

Reference: Holland et al., as cited in Coltharp et al., 1979.

TABLE A-6. EQUILIBRIUM CONCENTRATIONS OF TRACE ELEMENTS IN FGD
SLUDGE LEACHATE (ppm)

	Station 4 Sludge	Station 5 Sludge
Coal source:	Eastern	Eastern
Sulfur content:	4	5
Scrubber absorbent:	Limestone	Limestone
Ash collection:	ESP upstream	With sludge
pH	9.7	8.4
Antimony	0.013	0.035
Arsenic	<0.002	0.03
Barium	<0.3	<0.3
Beryllium	0.001	0.002
Boron	6.3	0.96
Cadmium	<0.001	0.002
Chromium	0.011	<0.001
Copper	0.045	<0.005
Fluorine	8.7	7.6
Germanium	<0.01	0.02
Lead	0.0033	0.0061
Manganese	<0.002	<0.002
Mercury	0.001	0.0008
Molybdenum	0.061	0.075
Nickel	<0.05	<0.05
Selenium	0.0096	0.016
Vanadium	<0.1	<0.1
Zinc	0.052	<0.005

Reference: Holland et al., 1975 as cited in Coltharp et al., 1979

TABLE A-7. SOLUBILIZATION OF METALS AND CHLORIDE FROM PLANT C BY-PRODUCT FOR THREE pH VALUES
(Double Alkali Process/Ohio Coal)

Grams Waste to 200 ml water	pH	Concentration (mg/L)									
		Cd	Cr	Cu	Ni	Pb	Zn	Ca	Mg	Na	Cl
20	5.0	0.06	0.08	0.14	0.65	0.60	3.00	2800	250	610	43
40	5.0	0.11	0.14	0.19	1.10	1.00	4.40	4450	480	575	88
20	7.0	0.02	< 0.05	0.04	0.15	0.40	0.02	1870	50	505	66
40	7.0	0.03	0.07	0.07	0.20	0.60	0.04	2520	73	700	109
20	9.0	< 0.02	< 0.05	< 0.02	0.06	0.10	< 0.02	570	8.6	465	65
40	9.0	< 0.02	< 0.05	0.02	0.08	0.20	0.02	870	20	790	130

Reference: U.S. Army Dugway Proving Ground, 1976a as cited in Coltharp et al., 1979.

APPENDIX B
DATA TABLES PERTAINING TO ADVANCED
DRY FLUE GAS DESULFURIZATION BY-PRODUCTS

TABLE B-1. SOLIDS LEACHATE ANALYSIS:
5-MW DOE-HALT TORONTO PILOT
(LAB REPORT)

RCRA Metals	Range of 11 Analyses (mg/L)
Arsenic	<0.002 - 0.084
Barium	0.3 - 5.6
Cadmium	<0.005 - 0.023
Chromium	0.05 - 0.08
Lead	<0.03 - 0.08
Mercury	<0.0002 - 0.0006
Selenium	<0.004 - 0.06
Silver	0.01 - 0.05

Reference: Babu, 1989.

TABLE B-2. MAJOR AND MINOR SPECIES IN SPRAY DRYER BY-PRODUCTS

Station	Sample Collection Point	Recycle [lb recycled lb feed]	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₂	SO ₃	CU ₂	MnO ^a	Total
Conasche	Spray Dryer	2	18.	8.9 7.7 ^d	0.77 0.82 ^d	3.1 3.1 ^d	23. 23.	2.0 2.0 ^d	1.5 1.6 ^d	0.40 0.37 ^d	5.3	5.7	6.5 6.6 ^d	2.6	78.
Conasche	Baghouse	2	18.	12.	0.97	3.9	28.	2.8	1.3	0.58	4.3	4.9	3.3	6.0	83.
Joliet	Baghouse	9	51.	13.	0.87	6.3	13.	2.2	2.0	0.76	3.8	2.6	0.44	2.0	98.
Joliet	Baghouse	9.4	32.	14.	0.77	6.7	17.	3.0	1.9	1.0	7.0	6.3	0.70	0.8	88.
Joliet	Baghouse	11.5	30.	17.	1.1	6.3	21.	3.6	2.0	0.95	4.5	2.9	0.75	2.7	93.
Martin Drake	Mixed ^b	NR ^c	51.	21.	0.65	4.1	9.9	1.4	1.6	1.1	2.2	1.5	0.53	0.4	95
Riverside	Baghouse	NR	24.	11. 11.4	0.51 0.53 ^d	2.8 3.0 ^d	20. 20.	2.5 2.5 ^d	.36 .35 ^d	0.52 0.55 ^d	5.2 4.5 ^d	11.4 11.5 ^d	1.1	1.9	81.
Sherburne County	Baghouse	5	34.	14.	0.55	5.4	28.	3.2	.98	0.92	1.4	8.4	4.1	1.8	103.

^aThese values represent estimates of hydrosulfide concentrations and do not include water of hydration.

^bMixed sample: 75 percent spray dryer product and 25 percent baghouse product.

^cNot reported.

^dDuplicate determination.

Reference: Thompson et al., 1982

TABLE B-3. CONCENTRATIONS OF MAJOR AND MINOR SPECIES IN BY-PRODUCTS
FROM SPRAY DRYER SYSTEMS

Component	Boyd et al., 1986	Dawson et al., 1988b
SiO ₂	21.1 - 32.4 %	16 - 26 %
Al ₂ O ₃	8.5 - 23	6.3 - 13
Fe ₂ O ₃	4.2 - 6.8	1.6 - 7.7
CaO	19.7 - 32.2	18 - 31
Na ₂ O	2.7 - 4.7	0.9 - 4.6
K ₂ O	0.37- 0.5	0.2 - 0.84
MgO	5.8 - 6.0	0.65- 4.6
Sulfate	6.2 - 6.6	12 - 22
TiO ₂	NR	0.27- 0.92
Hydroxide	NR	0.45- 8.2

NR = Not reported.

Note: Sulfur content of coal was not stated in report by Boyd et al., 1986.
All systems operated on flue gas from boilers burning low-sulfur
western subbituminous or northern Great Plains lignite coals in report
by Dawson et al., 1988b.

TABLE B-4. TYPICAL CALCIUM SPRAY DRYER BY-PRODUCT COMPOSITIONS

Parameter	Low Sulfur Coal (%)	High Sulfur Coal (%)
Fly ash	75	40
CaSO ₄ (mixed hydrates)	6	15
CaSO ₃ ·½H ₂ O	13	38
Ca(OH) ₂	4	5
Water	2	2

Reference: Dawson et al., 1987.

TABLE B-5. CHEMICAL CHARACTERIZATION OF SPRAY DRYER SOLIDS
(mg/kg except where noted)

Parameter	Concentration Ranges
<u>Inorganic Elements</u>	
Aluminum	33,300 - 66,700
Antimony	5.6 - 29
Arsenic	< 12 - 22
Barium	190 - 6,060
Beryllium	0.8 - 3.1
Boron	< 10 - 230
Cadmium	< 0.4 - 5.8
Calcium	126,200 - 223,000
Chromium	36 - 210
Cobalt	9.9 - 26
Copper	20 - 160
Iron	10,900 - 53,700
Lead	< 16 - 44
Lithium	18 - 42
Magnesium	3,880 - 27,700
Manganese	55 - 680
Molybdenum	2.7 - 514
Nickel	17 - 110
Potassium	1,760 - 7,020
Selenium	71 - 283
Silicon	72,800 - 120,000
Silver	1.6 - 5.8
Sodium	6,540 - 34,000
Strontium	184 - 3,040
Thallium	< 18
Tin	< 24 - 349
Titanium	1,610 - 5,360
Uranium	< 25 - 140
Vanadium	72 - 180
Zinc	< 6 - 79

TABLE B-5. (Continued)

Parameter	Concentration Ranges
<u>Volatile Metals</u>	
Arsenic	6.5 - 48
Cadmium	< 0.2 - 0.6
Lead	< 0.3 - 14
Mercury	< 0.05 - 0.4
Selenium	< 0.4 - 7.3
Hydroxide (mg/g)	4.4 - 81.8
Acid Soluble Sulfur (mg/g as S)	41 - 73
Water Soluble Sulfate (mg/g as S)	3 - 22
Water Soluble Sulfite (mg/g as S)	19 - 69
Water Soluble Chloride (mg/g)	0.3 - 2.2
Water Soluble Carbonate (mg/g)	< 2.5 - 4.3
Water Soluble Fluoride (mg/g)	0.3 - 0.5
<u>Radioactivity</u>	
Gross alpha (pCi/g)	6.0 - 29
Gross beta (pCi/g)	34.6 - 54
Ra-226 (pCi/g)	1.79 - 7.63
U-235 (pCi/g)	0.02 - 1.71

Organics (primarily polyaromatic hydrocarbons) not detected.

Reference: Dawson et al., 1988b.

TABLE B-6. TRACE ELEMENT ANALYSES^a OF CALCIUM SPRAY DRYER BY-PRODUCT

Element	SOLID SAMPLE ^b		NEUTRAL EXTRACT ^c		EP EXTRACT ^d		MCL for Drinking Water	Detection Limit (mg/L)
	(µg/g)	(µg/g)	Unacid ^e (mg/L)	Acid (mg/L)	Unacid ^e (mg/L)	Acid (mg/L)		
Aluminum	58,000	58,000	1.8	1.1	1.3	2.3	-	0.05
Antimony	8	8	<0.2	<0.2	<0.2	<0.2	-	0.03
Arsenic	30	28	<0.003	<0.003	<0.003	<0.003	0.05(P)	0.003
Barium	350	820	0.96	1.0	0.93	1.5	1. (P)	0.0006
Beryllium	4.3	4.0	<0.003	<0.003	<0.003	<0.003	-	0.0005
Boron	ND ^f	ND ^f	1.9	1.7	1.4	1.6	-	0.009
Cadmium	11.0	11.0	<0.0005	<0.0005	<0.0005	<0.0005	0.010(P)	0.0005
Calcium	150,000	150,000	360	360	2,300	2,400	-	0.04
Chromium	52	39	0.31	0.24	<0.005	0.099	0.05(P)	0.001
Cobalt	4.9	4.8	<0.03	<0.03	<0.03	<0.03	-	0.006
Copper	16	33	0.19	0.066	0.019	0.086	1. (S)	0.001
Iron	20,000	21,000	0.082	0.064	0.084	0.089	0.3 (S)	0.007
Lead ^g	120	120	<0.002	<0.002	<0.002	<0.002	0.05(P)	0.003
Magnesium	15,000	15,000	0.62	0.33	0.56	240	-	0.003
Manganese	630	630	0.015	0.009	0.009	4.6	0.05(S)	0.001
Mercury	ND ^f	ND ^f	0.0004	0.001	<0.0002	0.0004	0.002(P)	0.0002
Molybdenum	16	16	0.53	0.49	0.52	0.55	-	0.002
Nickel	215	220	0.05	0.031	0.03	0.18	-	0.003
Potassium	4,300	4,600	7.9	9.7	9.5	8.9	-	0.04
Selenium	120	120	<0.004	<0.003	0.01	0.012	0.01(P)	0.004
Silver	10.5	10.5	<0.01	<0.01	<0.01	<0.01	0.05(P)	0.002
Sodium	2,700	2,600	15	14	17	19	-	0.005
Strontium	1,900	1,960	12	12	16	17	-	0.001
Thallium	125	125	<0.4	<0.4	<0.4	<0.45	-	0.09
Tin	136	130	<0.6	<0.6	<0.6	<0.6	-	0.12
Titanium	3,100	3,200	0.03	<0.03	<0.02	<0.025	-	0.003
Vanadium	580	610	0.47	0.35	0.7	0.82	-	0.003
Zinc	37	23	0.022	<0.02	<0.02	<0.02	5. (S)	0.003

^aConcentrations measured using inductively coupled argon plasma emission spectrometry unless otherwise noted.

^bDuplicate digestion and analysis were carried out on solid samples; duplicate extractions and analyses were carried out on unacid samples.

^cNeutral extract obtained using EP extraction procedure, but without acetic acid addition.

^dEP Extraction Procedure described in Federal Register 42 (98) 33127, May 19, 1980.

^eMaximum Contaminant Levels for public drinking water supplies: Primary (P), Federal Register 40 (24), December 24, 1975; Secondary (S), Federal Register 42 (62), March 31, 1977.

^fND, Not determined because boron and mercury are lost during digestion procedure.

^gNot determined because boron and mercury are lost during digestion procedure.

Reference: Thompson et al., 1982

TABLE B-7. TRACE ELEMENT CONCENTRATIONS FOUND IN BY-PRODUCTS
FROM SPRAY DRYER SYSTEMS

Element	Concentrations
Aluminum	1.8 - 11 %
Antimony	7.5 - 8 ppm
Arsenic	14.2 - 47 ppm
Barium	100 - 2000 ppm
Beryllium	4 - 63 ppm
Boron	500 ppm
Cadmium	0.5 - 70 ppm
Chromium	27 - 130 ppm
Cobalt	4.8 - 80 ppm
Copper	8.1 - 170 ppm
Iron	1 - 36.7 %
Lead	4.4 - 150 ppm
Manganese	45 - 630 ppm
Mercury	< 0.5 ppm
Molybdenum	0.5 - 33 ppm
Nickel	13 - 460 ppm
Selenium	4.7 - 20 ppm
Silver	0.2 - 0.5 ppm
Strontium	84 - 2500 ppm
Sulfate	6.2 - 6.6 %
Thallium	20 - 30 ppm
Tin	30 - 36 ppm
Vanadium	0.4 - 610 ppm
Zinc	12 - 330 ppm
Radioactivity	0.3 - 74 pCi

Reference: Boyd et al., 1986. (Sulfur content of coal was not indicated.)

TABLE B-8. SUMMARY OF ELEMENTAL CONCENTRATION RANGES
IN EIGHT SPRAY DRYER BY-PRODUCTS

Component	Concentration (mg/kg)	
Aluminum	33,300	- 66,700
Barium	190	- 3,390
Beryllium	1.4	- 3.1
Boron	< 10	- 230
Calcium	126,200	- 223,000
Chromium	36	- 210
Cobalt	9.9	- 26
Copper	20	- 160
Iron	10,900	- 53,700
Lithium	18	- 42
Magnesium	3,880	- 27,700
Manganese	55	- 680
Molybdenum	2.7	- 514
Nickel	17	- 52
Potassium	1,760	- 7,020
Silicon	72,800	- 120,000
Silver	1.6	- 5.8
Sodium	6,540	- 34,000
Strontium	184	- 3,390
Titanium	1,610	- 4,500
Vanadium	72	- 180
Zinc	22	- 110
<u>Volatile Metals</u>		
Arsenic	3.6	- 4.8
Cadmium	0.2	- 0.63
Lead	< 0.3	- 19
Mercury	0.07	- 0.39
Selenium	< 0.5	- 7.3
<u>Soluble Anions</u>		
Chloride	0.4	- 1.9
Fluoride	0.5	- 1.1
Hydroxide (mg/g)	5	- 83
Sulfur (Total)	51	- 134
Sulfite	16	- 103

Reference: Eklund et al., 1986. (Sulfur content of coal not indicated.)

TABLE B-9. CRYSTALLINE SPECIES IDENTIFIED IN BY-PRODUCTS FROM DRY SCRUBBING SYSTEMS

Sulfites

Calcium sulfite hemihydrate
 Sodium sulfite

Sulfates

Calcium sulfate
 Calcium sulfate hemihydrate
 (plaster of Paris)
 Calcium sulfate dihydrate (gypsum)
 Calcium aluminum sulfate hydrate
 (ettringite)
 Sodium sulfate (thenardite)
 Sodium carbonate sulfate (burkeite)

Hydroxides

Calcium hydroxide (portlandite)
 Magnesium hydroxide (brucite)

Carbonates

Calcium carbonate (calcite)

Silicates

Silica (a-quartz)
 Aluminum silicate (mullite)

Reference: Thompson et al., 1982.

TABLE B-10. SUMMARY OF ELEMENTAL CONCENTRATION RANGES IN RCRA EP LEACHATES
AND ASTM LEACHATE FOR SPRAY DRYER BY-PRODUCTS (in mg/L)

Component	EP	ASTM
<u>Metals</u>		
Aluminum	<0.05 - 2.3	<0.05 - 13
Barium	0.23 - 1.5	0.40 - 2.7
Beryllium	<0.001 - 0.002	<0.001 - 0.009
Boron	0.31 - 11	2.6 - 7.8
Calcium	2240 - 2870	140 - 1090
Chromium	0.019 - 0.28	0.12 - 0.51
Cobalt	<0.006 - 0.025	<0.006 - 0.096
Copper	0.003 - 0.026	0.007 - 0.16
Iron	0.024 - 0.13	0.016 - 0.14
Lithium	0.015 - 0.43	0.13 - 0.72
Magnesium	0.29 - 370	0.12 - 2.6
Manganese	<0.001 - 0.19	0.002 - 0.22
Molybdenum	0.05 - 0.35	0.17 - 0.51
Nickel	<0.003 - 0.73	<0.003 - 0.093
Potassium	<0.05 - 6.5	2.9 - 22
Silicon	<0.02 - 13	0.34 - 0.72
Silver	0.003 - 0.037	0.009 - 0.23
Sodium	7.7 - 77	16 - 97
Strontium	<0.001 - 24	2.3 - 16
Titanium	<0.005 - 0.045	0.015 - 0.31
Vanadium	0.057 - 0.17	0.015 - 0.30
Zinc	<0.003 - 0.064	0.01 - 0.22
<u>Volatile Metals</u>		
Arsenic	<0.002 - 0.004	<0.002 - 0.005
Cadmium	<0.0005 - 0.0006	<0.0005 - 0.001
Lead	<0.002	<0.002
Mercury	<0.0002	<0.0002
Selenium	<0.002 - 0.034	<0.003 - 0.055
<u>Anions</u>		
Carbonate	30 - 110	20 - 40
Chloride	10 - 46	18 - 33
Fluoride	0.5 - 10	--
Sulfate	220 - 1800	320 - 2400
Nitrate	3.5 - 43	10 - 200
Nitrite	15.2 - 32	8 - 160
TDS	9100 - 10600	2180 - 3700

TABLE B-10 (Continued)

Component	EP	ASTM
<u>Anions (cont.)</u>		
Cyanide	<0.01 - 0.02	<0.01 - 0.04
Bromide	<0.5	<0.5
Phosphorus	<0.02	<0.02
pH	7.65 - 11.8	9.8 - 12
Hydroxide	--	--
Sulfite	41 - 491	102 - 1090

Reference: Eklund et al., 1986. Sulfur content of coal burned is not indicated.

TABLE B-11. RCRA EP CHEMICAL CHARACTERIZATION OF SPRAY DRYER BY-PRODUCTS
(mg/L except where noted)

Parameter	Concentration Ranges		
<u>Inorganic Elements</u>			
Aluminum	< 0.05	-	4.4
Antimony	< 0.02	-	0.4
Arsenic	< 0.06	-	0.46
Barium	0.1	-	1.5
Beryllium	< 0.001	-	0.37
Boron	< 0.5	-	19
Cadmium	< 0.002		
Calcium	2,110	-	2,980
Chromium	0.019	-	0.28
Cobalt	< 0.006	-	0.028
Copper	0.003	-	0.042
Iron	0.01	-	0.21
Lead	< 0.08	-	0.15
Lithium	0.014	-	0.43
Magnesium	0.29	-	410
Manganese	< 0.001	-	0.38
Molybdenum	0.05	-	0.35
Nickel	< 0.003	-	0.73
Potassium	< 0.05	-	21
Selenium	< 0.08	-	0.24
Silicon	< 0.02	-	13
Silver	0.003	-	0.066
Sodium	7.4	-	350
Strontium	< 0.001	-	40
Thallium	< 0.09	-	0.11
Tin	< 0.1		
Titanium	< 0.005	-	0.088
Uranium	< 0.3	-	5.1
Vandium	0.057	-	0.17

TABLE B-11. (Continued)

	Concentration Ranges	
Zinc	< 0.003	- 0.064
<u>Volatile Metals</u>		
Arsenic	< 0.002	- 0.016
Cadmium	0.0004	- 0.0006
Lead	< 0.0002	
Mercury	< 0.0002	- 0.0005
Selenium	< 0.002	- 0.047
Carbonate	< 5	- 110
Sulfate	220	- 2,100
Sulfite	18	- 490
Chloride	10	- 110
Nitrate	< 1	- 32
Total Dissolved Solids	9,040	- 10,600
Cyanide	< 0.01	- 0.03
Bromide	< 0.5	- 0.6
Phosphorus	< 0.007	- 0.16
Fluoride	0.5	- 10
pH	7.65	- 12.0

Reference: Dawson et al., 1988b.

TABLE B-12. NEUTRAL SPRAY DRYER LEACHATE CHEMICAL CHARACTERIZATION
(mg/L except where noted)

Component	Concentration Ranges		
<u>Inorganic Elements</u>			
Aluminum	< 0.05	-	13
Antimony	< 0.02	-	0.6
Arsenic	< 0.06	-	1.7
Barium	0.19	-	4.5
Beryllium	< 0.001	-	0.01
Boron	< 0.05	-	7.8
Cadmium	< 0.002	-	0.047
Calcium	140	-	1,230
Chromium	0.071	-	0.51
Cobalt	< 0.006	-	0.16
Copper	0.007	-	0.25
Iron	0.012	-	0.25
Lead	< 0.08	-	0.93
Lithium	0.051	-	0.72
Magnesium	0.12	-	1.6
Manganese	0.002	-	0.22
Molybdenum	0.074	-	0.51
Nickel	< 0.003	-	0.2
Potassium	2.9	-	89
Selenium	< 0.08	-	1.0
Silicon	0.34	-	5.3
Silver	0.009	-	0.37
Sodium	16	-	1,130
Strontium	2.3	-	19
Thallium	< 0.01	-	0.24
Tin	< 0.1	-	4.0
Titanium	0.015	-	0.47
Uranium	< 0.03	-	3.8

TABLE B-12. (Continued)

Component	Concentration Ranges		
Vanadium	0.015	-	0.5
Zinc	< 0.003	-	0.22
<u>Volatile Metals</u>			
Arsenic	< 0.002	-	0.005
Cadmium	< 0.0005		
Lead	< 0.001	-	0.008
Mercury	< 0.0002	-	0.0004
Selenium	< 0.003	-	0.14
Carbonate	< 5	-	40
Hydroxide	44	-	1,150
Sulfate	250	-	3,300
Sulfite	30	-	1,098
Chloride	13	-	330
Nitrate	10	-	200
Nitrite	< 2	-	160
Total Dissolved Solids	2,180	-	6,000
Cyanide	< 0.01	-	0.04
Bromide	< 0.15	-	18
Phosphorus	< 0.02	-	0.04
Fluoride	0.2	-	9.8
pH	9.8	-	12.1

Reference: Dawson et al., 1988b.

TABLE B-13. TCLP CHEMICAL CHARACTERIZATION OF SPRAY DRYER
BY-PRODUCTS (mg/L)

Element	Concentration Ranges
Arsenic	0.19 - 0.38
Barium	0.53 - 15
Cadmium	< 0.002 - 0.006
Chromium	0.053 - 0.29
Iron	0.015 - 0.18
Lead	0.10 - 0.17
Mercury	< 0.0002
Selenium	< 0.08 - 0.31
Silver	0.039 - 0.078

Reference: Dawson et al., 1988b.

TABLE B-14. CHEMICAL CHARACTERISTICS OF RAW AND SPENT NAHCOLITE

Raw Nahcolite		Spent Nahcolite	
Constituent	% Dry Weight	Constituent	% Dry Weight
NaHCO ₃	70	NaHCO ₃	1
Na ₂ CO ₃	<u>3</u>	Na ₂ CO ₃	17
Subtotal	73	Na ₂ SO ₃	35
		Na ₂ SO ₄	<u>14</u>
		Subtotal	67
MgCO ₃	3	MgCO ₃ -MgSO ₄	4
H ₂ O	2	H ₂ O	2
Other Materials	22	Other Materials	27
(CaCO ₃ , SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , FeS ₂ , Na ₂ O, K ₂ O, Organic Sulfur, Organic Carbon)		(CaCO ₃ , SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , FeS ₂ , Na ₂ O, K ₂ O, Organic Sulfur, Organic Carbon)	
Total	100	Total	100

Reference: Vuceta et al., 1980.

TABLE B-15. CHEMICAL CONSTITUENTS IN DRY SODIUM INJECTION
BY-PRODUCTS

Element	Composition Range*
Aluminum	3.3 - 4.5 %
Arsenic	16 - 32 ppm
Barium	87 - 820 ppm
Cadmium	0.5 - 0.8 ppm
Chromium	77 - 130 ppm
Copper	10 - 22 ppm
Iron	2.4 - 3.0 %
Lead	5.5 - 16 ppm
Manganese	190 - 300 ppm
Mercury	0.3 - 0.8 ppm
Molybdenum	0.5 - 1.7 ppm
Nickel	36 - 78 ppm
Selenium	4.2 - 4.9 ppm
Silver	0.1 - 1.7 ppm
Sodium	17 - 50 %
Strontium	270 - 960 ppm
Sulfate	12 - 23 %
Vanadium	35 - 44 ppm
Zinc	50 - 54 ppm

* Represent data from sources analyzed by Boyd et al. (1986).

TABLE B-16. PHYSICAL DATA FOR DRY SODIUM INJECTION BY-PRODUCTS

Physical/Engineering Parameter	Composition Range*
pH	10.8 - 12.8
Particle size	12 - 28 microns
Particle specific gravity	2.30 - 2.39 g/cc
Bulk density (aerated)	44.3 - 51.8 pcf
Bulk density (packed)	53.7 - 63.1 pcf
Moisture content (natural)	0.4 - 0.7 %

* Represent data from four sources analyzed by Boyd et al. (1986).

TABLE B-17. CHEMICAL COMPOSITION OF COOLSIDE BY-PRODUCTS

Component	By-Product Generated with the NaOH Additive	By-Product Generated without the NaOH Additive
<u>Analysis, wt% as received</u>		
Moisture	1.7	2.9
Ash	83.5	80.3
Carbon	5.8	7.6
Hydrogen	1.2	1.4
Nitrogen	0.1	0.1
Sulfur (Total)	7.7	4.8
Sulfate Sulfur	2.2	1.0
Sulfite Sulfur	5.6	4.2
Carbonate (CO ₃ ²⁻)	7.6	5.1
<u>Elemental Analysis, wt% of ash</u>		
Na ₂ O	4.9	0.5
K ₂ O	0.7	1.1
CaO	44.5	44.6
MgO	0.6	0.8
Fe ₂ O ₃	3.5	5.5
TiO ₂	0.3	0.4
P ₂ O ₅	0.1	0.2
SiO ₂	14.0	22.2
Al ₂ O ₃	5.9	9.4
SO ₃	23.4	14.5
Unaccounted	2.1	0.8

Reference: Wu and Winschel, 1988.

TABLE B-18. LEACHATE COMPOSITIONS OF COOLSIDE BY-PRODUCTS GENERATED WITH AND WITHOUT THE NaOH ADDITIVE

Analysis	Allowable Limit by RCRA (a)	Allowable Limit by the State of Ohio (b)	Leachate Concentration, mg/L			
			By-Product Generated With the Sodium Hydroxide Additive		By-Product Generated Without the Sodium Hydroxide Additive	
			Acetic Acid Extraction	Deionized Water Extraction	Acetic Acid Extraction	Deionized Water Extraction
Hydroxide as CaCO ₃	-	-	1,267	2,817	1,680	2,035
Carbonate as CaCO ₃	-	-	< 20	126	< 20	212
Total Suspended Solids	-	-	17	3	15	3
Total Dissolved Solids	-	15,000	12,598	5,478	9,858	2,688
Calcium	-	-	2,676	895	2,961	1,155
Sodium	-	-	1,245	1,320	48.8	43.3
Arsenic	5	1.5	0.003	0.001	< 0.005	0.001
Barium	100	30	< 0.4	0.35	0.52	0.51
Cadmium	1	0.3	0.0006	0.0007	0.0009	0.0008
Chromium	5	1.5	0.13	0.099	0.10	0.082
Lead	5	1.5	0.0031	0.0019	0.0029	0.0015
Mercury	0.2	0.06	0.0001	0.0002	< 0.0001	< 0.0002
Silver	5	1.5	< 0.025	< 0.025	< 0.025	< 0.025
Selenium	1	0.3	< 0.03	< 0.05	< 0.015	< 0.008
Nitrate (as N)	-	300	(c)	1.0	(c)	2.0
Fluoride	-	42 to 72	(c)	0.01	(c)	< 0.01
Chloride	-	7,500	(c)	6.0	(c)	8.0
Sulfate	-	7,500	1,437	2,032	557	944

TABLE B-18. (Continued)

Analysis	Allowable Limit by RCRA (a)	Allowable Limit by the State of Ohio (b)	Leachate Concentration, mg/L			
			By-Product Generated With the Sodium Hydroxide Additive		By-Product Generated Without the Sodium Hydroxide Additive	
			Acetic Acid Extraction	Deionized Water Extraction	Acetic Acid Extraction	Deionized Water Extraction
Iron	-	9	< 0.2	< 0.2	< 0.2	< 0.2
Zinc	-	150	0.059	< 0.02	< 0.02	< 0.02
Manganese	-	1.5	< 0.02	< 0.02	< 0.02	< 0.02
Copper	-	30	0.068	0.020	0.029	0.023

(a) 100 times the EPA primary drinking water standards

(b) 30 times the EPA primary and secondary water standards

(c) Not determined due to interferences in analytical procedure

Reference: Wu and Winschel, 1988.

TABLE B-19. THE EFFECT OF CURING ON COOLSIDE SLUDGE LEACHATE COMPOSITION

Analysis	Leachate Concentration, mg/L				
	Allowable Limit by RCRA (a)	Allowable Limit by the State of Ohio (b)	By-Product as Collected (c)		Cured By-Product (d)
			Acetic Acid Extraction	Deionized Water Extraction	Acetic Acid Extraction
Hydroxide as CaCO ₃	-	-	1,267	2,817	1,463
Carbonate as CaCO ₃	-	-	< 20	126	< 20
Total Suspended Solids	-	-	17	3	17
Total Dissolved Solids	-	15,000	12,598	5,478	10,266
Calcium	-	-	2,676	895	2,201
Sodium	-	-	1,245	1,320	1,097
Arsenic	5	1.5	0.003	0.001	< 0.005
Barium	100	30	< 0.4	0.35	1.0
Cadmium	1	0.3	0.0006	0.0007	0.0008
Chromium	5	1.5	0.13	0.099	0.076
Lead	5	1.5	0.0031	0.0019	0.0062
Mercury	0.2	0.06	0.0001	0.0002	0.0001
Silver	5	1.5	< 0.025	< 0.025	< 0.025
Selenium	1	0.3	< 0.03	< 0.050	< 0.0015
Nitrate (as N)	-	300	(e)	1.0	(e)
Fluoride	-	42 to 72	(e)	0.01	(e)
Chloride	-	7,500	(e)	6.0	(e)
					2.470
					211
					6
					4,848
					870.3
					1,265
					0.001
					0.35
					0.001
					0.07
					0.006
					0.0002
					< 0.025
					< 0.0015
					2.0
					0.01
					4.0

TABLE B-19. (Continued)

Analysis	Leachate Concentration, mg/L			
	Allowable Limit by RCRA (a)	Allowable Limit by the State of Ohio (b)	By-Product as Collected (c)	
			By-Product Acetic Acid Extraction	Deionized Water Extraction
Sulfate	-	7,500	1,437	1,391
Iron	-	9	< 0.02	< 0.2
Zinc	-	150	0.059	0.093
Manganese	-	1.5	< 0.02	< 0.02
Copper	-	30	0.068	0.098

(a) 100 times the EPA primary drinking water standards

(b) 30 times the EPA primary and secondary drinking water standards

(c) Waste generated with the NaOH additive

(d) The same waste as in (c), mixed with the optimum moisture, compacted (ASTM Method D-698) and cured in a humidity chamber for 28 days

(e) Not determined due to interferences in analytical procedure.

Reference: Wu and Winschel, 1988.

TABLE B-20. EPA-EP LEACHING TEST RESULTS FOR FLY ASHES FROM
PRESSURE-HYDRATED LIME INJECTION TESTS USING
PITTSBURGH NO. 8 BITUMINOUS COAL

Element*	Baseline Ash (No Lime Injected)	Ash from 50% SO ₂ Removal Test	Ash from 90% SO ₂ Removal Test
Arsenic	0.9	0.0085	0.0023
Barium	0.06	0.38	0.32
Cadmium	<0.1	<0.1	<0.1
Chromium (Total)	<0.05	0.08	0.1
Lead	<0.5	<0.5	<0.5
Mercury	0.0018	0.0008	0.0012
Selenium	0.0044	0.0026	<0.002
Silver	<0.5	<0.5	<0.5

* All elemental concentrations measured for the EPA-EP leachates have units of mg/L.

Source: Moretti and Henke, 1988.

TABLE B-21. MAXIMUM ALLOWABLE LEVELS OF LEACHATE CONTAMINANTS FOR RCRA
HAZARDOUS WASTE CLASSIFICATION

Element	Maximum Allowable Leachate Concentration (mg/L)
Arsenic	5.0
Barium	100
Cadmium	1.0
Chromium	5.0
Lead	5.0
Mercury	0.2
Selenium	1.0
Silver	5.0

Source: Moretti and Henke, 1988.

TABLE B-22. ASTM LEACHING TEST RESULTS FOR FLY ASHES FROM
PRESSURE-HYDRATED LIME INJECTION TESTS USING
PITTSBURGH NO. 8 BITUMINOUS COAL

Element*	Baseline Ash (No Lime Injected)	Ash from 50% SO ₂ Removal Test	Ash from 90% SO ₂ Removal Test
Aluminum	0.6	<0.5	<0.5
Arsenic	1.2	0.0046	0.0031
Barium	0.16	0.34	0.31
Boron	41	3.0	4.4
Cadmium	<0.1	<0.1	<0.1
Calcium	680	1700	2000
Chromium (Total)	<0.05	<0.05	0.22
Lead	<0.5	<0.5	<0.5
Mercury	0.001	0.0015	0.001
Selenium	0.0093	0.0096	0.0059
Sodium	39	8.4	8.1
Sulfate	2040	1720	1659
pH	5.9	12.5	12.5

* All elemental concentrations measured for the ASTM leachates have units of mg/L.

Source: Moretti and Henke, 1988.

TABLE B-23. ELEMENTAL COMPOSITIONS OF FLY ASHES FROM PRESSURE-HYDRATED LIME INJECTION TESTS USING PITTSBURGH NO. 8 BITUMINOUS COAL

Element*	Baseline Ash (No Lime Injected)	Ash from 50% SO ₂ Removal Test	Ash from 90% SO ₂ Removal Test
Silicon	23.5%	8.4%	3.4%
Aluminum	11.6%	4.4%	1.8%
Iron	14.7%	7.3%	3.4%
Calcium	1.75%	29.0%	42.8%
Magnesium	0.8%	0.5%	0.3%
Sodium	<0.1%	<0.1%	<0.1%
Potassium	2.2%	0.7%	0.1%
Sulfur	0.6%	8.2%	7.1%
Phosphorus	0.1%	0.4%	0.3%
Titanium	0.7%	0.4%	0.2%
Arsenic	240	90	40
Barium	360	300	190
Copper	70	40	40
Chromium	140	60	20
Manganese	1300	150	80
Nickel	120	<10	<10
Strontium	200	170	150
Zinc	160	70	10

* Elemental concentrations for the waste materials are in units of either percent of dry weight or micrograms/gram of waste. All analyses were done by X-ray fluorescence.

Source: Moretti and Henke, 1988.

TABLE B-24. MINERAL COMPOSITIONS OF FLY ASHES FROM PRESSURE-HYDRATED
LIME INJECTION TESTS USING PITTSBURGH NO. 8 BITUMINOUS COAL

Baseline Ash:
(No Lime Injected)

Major Phases: Amorphous Phases, Quartz (SiO_2), Spinel (Fe_3O_4)
Minor Phases: Hematite (Fe_2O_3)

Ash From 50% SO_2 Reduction Test:

Major Phases: Anhydrite (CaSO_4) and Lime (CaO)
Minor Phases: Quartz (SiO_2)

Ash From 90% SO_2 Reduction Test:

Major Phases: Anhydrite (CaSO_4) and Lime (CaO)

Source: Moretti and Henke, 1988.

TABLE B-25. PHYSICAL PROPERTIES OF FLY ASHES FROM HYDRATED-LIME INJECTION TESTS USING PITTSBURGH NO. 8 BITUMINOUS COAL

	Baseline Ash (0% SO Removal)	Ash from 50% SO ₂ Removal Test	Ash from 90% SO ₂ Removal Test
Permeability Coefficient (cm/sec)	1.3 x 10 ⁻⁶	2.5 x 10 ⁻⁸	1.3 x 10 ⁻⁸
Particle Density (gm/ml)	1.87	1.82	2.58
Compacted Dry Density (lbs/cu.ft)	93.5	80.9	66.0
Optimum Moisture Content (% Dry Wt.)	22.5	23.0	25.0
Specific Surface Area (m ² /gm)	1.47	1.52	1.91
Loss On Ignition (wt%)	3.2	1.0	1.8
Exothermal Hydration	None	Slight	Extreme

Source: Moretti and Henke, 1988.

APPENDIX C

DATA TABLES PERTAINING TO
FLUIDIZED BED COMBUSTION (FBC) BY-PRODUCTS

TABLE C-1. ANALYSIS OF CONVENTIONAL PCF¹ FLY ASH AND PFBC ASH
(weight percent as oxides)

Parameter	PCF Fly Ash ¹ (%)	PFBC Bed Ash ² (%)	PFBC Fly Ash ² (%)
Silica, SiO ₂	50.7	6.7	24.3
Aluminum Oxide, Al ₂ O ₃	24.3	3.4	10.1
Iron Oxide, Fe ₂ O ₃	17.3	1.6	12.3
Titanium Oxide, TiO ₂	1.4	0.1	0.7
Calcium Oxide, CaO	1.5	32.2	20.4
Magnesium Oxide, MgO	0.8	21.4	10.6
Sodium Oxide, Na ₂ O	0.4	0.1	0.3
Potassium Oxide, K ₂ O	2.4	0.2	1.1
Phosphorus Pentoxide, P ₂ O ₅	--	0.1	0.1
Sulfur Trioxide, SO ₃	0.5	26.1	9.9
Ignition Loss	0.7	8.1	10.2
	<u>100%</u>	<u>100%</u>	<u>100%</u>

1 Fly ash obtained from a conventional pulverized coal-fired plant burning similar coal.

2 PFBC bed ash and fly ash samples were obtained from a test burn of Pittsburgh No. 8 coal and Ohio dolomite shipped by AEP to the PFBC component test facility in Malmo, Sweden.

Reference: Robida et al., 1988.

TABLE C-2. CONVENTIONAL PCF FLY ASH AND PFBC ASH
EPA EP TOXICITY TEST RESULTS

Component	Fly Ash ¹ (mg/L)	PFBC Bed Ash ² (mg/L)	PFBC Fly Ash ² (mg/L)	Primary Drinking Water Standards (mg/L)
As	0.180	0.008	< 0.005	0.05
Ba	< 0.441	2.1	0.78	1.0
Cd	0.048	0.1	0.04	0.01
Cr	< 0.110	0.1	< 0.08	0.05
Pb	0.223	0.22	0.056	0.05
Hg	< 0.001	< 0.0002	< 0.002	0.002
Se	< 0.02	< 0.01	< 0.01	0.01
Ag	< 0.01	0.1	0.06	0.05
SO ₄	--	2790.0	2180.0	--
Ca	--	3900.0	1400.0	--
Mg	--	4400.0	720.0	--

1 Fly ash obtained from a conventional pulverized coal-fired plant burning similar coal.

2 PFBC bed ash and fly ash samples were obtained from a test burn of Pittsburgh No. 8 coal and Ohio dolomite shipped by AEP to the PFBC component test facility in Malmo, Sweden.

Reference: Robida et al., 1988.

TABLE C-3. CONVENTIONAL PCF FLY ASH AND PFBC ASH
ASTM D-3987-81 LEACHATE TEST RESULTS

Component	PCF Fly Ash ¹ (mg/L)	PFBC Bed Ash ² (mg/L)	PFBC Fly Ash ² (mg/L)	Primary Drinking Water Standards (mg/L)
As	0.766	< 0.01	< 0.005	0.05
Ba	0.64	0.58	0.66	1.0
Cd	0.059	0.02	< 0.012	0.01
Cr	0.848	< 0.08	0.08	0.05
Pb	0.315	0.03	0.038	0.05
Hg	< 0.002	0.0002	< 0.0002	0.002
Se	< 0.02	< 0.01	< 0.01	0.01
Ag	--	0.04	0.04	0.05
SO ₄	--	1980.0	1750.0	--
Ca	--	1100.0	980.0	--
Mg ³	--	0.4	0.3	--

- 1 Fly ash obtained from a conventional pulverized coal-fired plant.
- 2 PFBC bed ash and fly ash samples were obtained from a test burn of Pittsburgh No. 8 coal and Ohio dolomite shipped by AEP to the PFBC component test facility in Malmo, Sweden.
- 3 Magnesium bound up as magnesium hydroxide.

Reference: Robida et al., 1988.

TABLE C-4. SUMMARY OF CONCENTRATION RANGES IN FOUR AFBC WASTES

Component	Concentration (mg/kg)
<u>Metals</u>	
Aluminum	7,200 - 39,800
Barium	30 - 190
Beryllium	<0.2
Boron	<10 - 131
Calcium	161,700 - 321,900
Chromium	9.7 - 84
Cobalt	<1 - 6.7
Copper	8.8 - 35
Iron	16,700 - 66,100
Lithium	6.1 - 35
Magnesium	2,860 - 3,730
Manganese	87 - 160
Molybdenum	<0.4 - 17
Nickel	13 - 33
Potassium	1,300 - 8,020
Silicon	14,800 - 71,200
Silver	0.9 - 22
Sodium	180 - 1,260
Strontium	180 - 250
Titanium	430 - 2,360
Vanadium	64 - 150
Zinc	72 - 290
<u>Volatile Metals</u>	
Arsenic	11 - 44
Cadmium	0.6 - 1.1
Lead	1.1 - 9.0
Mercury	<0.05 - 1.4
Selenium	<0.7 - 1
<u>Soluble Anions</u>	
Chloride	0.4 - 1.2
Fluoride	<0.1 - 0.7
Hydroxide (mg/g)	105 - 180
Sulfur (Total)	127 - 342
Sulfite	5 - 148

Reference: Eklund et al., 1986. Sulfur content of the coal burned was not indicated.

TABLE C-5. MAJOR CHEMICAL CONTENTS OF AFBC BED BY-PRODUCTS FROM SIX UNITS

Site	Loss on Ignition*	Silicon	Iron	Aluminum	Calcium	Magnesium	Sulfur
1**	5.79	6.07	2.79	1.23	38.28	1.02	6.66
2***	12.46	7.90	2.71	1.44	20.20	7.17	8.12
3	11.79	6.50	10.10	1.57	29.90	1.92	5.85
4	3.19	6.30	2.88	2.07	34.09	0.58	9.39
5	3.72	1.93	2.67	0.93	40.38	0.12	9.70
6	10.49	1.51	2.84	0.13	40.31	0.65	6.00

Note: All analyses reported in weight percent.

* represents carbon and water of hydration.

** average of four samples.

*** average of two samples.

Reference: Dearborn Environmental Consulting Services and the Wastewater Technology Centre (1985).

TABLE C-6. TRACE COMPONENT COMPOSITION OF AN AFBC BED WASTE

Analyte	Concentration (weight percent)
Ag	< 0.0001
B	0.005
Be	0.001
Bi	< 0.001
Ca	39
Cd	< 0.003
Co	0.0005
Cr	0.005
Cu	0.003
Mg	> 0.1
Mn	0.019
Mo	0.003
Na	> 0.1
Ni	0.004
Pb	< 0.001
Sb	< 0.0033
Sn	< 0.001
Sr	0.05
Ti	> 0.1
V	0.004
Zn	< 0.0033
SO ₄	20

Reference: Dearborn Environmental Consulting Services and the Wastewater Technology Centre (1985).

TABLE C-7. RESULTS OF X-RAY DIFFRACTION ANALYSES OF FIVE AFBC BED WASTES

Compound	Source of AFBC Residue				
	Site No. 1	Site No. 2	Site No. 3	Site No. 4	Site No. 5
Calcium Sulfate	major	major	major	major	major
Calcium Oxide	major	-	major	major	major
Calcium Carbonate	-	major	minor	trace	trace
Silicon Dioxide	minor	major	minor	major	trace
Mixed Iron Oxides	minor	-	minor	minor	-

In the composition ranges, (-) is 1 percent or less, trace is 1 to 5 percent, minor is 5 to 25 percent, and major is 25 percent.

Reference: Dearborn Environmental Consulting Services and the Wastewater Technology Centre, 1985.

TABLE C-8. MAJOR CHEMICAL ELEMENT COMPOSITION OF AFBC BY-PRODUCT

Coal Type	Source	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	S	SO ₃	SO ₄	P ₂ O ₅	TiO ₂
Morgantown Energy Research Centre (subbituminous coal)	Cyclone-1	41.7	15.7	20.1	-	3.8	0.6	0.7	1.4	-	-	-	-
	Cyclone-2	40.0	16.8	15.1	-	4.6	1.6	0.8	1.4	-	-	-	-
	Bag Filter	32.9	17.3	24.8	-	6.0	1.4	0.9	2.3	-	-	-	-
Morgantown Energy Research Centre (Texas lignite)	Cyclone -1	Recycled											
	Cyclone-2	44.5	13.3	28.6	6.7	1.3	-	0.6	-	1.9	-	0.5	1.2
	Bag Filter	36.4	14.0	29.6	7.5	2.5	-	0.7	-	4.0	-	0.6	1.2
AFBC Test Facility (bituminous coal)	Fly Ash	17.5	10.5	31.5	12.5	0.4	0.4	1.0	0.4	-	17.0	-	-

* Individual elements are presented in oxide % form only. The elements may actually be present in the wastes in other forms.

Reference: Dearborn Environmental Consulting Services and Wastewater Technology Centre, 1985

TABLE C-9. TRACE CHEMICAL ANALYSES OF AFBC BY-PRODUCTS FROM THREE SITES

Analyte	Site No. 1	Site No. 2	Site No. 3	
			Cyclone	Bag Filter
Ag	<0.0001		< 0.0001	< 0.0001
As		0.003		
B	0.02	0.02	0.05	0.05
Be	0.0005	0.001	0.001	0.001
Bi	0.003	< 0.0003	< 0.001	< 0.001
Ca	9.44	16.64	18	16
Cd	<0.0003	< 0.003	< 0.0003	< 0.0003
Co	0.0005	< 0.0005	0.0015	0.0015
Cr	0.005	0.003	0.01	0.01
Cu	0.003	0.005	0.01	0.01
Mg	0.096	2.88	< 0.1	> 0.1
Mn	0.014	0.01	0.011	0.028
Mo	0.001	0.001	0.001	0.001
Na	0.02	0.1	< 0.1	> 0.1
Ni	0.002	0.005	0.007	0.007
Pb	<0.0005	0.001	0.01	0.013
Sb	<0.0033		< 0.0033	< 0.0033
Sn	<0.001	< 0.003	< 0.001	< 0.0001
Sr	0.02		0.1	0.01
Ti	<0.1	0.1	> 0.1	> 0.1
V	0.004	0.001	0.01	0.008
Zn	<0.0033	0.01	0.01	0.01
Zr	1.11	0.01		
S		15.10	4.29	3.96

Note: all analyses reported in weight percent

Reference: Dearborn Environmental Consulting Services and Wastewater Technology Centre, 1985

TABLE C-10. CHARACTERIZATION OF AFBC SOLIDS BEFORE LEACHING

Parameter/Material	Minto Bed	Devco	
		Bed	Baghouse
Aluminum	81 600	30 300	76 300
Antimony	< 100	< 100	< 100
Arsenic	176	120	308
Barium	130	65	365
Beryllium	0.27	< 0.05	8.35
Boron	94	86	183
Cadmium	4	5	5
Calcium	293 000	387 000	160 000
Total Carbon	4 000	3 000	38 000
Chromium	14	10	136
Cobalt	< 5	< 5	< 5
Copper	15.4	10.8	116
Iron	12 700	14 600	116 000
Lead	5	35	240
Lithium	40	40	130
Magnesium	4 920	2 820	7 150
Manganese	398	483	452
Molybdenum	< 30	< 30	180
Nickel	28	27	144
Phosphorus	1 530	390	1 230
Potassium	7 700	3 700	12 000
Silicon	107 000	48 300	90 100
Silver	0.7	0.7	< 0.5
Sodium	8 300	2 600	19 800
Strontium	162	150	775
Thallium	17.4 $\pm$ 2	20.6 $\pm$ 3	15 $\pm$ 3
Thorium	9.3	2.9	12
Titanium	585	845	4 260
Uranium	5.2	2.2	4.2
Vanadium	11.7	16.3	194
Zinc	49	31	154
Zirconium	57	26	87
Mercury	< 0.05	2.05	< 0.05
Total CN ⁻	< 0.1	< 0.1	< 0.1

Note: results in $\mu\text{g/g}$ unless otherwise indicated

Reference: Dearborn Environmental Consulting Services and Wastewater Technology Centre, 1985

TABLE C-11. CALCIUM SPECIES PERCENT COMPOSITION IN AFBC BY-PRODUCTS

Material	CaSO ₄	CaO	CaCO ₃
Minto Bed	3.4	33.8	5.2
Devco Bed	6.8	37.7	11.3

Reference: Dearborn Environmental Consulting Services and Wastewater Technology Centre, 1985

TABLE C-12. RADIOCHEMICAL ANALYSES OF THREE AFBC SOLID RESIDUES

Analyte	Minto	Devco	Baghouse
	Bed	Bed	
U 238	0.10	0.08	0.04
Th 234	0.10	0.07	0.05
Pa 234	0.10	0.07	0.05
U 234	0.10	0.07	0.05
Ra 226	0.11	0.10	0.03
Bi 214	0.11	0.13	0.03
Pb 210	0.20	0.12	<0.015
Pb 214	0.11	0.07	0.02
Th 232	0.035	0.07	0.015
Ra 228	0.035	0.07	0.015
Ac 228	0.035	0.07	0.015
Th 228	0.035	0.07	0.015
Ra 224	0.035	0.07	0.015
Daughters Rn 220	0.036	0.07	0.016

Note: all results are expressed in Bq/g

Reference: Dearborn Environmental Consulting Services and Wastewater Technology Centre, 1985

TABLE C-13. AFBC BY-PRODUCT PHYSICAL CHARACTERISTICS

Sample No.	Particle Size Distribution (%)				Density (lbs/ft ³)		Optimum Moisture %	Liquid Limit (%)	Plastic Limit (%)	Permeability (cm/sec)
	Gravel	Coarse Sand	Fine Sand	Silt Clay	Packed Bulk	Maximum Dry				
Spent Bed	10	7	18	0	100.46	94.28	32	NL	NP	3.4×10^{-4}
Recycle Char	0	2	38	60	82.68	73.89	36	32	NP	1.1×10^{-4}
Baghouse Ash	0	0	0	100	52.67	70.07	50	39	5	7.7×10^{-9}
Waste Composite	2	15	20	3	73.94	78.35	39	NL	NP	1.8×10^{-7}

Reference: Golden, 1988.

TABLE C-16. SUMMARY OF ELEMENTAL CONCENTRATION RANGES IN RCRA
EP LEACHATES FOR AFBC BY-PRODUCTS

Parameter	Concentration Range (in mg/L)
<u>Metals</u>	
Aluminum	<0.5
Barium	0.18 - 0.32
Beryllium	0.002
Boron	0.094 - 0.42
Calcium	3,300 - 3,450
Chromium	0.055 - 0.13
Cobalt	0.023
Copper	0.028 - 0.031
Iron	0.032 - 0.055
Lithium	<0.001 - 0.013
Magnesium	0.037 - 0.41
Manganese	0.006
Molybdenum	0.26 - 0.82
Nickel	0.017
Potassium	0.40 - 2.1
Silicon	0.38 - 0.50
Silver	0.040
Sodium	<0.30
Strontium	3.3 - 3.5
Titanium	0.060 - 0.064
Vandium	0.074 - 0.088
Zinc	0.044 - 0.057
<u>Volatile Metals</u>	
Arsenic	<0.003 - 0.003
Cadmium	<0.0005
Lead	<0.002
Mercury	<0.0002
Selenium	<0.003 - 0.008
<u>Anions</u>	
Carbonate	40 - 45
Chloride	22 - 44
Fluoride	2.8 - 4.2
Sulfate	1,000 - 1,400
Nitrate	<1

TABLE C-16. (Continued)

Parameter	Concentration Range
<u>Anions (cont.)</u>	
Nitrite	<1
TDS	11,100 - 11,800
Cyanide	0.06 - 0.10
Bromide	<0.5
Phosphorus	<0.02
pH	12.1 - 12.4
Hydroxide	ND
Sulfite	24 - 1,151

Reference: Elkund et al., 1986. Sulfur content of coal burned was not indicated.

TABLE C-14. SUMMARY OF PHYSICAL PROPERTY RANGES IN FOUR AFBC BY-PRODUCTS

Property	Range of Values
Bulk Density (poured g/mL)	0.44 - 0.97
Bulk Density (packed g/mL)	0.84 - 1.3
Compaction (Standard Proctor)	
Optimum Moisture (%)	18 - 40
Maximum Dry Density (KN/m ³)	11.0 - 14.8
Specific Gravity	2.72 - 2.78
Specific Surface Area m ² /g	17 - 23.8
Atterberg Limits	
Liquid Limit (%)	32 - 39
Plastic Index	Nonplastic-5

Reference: Eklund et al., 1986. Sulfur content of coal burned was not indicated.

TABLE C-15. PHYSICAL PROPERTIES OF THREE AFBC BY-PRODUCTS

Parameter	Minto	Devco	
	Bed	Bed	Baghouse
Moisture Content (%)	0.0	0.1	5.4
Specific Gravity at 20°C (g/cm ³)	2.82	2.93	2.80
pH (units)	12.1	12.2	10.8
Water Holding Capacity (%)	48	63	145
Permeability (cm/s)	2.2×10^{-2}	2.5×10^{-2}	3.3×10^{-5}

Reference: Dearborn Environmental Consulting Services and Wastewater
Technology Centre, 1985

APPENDIX D

DATA TABLES PERTAINING TO LIMB BY-PRODUCTS

TABLE D-1. CHEMICAL ANALYSES OF ASH/SORBENT MIXTURES PRODUCED
IN SRI COMBUSTOR (weight percent)

Parameter	Demonstration coal/ Marblehead hydrate 0292-32,38,46,49	Demonstration coal/ Mercer hydrate D292-118-1-D
Li ₂ O	0.01	0.01
Na ₂ O	0.12	0.13
K ₂ O	0.52	0.69
MgO	0.74	0.66
CaO	44.0	45.3
Fe ₂ O ₃	8.8	9.1
Al ₂ O ₃	7.3	8.0
SiO ₂	14.2	16.6
TiO ₂	0.5	0.5
P ₂ O ₅	0.04	0.24
S as SO ₃	21.6	18.4
LOI	3.0	2.5
BET, m ² /g	--	3.3
Density, g/cc	2.87	2.88
MMD, μm	3.5	3.0
S/Ca, mol/mol	0.34	0.28

Reference: Dahlin et al., 1986.

TABLE D-2. PERMEABILITY DATA FOR CONSOLIDATED LIMB ASH

Parameter	Demonstration coal ash/spent Mercer hydrate 0292-118-5A	Demonstration coal ash/spent Marblehead hydrate 0292-46-58
Free base as CaO, wt%	24.83	25.10
Optimum moisture content, wt%	28.00	28.5
Permeability, cm/sec:		
LIMB ash/water mix		
1 day cure	3.70×10^{-4}	2.75×10^{-4}
4 day cure	1.75×10^{-4}	1.90×10^{-4}
11 day cure	6.30×10^{-5}	4.35×10^{-5}
28 day cure	7.35×10^{-6}	5.80×10^{-6}
30 day cure	7.20×10^{-6}	3.65×10^{-6}
LIMB ash/water/cement mix		
28 day cure	1.23×10^{-5}	8.85×10^{-5}
30 day cure	5.65×10^{-6}	3.90×10^{-6}
Density, g/cc:		
LIMB ash/cure		
1 day cure	1.52	1.50
28 day cure	1.51	1.56
LIMB ash/water/cement mix		
28 day cure	1.57	1.58

Reference: Dahlin et al., 1986.

TABLE D-3. LEACHATE DATA FOR SIMULATED LIMB DEMONSTRATION BY-PRODUCTS
FROM SRI COMBUSTOR

Parameter	Concentration in extract, mg/L		
	Allowable limit per RCRA*	Demonstration coal/ Marblehead hydrate D292-46-5A	Demonstration coal/ Mercer hydrate D292-118-58
Arsenic	5	0.0145	0.0210
Barium	100	4.11	4.24
Cadmium	1	0.00095	<0.0005
Chromium	5	0.0394	0.0240
Lead	5	<0.0030	0.0045
Mercury	0.2	<0.0003	<0.0003
Selenium	1	0.0296	0.0228
Silver	5	<0.0005	<0.0005
pH	12.5	(12.4/12.2)+	(12.4/12.2)+

* Resource Conservation and Recovery Act. 42 CFR 35050, August 1976,
enacted by Congress on October 21, 1976.

+ Before/after addition of 4 mL of 0.5 N acetic acid per 1 g of sample.

Reference: Dahlin et al., 1986.

END

DATE
FILMED

9 / 7 / 193