**Land Application Uses for Dry FGD By-Products,
Phase 1 Report**

Topical Report

**J. Bigham
W. Dick
L. Forster
F. Hitzhusen
E. McCoy
R. Stehouwer
S. Traina
W. Wolfe**

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**For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880**

**By
Dravo Lime Company
3600 Neville Road
Pittsburgh, Pennsylvania 15225**

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ABSTRACT

The 1990 amendments to the Clean Air Act have spurred the development of flue gas desulfurization (FGD) processes, several of which produce a dry, solid by-product material consisting of excess sorbent, reaction products containing sulfates and sulfites, and coal fly ash. Presently FGD by-product materials are treated as solid wastes and must be landfilled. However, landfill sites are becoming more scarce and tipping fees are constantly increasing. It is, therefore, highly desirable to find beneficial reuses for these materials provided the environmental impacts are minimal and socially acceptable. Phase 1 results of a 4 and 1/2 year study to demonstrate large volume beneficial uses of FGD by-products are reported. The purpose of the Phase 1 portion of the project was to characterize the chemical, physical, mineralogical and engineering properties of the FGD by-product materials obtained from various FGD technologies being developed in the state of Ohio. Phase 1 also involved the collection of baseline economic data related to the beneficial reuse of these FGD materials. A total of 58 samples were collected and analyzed. Our results indicated the chemical composition of the FGD by-product materials were dominated by Ca, S, Al, and Si although the specific composition varies from one sample to another. Many of the elements regulated by the U.S. Environmental Protection Agency reside primarily in the fly ash. The presence of excess sorbent and reaction products causes a dilution of the concentrations of these elements in the FGD by-product materials as compared to the fly ash alone. Concentrations of the eight metals (Ag, As, Ba, Cd, Cr, Hg, Pb, and Se) regulated by the Resource Conservation Recovery Act (RCRA) were below drinking water standards when measured by either the ASTM or TCLP leachate tests. Engineering tests revealed that samples made from the compacted FGD by-product materials were generally higher in strength and had greater stiffness than natural soils typically used in the construction of a highway embankment. Compacted densities were also lower than typical compacted soil densities. These data suggest that FGD by-product materials, used in construction of a highway embankment, would be lighter and require less right-of-way due to the possibility of constructing steeper slopes. Dry FGD by-products can react with water to form ettringite, an expansive calcium sulfoaluminate hydrate mineral. This expansion may affect how dry FGD by-product is stockpiled and used by professional engineers and construction contractors. Based on analyses of the agricultural lime and supply demand relationships it was concluded that FGD by-product material, used as an agricultural lime substitute, would be entering a very competitive market. This substitution will be sensitive to transport distances and the FGD producer's willingness to subsidize its use in agricultural. In summary, Phase 1 results revealed that FGD by-product materials are essentially coal fly ash materials diluted with unreacted sorbent and reaction products. High volume beneficial reuses will depend on the economics of their substituting for existing materials for various types of applications (e.g. as an agricultural liming material, soil borrow for highway embankment construction, and reclamation of active and abandoned surface coal mines). Environmental constraints to the beneficial reuse of dry FGD by-product materials, based on laboratory and leachate studies, seem to be less than for coal fly ash.

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PROJECT PERSONNEL

Dravo Lime Company

Joel Beeghly

Ohio State University

Agronomy

Warren Dick
Jerry Bigham
Samuel Traina
Ed McCoy
Paul Sutton
Terry Logan
Rattan Lal
Richard Stehouwer
Randy Fowler
Peter Olah
Ubaldo Soto

Agricultural Economics

Fred Hitzhusen
Lynn Forster
Joseph Havlicek
Jonathan Rausch
Diane Hite
Najat Ennich

Civil Engineering

William Wolfe
Tien H. Wu
Sunghwan Kim
Dorothy Adams

United States Geological Survey

Ralph Haefner
Garry Rowe
Kevin Metzker
Al Sedam
William Yost
Rodney Sheets
Anthony Robinson

EXECUTIVE SUMMARY

Development of flue gas desulfurization (FGD) processes in the state of Ohio, as well as other coal producing states in the eastern United States, has been spurred by the 1990 amendments to the Clean Air Act. Much of the coal in the eastern United States contains sulfur at levels high enough that its combustion will cause utilities and other users to be out of compliance. The U.S. Department of Energy, the Electric Power Research Institute, the Ohio Coal Development Office, and various industries (mostly utilities) have been cooperating in the development and evaluation of a number of new sulfur dioxide removal technologies that can be retrofitted onto existing coal burning systems. Several of these technologies produce a dry, solid by-product material consisting of excess sorbent, reaction products containing sulfates and sulfites, and coal fly ash. Presently FGD by-product materials are treated as solid wastes and must be landfilled. However, landfill sites are becoming more scarce and tipping fees are constantly increasing. It is, therefore, highly desirable to find beneficial reuses for these materials provided the environmental impacts are minimal and socially acceptable.

In December of 1990, a project was begun to demonstrate high volume uses of FGD by-product materials which may substitute for other materials now being used for land reclamation (e.g. reclamation of active and abandoned acid mine lands), agriculture, and soil stabilization. This project, to be completed over a 4 and 1/2 year period, is divided into three phases: Phase 1 involves FGD by-product sample collection and characterization and collection of baseline economic data; Phase 2 focuses on laboratory and greenhouse studies of mixtures of FGD by-product materials with soil or spoil and the development of economic models; and Phase 3 is to conduct field demonstrations of high volume uses of FGD by-product materials and economic and environmental analyses related to these uses.

This volume provides a report of project activities completed during Phase 1. The specific objectives of Phase 1 were to 1) characterize the chemical, physical, mineralogical and engineering properties of dry FGD by-product materials and the variability in these properties associated with by-product source and dry FGD technology, 2) conduct preliminary investigations of the economic feasibility of using dry FGD by-products as agricultural lime substitutes, as alkaline amendments for stripmine reclamation, and as soil stabilizers for embankment construction, and 3) select field sites for demonstrations of the beneficial high volume uses.

A total of 58 samples were collected and analyzed. Of these 58 samples, five samples representing four different flue gas desulfurization technologies being tested or commercially used in Ohio, were selected for more detailed analyses. The four technologies that had samples analyzed in detail included duct injection, pressurized fluidized bed combustion, spray dryer, and lime injection multistage burners. The primary components of the FGD by-product materials were excess unreacted sorbent, reaction products (primarily sulfates and sulfites) and coal fly ash.

The chemical composition of the FGD by-product materials were dominated by Ca, S, Al, and Si although the specific composition varied from one sample to another.

There was wide variation in concentrations of elements in the FGD by-product samples and this variation seemed to be due more to variations in the coal composition than in the type of clean coal (or FGD) technology used at a facility. Exceptions to this were sulfite and $\text{Ca}(\text{OH})_2$ which were found primarily in FGD by-product samples obtained from the low temperature spray dryer, coolside, and duct injection processes. Sulfate was the dominant sulfur form in the furnace injection and fluidized bed combustion technologies. Unhydrated CaO was also found in samples from furnace injection FGD technologies.

Many of the elements regulated by the U.S. Environmental Protection Agency reside primarily in the coal fly ash. The presence of excess sorbent and reaction products causes a dilution of the concentrations of these elements in the FGD by-product materials as compared to fly ash alone. Concentrations of the eight metals (Ag, As, Ba, Cd, Cr, Hg, Pb, and Se) regulated by the Resource Conservation Recovery Act (RCRA) were below drinking water standards when measured by either the ASTM or TCLP leachate tests. Trace element contents in the FGD by-product materials could fall under the same regulatory restrictions as trace elements in fly ash from coal burning sources.

Engineering tests revealed that samples made from the compacted FGD by-product materials were generally higher in strength and had greater stiffness than natural soils typically used in the construction of highway embankments. Compacted densities were also lower than typical compacted soil densities and good compaction could be achieved over a fairly broad range of moisture contents. These data suggest that FGD by-product materials, used in construction of a highway embankment, would be lighter and require less right-of-way due to the possibility of constructing steeper slopes. Despite considerable range in values, compacted FGD samples exhibited permeabilities typical of clays. Dry FGD by-products can react with water to form the expansive mineral, ettringite, which is a calcium sulfoaluminate hydrate. This expansion may affect how dry FGD by-product is stockpiled and used by professional engineers and construction contractors. Swelling occurred in two distinct phases: an initial hydration causing an increase in volume of 0.1 to 12% and a second episode of swelling usually beginning after 10 days or more which yield an additional volume of swelling sometimes exceeding 10%. Under neutral pH regimes, precipitation of ettringite is likely to be inhibited but users of some dry FGD by-product materials for applications such as road construction, may first want to allow the materials to age and complete their swelling phase prior to use.

Based on analyses of the agricultural lime and supply demand relationships it was concluded that FGD by-product material, used as an agricultural lime substitute, could be entering a very competitive market. This substitution will be sensitive to transport distances and the FGD producer's willingness to subsidize its use in agricultural.

Field sites for three types of beneficial reuses (i.e. as an agricultural lime substitute, for reclamation of an abandoned (toxic) mine site and reclamation of an active mine site) of dry FGD by-products were selected. Criteria common to the selection of sites for these beneficial reuses included 1) the soil (spoil) must be deficient in exchangeable bases, i.e. it must have a low pH and a calcium carbonate deficiency, 2)

the sites must be representative of a large area of the state, 3) the land must be readily accessible and available to project participants, 4) timing of the reclamation plans must fit with our research plans, 5) distance to the FGD by-product source and from Wooster should be minimized, and 6) we must know the history of land use prior to the addition of the FGD by-product material. Based on these criteria three sites in eastern Ohio (Wayne, Mahoning and Coshocton counties) were selected for conducting tests of the effectiveness of FGD by-product material as an agricultural lime substitute, the Fleming site in Tuscarawas county was selected to study beneficial reuse of FGD by-product material for the reclamation of an abandoned mine site, and four primary and seven secondary sites were selected for use of FGD by-product materials for reclamation of an active surface coal mine.

Greenhouse and field studies are planned for Phases 2 and 3 of this project.

1 INTRODUCTION

1.1 Background and Project Description

The recently passed Clean Air Act has confirmed the need to develop and implement processes for sulfur dioxide (SO₂) removal from flue gases of coal burning utility generating units. Some of these flue gas desulfurization (FGD) processes generate dry, solid by-product material consisting of calcium-based excess sorbent, reaction products containing sulfates/sulfites and fly ash (Batelle, 1989).

Recent studies indicate that as much as 7,000 to 11,000 MW of Ohio Electric Utility generating capacity may be required to install some type of FGD system (Ohio Electric Institute, 1986). A portion of the newly installed FGD systems will be "dry" type systems, but the number of such dry systems and the tons of FGD by-product to be produced each year is yet to be determined by market forces. Presently FGD by-product materials are treated as solid waste and must be landfilled. However, landfill sites are becoming more scarce and tipping fees are increasing. Provided the environmental consequences of FGD by-product materials reuse are socially acceptable, it is highly desirable to find beneficial uses for these materials.

In December of 1990, this project was initiated to demonstrate high volume uses of dry FGD by-product materials which will substitute for other materials now being used for land reclamation (e.g. reclamation of abandoned acid mine lands), agriculture, and soil stabilization. The work for the project is being performed by Ohio State University with cooperation from the United States Geological Survey. Dravo Lime Company is the prime contractor with additional direction being provided by a steering committee made up of representatives from funding organizations, industry, state regulatory agencies and a citizens group (Appendix A).

Project objectives were developed over an 18-month period during extensive discussions with personnel from industry, regulatory agencies, and research institutions. The specific objectives of the demonstration project are as follows:

1. To characterize the material generated by dry FGD processes,
2. To demonstrate the utilization of dry FGD by-products as a soil amendment material on agricultural lands and on abandoned and active surface coal mines in Ohio,
3. To demonstrate the use of dry FGD by-product as an engineering material for soil stabilization,
4. To determine the quantities of dry FGD material that can be utilized in each of these applications,
5. To determine the environmental and economic impact of utilizing the material, and
6. To calibrate environmental, engineering, and economic models that can be used to determine the applicability and costs of utilizing these processes at other sites.

The study, to be completed in approximately 4½ years, is being conducted at The Ohio State University main campus (Columbus), at The Ohio Agricultural Research

and Development Center (Wooster), at The Ohio State University branch stations, at field-scale active and abandoned coal mine sites, and at various other sites in Ohio. The project is divided into three phases. The first phase focuses on characterization of FGD by-products and collection of baseline economic data. The second phase focuses on laboratory and greenhouse studies of mixtures of FGD by-products and soil or spoil, and the development of economic models. The third phase focuses on field demonstration of various high volume uses for FGD by-products and the development of environmental, engineering and economic models.

1.2 Phase 1 Objectives

The specific objectives for Phase 1 of the project are listed below.

1. Determine the chemical, physical, mineralogical, and engineering properties of dry FGD by-products and the variability in these properties associated with by-product source and dry FGD technology.
2. Conduct preliminary investigations of the economic feasibility of using dry FGD by-products as agricultural lime substitutes, as alkaline amendments for stripmine reclamation, and as soil stabilizers for embankment construction.
3. Select field sites for demonstrations of the use of dry FGD by-products as agricultural lime substitutes, as alkaline amendments for stripmine reclamation, and as soil stabilizers for embankment construction.

1.3 Approach

An extensive search and review of the scientific literature related to all aspects of characterization and land application of FGD by-products was conducted at the beginning of the project and will continue throughout the project. Bibliographies of relevant literature were constructed by the USGS Water Resources Division, and the OSU Department of Agronomy and are given in Appendix B. The USGS bibliography contains references of published works on the geology and hydrology of coal strata, geochemical considerations of coal and FGD by-products, and data-acquisition techniques. The OSU bibliography contains references of published works on chemical, mineralogical, physical, and engineering characterization, and environmental impacts of various land application uses for FGD and related by-products. There are several references which appear in both bibliographies.

1.3.1 Characterization Studies

The characterization studies were designed to assess the chemical, mineralogical, physical, and engineering properties of dry FGD by-products and to determine (1) how the measured properties were affected by the type of FGD process utilized, (2) how specific operating conditions within the various dry FGD processes affect the measured properties of the by-products, and (3) the variability of the measured

properties both within specific dry FGD processes and among all dry FGD by-product samples.

Characterization studies were conducted on 58 samples collected from 13 coal-fired boilers representing the following nine dry FGD technologies: coolside, duct injection, atmospheric fluidized bed combustion, pressurized fluidized bed combustion, LIDS, lime injection multistage burners, rotary cascading bed boiler, spray dryer, and $\text{SO}_x\text{-NO}_x\text{-R}_x\text{-Box}$. These samples are listed in Table 1, and sample sources and sampling protocol is described in section 2.1.1. Of the 58 total samples, five samples from four FGD processes in Ohio were selected for more extensive characterization. The analytical procedures used are described in section 2.1.2 and results and discussion are presented in section 2.1.3.

Table 1. Dry FGD by-product samples and sample description.

Sample Code	Plant	FGD Process	Sampling Point	Sampling Date
BAB-LID-01	B&W Alliance Research Center	LIDS	Baghouse	July 3, 1990
BAB-LID-02	B&W ARC	LIDS	Baghouse	July 20, 1990
BAB-LID-03	B&W ARC	LIDS	Dry scrubber	Jan. 4, 1991
BEV-DUC-02	Muskingum River	Duct injection	ESP	Dec. 17, 1990
BEV-DUC-03	Muskingum River	Duct injection	ESP	Jan. 4, 1991
BEV-DUC-05	Muskingum River	Duct injection (slurry recycle)	ESP	July 23, 1991
BEV-DUC-06	Muskingum River	Duct injection (Cl additive)	ESP	Jan. 3, 1992
BEV-DUC-07	Muskingum River	Duct injection (slurry recycle)	ESP	Feb. 10, 1992
BEV-DUC-08	Muskingum River	Duct injection (slurry recycle)	ESP	Feb. 25, 1992
BUR-SNR-01	Burger	SO _x -NO _x -R _{OX} -Box	Fly ash silo	June 10, 1992
EDG-CLS-01	Edgewater	Coolside	ESP	Feb. 14, 1990
EDG-LIM-03	Edgewater	LIMB	ESP	June 14, 1990
EDG-LIM-04	Edgewater	LIMB	ESP	Oct. 23, 1990
EDG-LIM-05	Edgewater	LIMB	ESP	Oct. 29, 1990
EDG-LIM-06	Edgewater	LIMB	ESP	Nov. 16, 1990
EDG-LIM-07	Edgewater	LIMB	ESP	Nov. 20, 1990
EDG-LIM-08	Edgewater	LIMB	ESP	Jan. 25, 1991
EDG-LIM-09	Edgewater	LIMB	ESP	Feb. 13, 1991
EDG-LIM-10	Edgewater	LIMB	ESP	Mar. 8, 1991
EDG-LIM-11	Edgewater	LIMB	ESP	Apr. 16, 1991
EDG-LIM-12	Edgewater	LIMB	ESP	May 24, 1991
EDG-LIM-13	Edgewater	LIMB	ESP	July 10, 1991
EDG-LIM-14	Edgewater	LIMB	ESP	July 15, 1991
GMC-FLB-01	General Motors	Fluidized Bed	Bed ash	Jan. 13, 1992
GMC-FLB-02	General Motors	Fluidized Bed	Fly ash	Jan. 13, 1992
GMC-FLB-03	General Motors	Fluidized Bed	Bed + fly ash	Feb. 1992

Table 1. continued

Sample Code	Plant	FGD Process	Sampling Point	Sampling Date
HST-SPD-01	EPRI High Sulfur Test Center	Spray Dryer	Baghouse	Mar. 20, 1991
HST-SPD-02	EPRI HST	Spray Dryer	Spray dryer drop-out solids	Mar. 20, 1991
HST-SPD-03	EPRI HST	Spray Dryer	Baghouse	Apr. 15, 1991
HST-SPD-04	EPRI HST	Spray Dryer	Drop-out solids	Apr. 15, 1991
HST-SPD-05	EPRI HST	Spray Dryer	Baghouse + drop-out solids	Sep. 27, 1991
NSP-SPD-01	Northern States Power	Spray Dryer	Baghouse	Mar. 7, 1991
NSP-SPD-02	N. St. Power	Spray Dryer	Baghouse	Feb., 1992
OSU-SPD-01	McCracken	Spray Dryer	Baghouse	Jan. 11, 1991
OSU-SPD-02	McCracken	Spray Dryer	Baghouse	Feb. 22, 1991
OSU-SPD-03	McCracken	Spray Dryer	Baghouse	Apr. 1, 1991
OSU-SPD-04	McCracken	Spray Dryer	Bottom ash	Apr. 1, 1991
OSU-SPD-05	McCracken	Spray Dryer	Baghouse	May 23, 1991
OSU-SPD-07	McCracken	Spray Dryer	Economizer	May 23, 1991
OSU-SPD-08	McCracken	Spray Dryer	Bottom ash	May 23, 1991
OSU-SPD-09	McCracken	Spray Dryer	Bottom siftings	May 23, 1991
OSU-SPD-10	McCracken	Spray Dryer	Baghouse	Jan. 29, 1992
OSU-SPD-11	McCracken	Spray Dryer	Baghouse + bed	Feb. 13, 1992
PED-RCB-01	PEDCO	Rotary Cascading Bed Combustion	Baghouse	Sep. 24, 1991
QST-FLB-01	Quaker State	Fluidized Bed	Economizer ash	Oct. 10, 1990
QST-FLB-02	Quaker State	Fluidized Bed	Baghouse	Oct. 10, 1990
QST-FLB-03	Quaker State	Fluidized Bed	Bottom ash	Oct. 24, 1990
RPT-FLY-01	Rockport (AEP)	Class C fly ash	Fly ash	Sep. 18, 1991
STA-FLB-01	Staley	Fluidized Bed	Fly ash	Mar. 6, 1991

Table 1. continued.

Sample Code	Plant	FGD Process	Sampling Point	Sampling Date
TID-FLB-01	Tidd	Pressurized Fluidized Bed	Primary cyclone	Aug. 28, 1991
TID-FLB-02	Tidd	PFBC	Boiler bed	Aug. 28, 1991
TID-FLB-03	Tidd	PFBC	Primary cyclone	Sep. 16, 1991
TID-FLB-04	Tidd	PFBC	Boiler bed	Sep. 16, 1991
TID-FLB-05	Tidd	PFBC	ESP	Sep. 17, 1991
TID-FLB-06	Tidd	PFBC	Primary cyclone	Mar. 6, 1992
TID-FLB-07	Tidd	PFBC	Boiler bed	Mar. 6, 1992
TVA-FLB-01	TVA Shawnee	Fluidized Bed	Char overflow	Mar. 4, 1991
TVA-FLB-02	TVA Shawnee	Fluidized Bed	Fly ash	Jan.-Feb., 1991
TVA-FLB-03	TVA Shawnee	Fluidized Bed	Bed ash	Mar. 4, 1991

1.3.2 Economic Studies

The "economics" of reusing coal-fired electric power plant dry FGD by-products as an agronomic lime substitute, as an amendment on active and abandoned stripmine spoil, and as an embankment stabilizer for highway construction will be based on two perspectives or accounting stances. The first is a financial analysis in which cost and returns are evaluated from the power plant perspective. In this case, actual costs and returns incurred by the power plant in pursuing FGD reuse options determine the "economics" of alternative options.

The second approach considers the economics of FGD disposal and reuse from a societal perspective or what is commonly referred to as benefit-cost analysis (BCA). In BCA the concern is with estimating full willingness to pay and accept measures of economic value regardless of whether or not those values are currently reflected in market prices. It recognizes that technological externalities or unpriced environment services can result in large gaps between private and social costs and benefits. Examples in the case of FGD by-product reuse include but are not limited to: monitoring, testing and remediation costs of groundwater contamination, adjacent property value impacts from reclaiming stripmines or landfilling activities, and downstream sediment impacts from reclaiming abandoned stripmines.

1.3.3 Field Study Site Selection

The U.S. Geological Survey, Water Resources Division, was assigned the task of investigating the effects of applying FGD by-products to an active mine site. As part of Phase I, the initial work objectives entailed finding an active mine site (task 1.3.2). The specific objectives of the site selection were to investigate available surface coal mines and devise a site-selection strategy that included environmental and socio-political factors that govern the site. This task involved several subtasks that included a literature search and review, field surveys, and detailed mapping of the final site. This work will insure the transferability and value of the results of the research project.

2 Reports on Phase 1 Tasks

2.1 Characterization of Dry FGD By-products (Task 1.1)

2.1.1 Sample Source Description

Samples collected for the characterization studies are listed in Table 1. Of the 58 samples listed, 54 are actual FGD by-product samples. The bottom and economizer ash samples from the O.S.U. McCracken plant are not true FGD by-products in that they were collected upstream from the sorbent injection point (spray dryer). In addition a Type C fly ash sample (RPT-FLY-01) was collected from AEP's Rockport plant. Type C fly ash is an alkaline ash and was included as a comparison material to the dry FGD by-product samples.

2.1.1.1 Sampling Protocol and QA/QC measures

Obtaining samples which are representative of the matrix being sampled is the first step to producing data of high quality. To assure representativeness, attempts were made to sample from a homogeneous by-product matrix produced under stable, well-defined plant operating conditions. For those samples collected from sources within Ohio, project personnel worked closely with plant personnel and monitored sampling activities. For samples collected from out-of-state sources, we relied on plant personnel to do the sampling and were unable to monitor sampling procedures. Whenever possible, records of plant operating parameters were obtained at the time of sampling. For some samples plant personnel were unable to provide us with specific operating parameters. Known operating parameters for each sample are given in Appendix C.

Samples were collected in 55 gal steel drums with plastic liner bags when possible, or in 5 gal plastic buckets with lids. All containers were filled as full as possible and tightly sealed to minimize sample contact with air and moisture.

Samples were assigned a sample number at the time of collection. The sample number is an alpha-numeric code in which the first three letters identify the plant, the second three letters identify the FGD process and the last two digits identify the sequential sample number for the particular plant. The sample number and other sample information was written on adhesive labels which were affixed to the sample container and lid. All information regarding the samples (sample number, date of collection, sampler, sample volume, plant operating parameters, and sample distribution) was entered into a sample data base.

2.1.1.2 Source Description

Dry FGD by-product samples were collected from 13 sources representing 9 dry FGD processes. These 9 processes are representative of the four dry FGD technologies described below.

Duct Injection. Sorbent (hydrated lime) is injected into the flue gas as it enters a humidification chamber in the ductwork downstream of the boiler and air heater. Here, injection of a fine water mist lowers the gas temperature from about 300°F (150°C) to about 140 to 150°F (60 to 65°C) and raises the humidity of the flue gas to a 20 to 25F° (11 to 14C°) approach to saturation. The sorbent reacts with the SO₂ in the flue gas ductwork. Dry FGD by-product is removed from the flue gas stream in a baghouse or electrostatic precipitator and contains the reaction products, fly ash, and unspent sorbent. In most configurations, recycling and reinjection of the FGD by-product with fresh hydrated lime is an option to reduce requirements for fresh sorbent.

Duct injection samples were collected from the Coolside process, a full-scale commercial demonstration at Ohio Edison's Edgewater plant; from the Duct Injection Test Facility operated on a 12 MW slipstream from AEP's Muskingum River Power Plant; and from the SO_x-NO_x-RO_x-Box (SNRB) test facility operating on a slipstream from Ohio Edison's Burger Plant.

Lime Injection Multistage Burners (LIMB). In the LIMB process a calcium-based sorbent is injected into the boiler where it calcines to CaO, and reacts with SO₂ and O₂ in the combustion gasses to produce CaSO₄. Temperatures at the point of injection approach 2,300°F (1260°C) and the reaction occurs between this temperature and about 1,600°F (870°C). The reaction product, and unspent sorbent are collected with the fly ash in the electrostatic precipitators. Samples were collected from the full-scale commercial LIMB demonstration at Ohio Edison's Edgewater Plant, and from the LIDS process at the Babcock and Wilcox Alliance Research Center.

Fluidized Bed Combustion (FBC). In FBC systems a calcium-based sorbent (usually limestone or dolomite) and crushed coal are introduced together into the boiler bed where they are "fluidized" or suspended by jets of air. The fluidizing process intimately mixes the coal and sorbent. Reaction of the sorbent with SO₂ occurs in the boiler at temperatures generally somewhat less than 1,600°F. Two FGD by-product streams result; the heavier, granular bed ash material, and smaller particles suspended in the flue gas which are removed with the particulate emission control system. Both by-product streams contain reaction products and unspent sorbent as well as conventional bed or fly ash.

Samples were collected from several atmospheric FBC boilers; General Motors, Quaker State, Staley, and TVA Shawnee. Several samples were collected from the full-scale commercial demonstration of Pressurized FBC at AEP's Tidd plant. In this system the boiler is pressurized and in addition to steam generation, pressurized gasses are used to power a gas turbine. Dolomite is the sorbent used in this system and boiler temperatures are high enough to calcine MgCO₃ to MgO, but are too low to calcine CaCO₃. Also placed in this grouping are samples collected from a rotary cascading bed boiler (PEDCO). In this system coal and

crushed sorbent are not fluidized by air, but are mixed by the rotating action of the boiler.

Spray Dryer. Flue gasses enter a separate scrubber vessel located downstream of the boiler and air heater where sorbent, usually a slurry of hydrated lime, is injected. The scrubber vessel allows for increased residence time of flue gas and therefore lengthens the time period for injected sorbent to react with SO_2 in the flue gas. Temperature in the scrubber vessel is usually around 300°F (150°C). These systems can be configured to allow for recycling and reinjection of by-product together with fresh sorbent. Reaction products and unspent sorbent are removed together with the fly ash in the particulate emission control system. Samples of spray dryer FGD by-products were collected from the EPRI High Sulfur Test Center, Northern States Power, and the OSU McCracken Power Plant.

Five samples from four sources in Ohio representing each of the above four dry FGD systems were selected for more comprehensive characterization. These are; BEV-DUC-02, EDG-LIM-14, TID-FLB-03 (fly ash), TID-FLB-04 (bed ash), and OSU-SPD-03.

2.1.2 Procedures used in Characterization Studies

2.1.2.1 Chemical Methods and QA/QC Measures

The methods used for all chemical analyses described below are collected for the convenience of the reader in Table 2.

Table 2. Test protocols for laboratory determination of chemical properties of dry FGD by-products.

Laboratory Procedure	Reference
Total Chemical Analysis	Bernas, 1968
Total Boron	Custom Method (USGS)
pH	ASTM D 1293-84 ¹
Eh	ASTM D 1498-76 ¹
ASTM Water Extraction	ASTM 3987-85
TCLP	Method 1311 ²
Total Neutralizing Potential	ASTM C 602-90 ³
Available Lime Index	ASTM C 25-90 ³
Thermal Reactivity	ASTM C 110-8-7 ³
Long-term Equilibrium Study	Custom Method
Inorganic Carbon	Custom Method
Equilibrium Geochemical Modelling	Sposito and Coves, 1988 Allison et al., 1990 Sposito and Traina, 1987 Lindsay, 1979
Anion Analysis	Method 429 ⁴
Specific Conductance	Method 205 ⁴

¹1991 Annual Book of ASTM Standards, Vol. 11.01.

²Code of Federal Regulations, July 1991, Vol 40, Part 261, App. II, pp. 66-81.

³1990 Annual Book of ASTM Standards, Vol. 04.01.

⁴Standard Methods for the Examination of Water and Waste Water, 1985.

2.1.2.1.1 Total Chemical Analysis

Total chemical analysis of solids was determined according to the method of Bernas whereby 100 mg samples were placed in Teflon® decomposition vessels and wetted with an aqua-regia-HF mixture. The vessels were then placed in stainless steel digestion bombs and heated at 110°C for 40 min. The digested samples were mixed with excess H_3BO_4 and diluted to 100 mL total volume with distilled H_2O . Individual samples were duplicated. Two standard reference materials (NIST coal fly ash 1633a and 2691) were analyzed after every 20th sample.

The digests were analyzed for Al, Ba, Be, Ca, Fe, K, Li, Mg, Mn, Mo, Na, P, S, Si, and Sr using inductively coupled plasma emission spectrometry (ICP) with a Leeman PS2000 instrument. The ICP was subjected to the following operating procedures and QA/QC measures. The sample induction system was checked and adjusted for optimum operating conditions at the beginning of each operating period. Pump tubing was inspected and replaced when necessary. Instrument peaking routines were performed to optimize the torch placement and to align the optics. The instrument was programmed to recheck and peak the optics every twenty minutes thereafter. Standardization was performed using a four point calibration curve. Standards consisted of one blank and three solutions containing different concentrations of each element analyzed. Intermediate standard solutions served as check standards and were analyzed every ten samples. The low and high standards were also analyzed every ten samples and used to update the standardization.

Total S was also determined with a Leco Model 521 Induction Furnace equipped with a semi-automatic titrator by placing a small sample (15-100 mg) in a crucible containing accelerator metal. The sample was heated to 3000°C where, in the presence of oxygen, S in the sample is oxidized to SO_2 . The SO_2 produced was bubbled through a blue standardized solution ($\text{KIO}_3 + \text{KI} + \text{HCl} + \text{starch}$) which fades as SO_2 is added. The color of the solution was monitored by a photoelectric cell and was back titrated to the original blue color. Percent S was based on the amount of titrant (KIO_3) used and was read directly from the calibrated buret. Standardization was performed by using a three point calibration curve using Leco metal rings containing known amounts of S. Two standard reference materials (NIST coal fly ash 2690 and 2691) were analyzed during each operating period.

Zn contents were determined by atomic absorption using a Varian Techtron Atomic Absorption Spectrophotometer AA6 instrument. The instrument was calibrated using a 5mA lamp current, 213.9 nm wavelength, 0.2 nm spectral band pass, and an air-acetylene flame. Standardization was performed using a three point calibration curve selecting standards within the optimum working range of $0.4 - 1.6 \mu\text{g mL}^{-1}$. The low, intermediate, and high standards were analyzed every six samples and used to update the standardization. Samples were analyzed in duplicate. A standard reference material (NIST coal fly ash 1633a) was analyzed during the operation period.

Total B contents were determined by a custom method (USGS-sodium peroxide sinter procedure) whereby 100 mg samples were placed in platinum crucibles and mixed with 0.4 g of $\text{Na}_2\text{H}_2\text{O}_2$. The crucibles were heated at 445°C for 30 minutes and

allowed to sinter. The samples were then removed from the furnace and cooled rapidly. Fourteen mL of distilled H₂O was added to the sinter cakes and stirred for 10 minutes. Six mL of 6M HCl were then added to the solution and stirred until the sinter cakes were completely dissolved. The solutions were diluted to 100 mL total volume with distilled H₂O and heated in a drying oven for one hour at 100°C. The solutions were analyzed for B using inductively coupled plasma emission spectrometry with a Leeman PS 2000 instrument. Calibration and standardization of the instrument was performed as described previously in this section. Individual samples were duplicated. Two standard reference materials (CANMET Sy-2 and Sy-3 rock samples) were analyzed after every 10th sample.

The concentrations of As, Cd, Co, Cr, Cu, Ni, Pb, and Se in the aqua-regia-HF digests were measured with a Perkin-Elmer 4100-ZL, graphite-furnace, atomic absorption spectrophotometer, equipped with a Zeeman background corrector and L'vov-platform atomization. Electrode-discharge lamps were used for As and Se analysis, and hollow cathode lamps were used for all other elements. Matrix-modifier composition and the temperature program of the graphite furnace were optimized for each element. The graphite pyrolysis tubes were inspected daily and replaced when necessary. Standardization was performed using a four point calibration curve. Standards consisted of one blank and three solutions containing different concentrations of each element analyzed. Intermediate standard solutions served as check standards and were analyzed every 8 samples, after which standard resloping was initiated. An aqua-regia-HF digest of a standard fly ash, NIST-1633a was also analyzed every 8 samples. Analytical matrix blanks were run for each element analyzed. Automatic sample dilution was initiated by the auto-sampler whenever the total absorbance from the analyte exceeded the linear response range.

2.1.2.1.2 Leaching Analysis (ASTM and TCLP)

Standard 20:1 (w/w extractant to FGD), 18 h leachings were performed using the ASTM water leaching method (ASTM D 3987-85) and the U.S. EPA Toxicity Characteristic Leaching Procedure (TCLP) dilute acetic acid method (Method 1311). For both procedures, 2 L of extractant was added to 100 g of FGD by-product in a Teflon® bottle. For the ASTM procedure the extractant was de-ionized water. For the TCLP procedure extractant 2 was used (5.7 mL glacial acetic acid diluted to 1 L with de-ionized water, pH=2.88±0.05). Bottles were placed on an end-over-end rotary shaker for 18 h rotating at 30 rpm at 25°C. Leachates were filtered and analyzed for pH, total dissolved solids, for 5 anions by ion chromatography (IC), and for 30 elements by ICP and graphite furnace atomic absorption spectrophotometry (GFAA). A total of 26 samples were analyzed using the ASTM water method, and 7 samples by the TCLP method.

Quality assurance and control measures consisted of the standard operation protocols for the analytical instruments used: pH meter, IC, ICP, and GFAA (described elsewhere in section 2.1.2.1). The ASTM extraction and analyses were performed in duplicate on 6 samples and the TCLP extraction and analyses were

performed in duplicate on 3 samples. Results of the duplicate extractions and analyses are given in Appendix D, Table D1.

2.1.2.1.3 Total Neutralizing Power (TNP), Available Lime Index, pH, and Thermal Reactivity

Total neutralizing power was determined using ASTM C 602-90, where samples are heated with excess standard hydrochloric acid and back-titrated with standard sodium hydroxide. Samples were analyzed in triplicate and reagent grade $\text{Ca}(\text{CO}_3)_2$ was used as a standard reference material.

Available lime index was determined on selected samples using ASTM C 25-90 section 33, (the rapid sugar method). Samples are slaked with water and the lime is solubilized by reaction with sugar to form calcium sucrose which is then determined by titration with standard HCl.

Paste pH of FGD samples was determined by placing equal volumes of FGD by-product and distilled water into a 70 mL cup. The mixture was stirred and allowed to equilibrate for 30 minutes. The stirring and equilibration step was then repeated. Measurements were conducted with an Orion Research Expandable Ion Analyzer EA920. The meter was calibrated at the beginning of each operation period using two commercially-prepared buffer solutions. Buffer solutions were used once and discarded. The electrode was inspected weekly for scratches, cracks, salt crystal build-up or membrane-junction deposits. The reference chamber was drained, flushed, and filled weekly with fresh Ross Filling Solution. The electrode was soaked in 0.1M HCl for half an hour, followed by soaking in storage solution for one hour monthly. Sample pH's of the FGD by-products were measured in duplicate.

2.1.2.1.4 Long-term Equilibrium Studies

Long-term solubility studies were initiated on five samples; BEV-DUC-02, EDG-LIM-14, OSU-SPD-03, TID-FLB-03, and TID-FLB-04, and TID-FLB-MIX, a mixture of 59.5% TID-FLB-03 and 40.5% TID-FLB-04. Eight g of sample and 40 g of distilled water (1:5 solid/solution ratio) were placed in a 50 mL polypropylene centrifuge tube and capped. Sufficient replicates of each sample were prepared to allow destructive sampling for eight sampling events over a four month period. The samples were stored in an incubator at 25°C and were shaken and aerated weekly. The concentrations of elemental constituents released to solution were measured in duplicate tubes at each sampling event (1, 7, 21, 36, 56, 70, 84 and 112 days). Therefore, all parameters measured are represented by two data points for each of the samples at all of the eight sampling times. At each sampling time the solutions were centrifuged at 5000 rpm for one hour, filtered (except for solutions for conductivity, pH and Eh) through 0.2 μm polycarbonate filters and analyzed. The solid residues were quick-frozen with liquid N_2 and freeze-dried for subsequent XRD analysis.

Elemental analysis of solutions. The solutions from each sampling time were analyzed for Al, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, S, Si, Sr, and Zn using inductively coupled plasma emission spectrometry with a Leeman PS2000 instrument. Calibration and standardization was performed as described in section 2.1.2.1.1. Solutions from days 1 to 36, and from days 56 and 70 were analyzed at 1:2 and 1:1 sample/diluent ratios, respectively. Solutions from day 84 and 112 were not diluted prior to analysis.

The aqueous concentrations of Cl^- , SO_3^{2-} , and SO_4^{2-} , were determined according to Method 429, Standard Methods for the Examination of Water and Waste Water (1985). Analyses were performed on a Dionex 2000i ion chromatograph equipped with a AS4A anion separator column and a AG4A guard column. Before each day's work, eluant flow rate and the detector were adjusted to achieve the ion peak separation outlined in the method. The system was then allowed to come to equilibrium indicated by a stable baseline. A standard containing a mixture of anions (Cl^- and SO_4^{2-} ; SO_3^- determined separately) was injected to determine anion retention times. Three different concentrations of each of the anions were injected and a calibration curve plotting peak area against concentration was constructed. The instrument was re-calibrated whenever the detector setting was changed.

Inorganic carbon. Inorganic carbon concentrations were determined by the sparge technique using a Dohrmann DC-80 Carbon Analyzer. One mL volumes of sample were injected into a reactor vessel where carbon due to carbonates and bicarbonates were removed by first acidifying (phosphoric acid) the sample and then bubbling a clean gas (O_2) through it to remove CO_2 from solution. The CO_2 evolved was measured by infrared detection. Calibration was performed at the beginning of each operating period by injecting a 10 mg C/L standard three times and averaging the values. The C standards were prepared from reagent grade anhydrous Na_2CO_3 , stored in dark glass under refrigeration, and replaced weekly. Standardization was performed using a five point calibration curve.

Solution pH. Solution pH values were determined according to the method described in ASTM D1293 by electrometric measurement using the glass electrode as the sensor. Measurements were conducted with an Orion Research Expandable Ion Analyzer EA920. The meter was calibrated at the beginning of each operating period using two commercially-prepared buffer solutions. Buffer solutions were used once and discarded. The electrode was inspected weekly for scratches, cracks, salt crystal build-up, or membrane/junction deposits. The reference chamber was drained, flushed, and filled weekly with fresh Ross Filling Solution. The electrode was soaked in 0.1M HCl for half an hour, followed by soaking in storage solution for one hour monthly. The solution pH was measured while degassing the head space with nitrogen gas.

Oxidation-reduction potentials. The oxidation-reduction potentials (Eh) were determined according to the method described in ASTM D1498. The measurements were conducted on a Orion Research Expandable Ion Analyzer EA920 fitted with a platinum electrode coupled with a silver-silver chloride reference electrode. The meter was calibrated at the beginning of each operating period using a ferrous-ferric reference solution. The ferrous-ferric solution was discarded and replaced every 30 days. The electrodes were inspected weekly for scratches, cracks, or deposits. In addition, the electrodes were cleaned at the beginning of each operating period. The Eh of the ferrous-ferric reference solution was measured at least after each 12th sample. If the measured value was different from the published value for the reference solution by more than 2%, the meter was recalibrated and all samples measured after the previous calibration were repeated.

Solution Conductivity. Conductivity was determined according to Method 205, Standard Methods for the Examination of Water and Waste Water (1985). Measurements were conducted with a YSI Specific Conductance Meter (Model 32) fitted with a YSI 3403 conductivity cell. The meter was calibrated at the beginning of each operating period using a YSI calibrator solution (1000 $\mu\text{mhos/cm}$). The calibration solution was used once and discarded. The electrode was inspected weekly for scratches, cracks, and deposits. The electrode was rinsed thoroughly between measurements and was kept immersed in distilled water when not in use.

Equilibrium Geochemical Modeling. The aqueous-phase geochemical speciation of the long-term solubility data for sample solutions collected at 56 and 112 d, were calculated with the geochemical speciation computer programs, Soilchem (Sposito and Coves, 1988) and MinteqA2 (Allison et. al, 1990). The former model contains an extended Debye-Huckle expression which allows for accurate calculation of single ion activity coefficients, and accurate predictions of mineral solubilities in solutions with ionic strengths (I_s) $\leq 2 \text{ mol L}^{-1}$ (Sposito and Traina, 1987). In the present study, molar solution composition data were input into the Soilchem model and the chemical species that would occur under closed conditions (no reaction with atmospheric CO_2) and with precipitation prohibited were predicted. The predicted equilibrium solution concentration of free cations and anions and the calculated values of ionic strength (based on the Soilchem results) were recorded. The total solution composition data were then input into MinteqA2, along with the values of ionic strength calculated by the Soilchem program. The solution concentrations of free cations and anions from the Soilchem output were used as the initial "guesses" for the "free" ion concentrations in the MinteqA2 calculations. All MinteqA2 calculations were conducted with precipitation prohibited. Log Saturation Index values (log SI) were calculated by MinteqA2 with the following equation

$$\log \text{SI} = \log \text{IAP} - \log K_{\text{sp}}$$

where IAP is the activity product of the solution concentrations of "free" cations and

anions present in a given solid, and K_{sp} is the solubility product for that solid. Given a general solid, $A_aB_b(s)$ the K_{sp} for each solid is given by:

$$K_{sp} = (aA^{b+})(bB^{a-})$$

where () denotes ion activities. The ion activity product is given by:

$$IAP = (aA^{b+})(bB^{a-}).$$

Equality between the K_{sp} and the IAP indicate that a solution may be at equilibrium with a given solid, this is denoted by a log SI value equal to 0.

Values of log SI for the solids, ettringite and Ca-molybdate ($CaMoO_4$), were calculated manually using the aqueous activities of the cations and anions obtained from the geochemical computer modeling. A value of 111.32 was used for the log K_{sp} of ettringite and the log K_{sp} for Ca-molybdate was -7.94 (Lindsay, 1979).

2.1.2.2 Mineralogical Methods and QA/QC Measures

Mineralogical analyses were limited to FGD by-products obtained from the Beverly (BEV), Edgewater (EDG), McCracken (OSU), Pontiac (GMC) and Tidd (TID) power plants. A variety of analytical methods were employed to derive semi-quantitative measures of mineralogical composition from these materials. These methods and references are listed in Table 3.

Table 3. Test protocols for laboratory determination of mineralogical properties of dry FGD by-products.

Laboratory Procedure	Reference
X-Ray Diffraction	Custom Method
Thermal Analysis	ASTM STP 997 ¹
Ash Content	Custom Method
Calcite and Dolomite Determination	Dreimanis, 1962

¹Earnest, C.M. 1988. Compositional Analysis by Thermogravimetry, ASTM STP 997.

2.1.2.2.1 X-ray diffraction

X-ray diffraction (XRD) patterns were obtained from randomly-oriented powder mounts using Cu K α radiation and a Phillips PW 1216/90 wide-range goniometer equipped with a theta-compensating slit and a graphite monochromator. Diffraction patterns were recorded from 5 to 70°2 θ with a step interval of 0.05°2 θ and a counting time of 4 sec per step. The instrument was calibrated using both low (cholesterol) and high angle (NIST SRM 640b Si powder) diffraction standards. Quartz, a ubiquitous phase in coal fly ash, was employed as an internal standard to verify the accuracy of diffractometer readings from sample materials. Crystalline phase assignments were based on published literature, searches of the JCPDS-international data base, and comparative analyses of reference mineral samples.

2.1.2.2.2 Thermal analysis

Thermal studies were conducted using a Seiko SSC5020 instrument that provided simultaneous thermogravimetric (TGA) and differential thermal analysis (DTA). Samples were heated from 105 to 1125°C at a rate of 20°C/min under a continuous flow (200 ml/min) of dry N₂. Calibration of the temperature signal was achieved using the melting points of In and Sn. Calibration of the thermal balance was performed using a reference weight provided by the instrument manufacturer. Thermal events observed with heating of sample materials were assigned to phase transitions based on published literature and analyses of standard mineral samples. A reference calcite (CaCO₃) was analyzed after every 20 samples to assure instrument standardization. Weight losses induced by thermal decomposition of the standard were maintained within $\pm$ 5% of calculated (ideal) values.

2.1.2.2.3 Calcite and Dolomite

Calcite and dolomite could not be consistently distinguished by thermal analysis. When both phases were present in a sample, contents were determined by the gasometric method of Dreimanis (1962) using a Chittick apparatus. The amount of CO₂ evolved from the sample following the addition of 20 mL of 6M HCl containing 0.6 g of FeCl₂ was measured after 30 sec (for calcite) and 30 min (for dolomite). After volume corrections were made for temperature and pressure, regression equations developed from the results of Dreimanis (1962) were used to calculate the percent calcite and dolomite.

2.1.2.2.4 Ash content

Ash contents were determined by mixing weighed samples (10 - 20g) of FGD by-product with sodium acetate-acetic acid buffer (pH 5.0) to form thick slurries. The slurries were then treated with 30% H₂O₂ to convert CaSO₃•0.5H₂O to the more soluble CaSO₄•2H₂O. Following oxidation and heating at 60°C to decompose excess

H₂O₂, the samples were quantitatively transferred to cellulose dialysis bags and submerged in sodium acetate-acetic acid buffer (pH 5.0) for 4 to 6 days to remove acid-soluble materials. The samples were then dialyzed against distilled H₂O to remove excess salt and to dissolve residual CaSO₄•2H₂O. Removal was judged to be complete when a negative test for dissolved SO₄²⁻ was obtained with BaCl₂. The samples were then quantitatively transferred to tared beakers, dried at 100°C, and weighed to determine the residual ash contents.

2.1.2.3 Physical Methods and QA/QC Measures

Physical properties included measurements of particle size distributions, particle density, specific surface area, compression index, compressed bulk density, water retention characteristics and saturated hydraulic conductivity. These methods and references are listed in Table 4. All pressure gauges and electronic balances employed in the preceding methods were checked for accuracy yearly. These units were serviced and rechecked if deviations exceeded manufacturer recommended tolerances.

Table 4. Test protocols for laboratory determination of physical properties of dry FGD by-products.

Procedure	Reference
Particle Size Distribution	ASTM D 422-63 ^a
Surface Area	ASTM D 4567 ^a
Particle Density	Custom Method (Micromeritics)
Bulk Density and Compression Index	Bradford and Gupta (1986)
Water Retention	Klute (1986) Rawlins and Campbel (1986)
Hydraulic Conductivity	Klute and Dirksen (1986)

^a1990 Annual Book of ASTM Standards, Vol. 4.08

2.1.2.3.1 Particle Size Distribution

Particle size distributions were determined using the hydrometer and dry sieving methods of ASTM D 422-63, employing Dispersion Apparatus A. Independent particle density values were employed for all size distribution calculations. Results were expressed as the percent of particles finer than 0.025 mm (or for coarse samples the percent of particles finer than 0.25 mm) and the Coefficient of Uniformity (C_u) given by (Gee and Bauder, 1986):

$$C_u = D_{60}/D_{10}$$

where D_x is the effective particle diameter separating the finer x percent of the particles from the coarser. For example, D_{10} corresponds to the diameter of a hypothetical sieve that would retain 90% of the particles and allow 10% of the particles to pass. Duplicate particle size determinations were conducted on each sample. All QA/QC protocols as recommended by ASTM D 422-63 were employed during particle size measurements.

2.1.2.3.2 Surface Area

Single-point determinations of specific surface area were performed using nitrogen adsorption by the continuous flow method (ASTM D4567) with a Micromeritics Flowsorb II 300 instrument. The instrument was calibrated at the beginning of each operating period. Calibration was achieved by injecting a known volume of analytical grade nitrogen gas as described in ASTM D4567. Two standard reference materials (NIST 8570 and 8571) were analyzed at the beginning of each operating period and after every 20th sample. The quantities of both standards and samples were adjusted to yield surface areas in the range of 0.5 to 25 m² as per instrument manufacturer specifications. Sample materials were analyzed in triplicate or until individual analyses were within $\pm 10\%$ of the mean values following removal of any outlying data points.

2.1.2.3.3 Particle Density

Particle densities were determined using a Micromeritics 1305 Multivolume Gas Pycnometer by placing approximately 4 cm³ of weighed sample into a sample chamber of known volume. The sample chamber was pressurized to a predetermined level with helium. The gas in the chamber was then allowed to expand into a second precisely measured volume yielding a lower pressure which becomes progressively smaller for larger particle volumes. Application of mass balance equations for the gas permits computation of skeletal volumes and the determination of particle densities. The instrument was initially calibrated by placing steel balls in the sample chamber. Two checks were made to determine if the instrument needed recalibration. One checks the zero offset or additive errors of the instrument and the other checks the scale factor. These checks were made if changes occurred in the instrumentation or if

the temperature differed appreciably from the temperature at the time of the previous calibration. Individual samples were duplicated. Particle densities reported represent the mean of three instrument measurements for each replicate. A standard reference material (NIST 1825) was analyzed to verify precision and accuracy at the beginning of each operating period and after every 20th sample.

2.1.2.3.4 Bulk Density and Compression Index

The compression index and compressed bulk density were determined on water saturated samples using a fixed ring consolidimeter that allowed for drainage of the sample during consolidation (Bradford and Gupta, 1986). Stresses employed were 0, 4, 13, 30, 64, 128 and 172 kPa. Equilibration times between successive loading were 1.5 h as determined from a preliminary study. The compression index was calculated as the slope of the relation between bulk density and the natural log of stress (Bradford and Gupta, 1986). Compressed bulk density was the bulk density of the sample determined following equilibration at maximum stress (172 kPa or 25 psi).

Compression index and compressed bulk density measurements were determined on three replicates of each sample. The only non-mechanical device used in the consolidation apparatus was a linear voltage displacement transducer (LVDT, Model 0244, Trans-tek Inc., Ellington, CT). This device was calibrated daily using an adjustable height stand allowing displacement measurements at a resolution of 0.1 mm. The LVDT was placed on the stand and 11 measurements ranging over 1 cm were collected. Linearity of the LVDT response as indicated by linear regression of the calibration data consistently yielded r^2 values exceeding 0.9999.

2.1.2.3.5 Water Retention

Samples for water retention measurements were consolidated at 172 kPa (25 psi) stress using the compression index protocol. Water retention measurements were conducted using Tempe cells for pressure ranges of 0 to 100 kPa, volumetric pressure extractors for pressure ranges of 100 to 200 kPa, and a Decagon (Pullman, WA) thermocouple psychrometer for soil water suctions exceeding 200 kPa (Klute, 1986; Rawlins and Campbell, 1986). Duplicate water retention measurement values for a given sample were pooled and fit to the Van Genuchten equation (Van Genuchten, 1980), an empirical relation commonly used to describe water retention properties of porous media. The required inputs to the equation are the saturated and residual water contents ($m\ m^{-3}$), and the fitted variables are the α (MPa^{-1}) and n parameters.

The only non-mechanical device employed for these measurements was the thermocouple psychrometer. The calibration curve for this device was constructed daily using stock solutions of 100, 500, 900, 1100 and 1500 mOsmol (a measure of solution osmotic potential). Additionally, the 500 mOsmol solution was included with the samples as an internal standard. Periodically (after approximately 10 successive measurements using this device) the osmolarity of the stock solutions was checked using solutions of 100 and 500 mOsmol in sealed ampoules. If the readings from the

100 and 500 mOsmol stock solutions varied by more than 5.0% from that of the solutions in sealed ampules, then all stock solutions were replaced.

2.1.2.3.6 Hydraulic Conductivity

Samples for saturated hydraulic conductivity measurements were consolidated at 172 kPa (25 psi) stress using the compression index protocol. The samples were subsequently resaturated by capillarity and hydraulic conductivity measurements were determined using the falling head or constant head techniques as appropriate (Klute and Dirksen, 1986). Following hydraulic conductivity measurements, the samples were allowed to drain overnight, encased in a plastic bag, and stored for seven days. Hydraulic conductivity measurements were repeated on the seven day old samples.

Saturated hydraulic conductivity measurements were conducted using four replications for each sample. Hydraulic head measurements for this procedure were conducted using a Vernier gauge with resolution of 0.02 mm. Outflow from the conductivity device was determined gravimetrically using an electronic balance.

2.1.2.4 Engineering Methods and QA/QC Measures

All engineering tests made were based on the assumption that the FGD by-product could satisfactorily be analyzed as a geotechnical material having specific, measurable engineering properties. With the engineering properties properly evaluated, the substitution of FGD by-products for natural soils in many engineering applications could then be included in standard construction specifications. To implement this approach, laboratory experiments were conducted to identify the properties a highway engineer would need to know before recommending the use of an FGD by-product as a fill material in a typical highway construction project.

All tests were conducted using equipment that should be readily available in a quality commercial or state department of transportation geotechnical laboratory. American Society for Testing and Materials (ASTM) Standard procedures were employed to obtain the desired engineering properties in all cases where an appropriate standard existed. QA/QC procedures as specified in the relevant ASTM Standards were followed during testing. The purpose for this approach to the testing was twofold; first, to take advantage of the quality control procedures already established by ASTM and recognized throughout the engineering community; and second, to provide the interested highway or geotechnical engineer with the results of our test program in a form readily understood by the profession. Table 5 is a list of the ASTM Standard Procedures followed in the laboratory program. A listing of the FGD samples on which the tests were conducted is presented in Table 6.

Table 5. Test protocols for laboratory determination of engineering properties of dry FGD by-products.

Laboratory Procedure	Reference
Optimum Moisture and Density (Standard Proctor Compaction)	ASTM D 698-78 ¹
Unconfined Compression	ASTM D 2166-85 ¹
One-dimensional Swell	ASTM D 4546-85 ¹
One-dimensional Consolidation	ASTM D 2435-80 ¹
Falling Head Permeability	Lin and Evett, 1990 ²

¹ 1990 Annual Book of ASTM Standards, Vol. 4.08

² Soil Properties Testing, Measurement and Evaluation, 2nd edition, Cheng Lin and Jack B. Evett, Prentice-Hall Inc., 1990

Table 6. Laboratory test program to determine the engineering properties of dry FGD by-product.

Sample ID	Optimum Moisture Content	Optimum Density	Unconfined Compression (days)			Swelling	Permeability (days)		
			0	7	28		0	7	28
CLS-01	✓	✓	✓	✓	✓	✓	✓	✓	✓
LIM-06	✓	✓	✓	✓	✓	✓	✓	✓	✓
LIM-07	✓	✓	✓	✓	✓	✓	✓	✓	✓
LIM-08	✓	✓	✓	✓	✓	✓	✓	✓	✓
LIM-09	✓	✓	✓	✓	✓		✓	✓	*
LIM-10	✓	✓	✓	✓	✓	✓	✓	✓	*
LIM-11	✓	✓	✓	✓	✓		✓	✓	✓
LIM-12	✓	✓	✓	✓	✓		✓	✓	✓
LIM-13	✓	✓	✓	✓	✓		✓	✓	✓
LIM-14	✓	✓	✓	✓	✓	✓	✓	✓	✓
OSU-01	✓	✓	✓	✓	✓		✓	✓	✓
OSU-02	✓	✓	✓	✓	✓		✓	ND	ND
OSU-03	✓	✓	✓	✓	✓	✓	✓	✓	✓
OSU-11	✓	✓	✓	✓	✓		✓	✓	✓
HST-01	✓	✓	✓	✓	✓		✓	✓	✓
HST-03	✓	✓	✓	✓	✓		✓	✓	✓
HST-05	✓	✓	✓	✓	✓	✓	✓	✓	✓
BEV-05	✓	✓	✓	✓	✓		✓	✓	✓
BEV-06	✓	✓	✓	✓	✓		✓	✓	✓
TID-1/2 60%/40%	✓	✓	ND	✓	ND		✓	*	*
TID-1/2 50%/50%	✓	✓	✓	✓	✓		✓	✓	✓
TID-3/4 40%/60%	✓	✓	✓	✓	✓	✓	✓	✓	✓
TID-05	✓	✓	✓	✓	✓		ND	ND	ND

Table 6. continued

Sample ID	Optimum Moisture Content	Optimum Density	Unconfined Compression (days)			Swelling	Permeability (days)		
			0	7	28		0	7	28
TID-06	✓	✓	✓	✓	✓		✓	✓	✓
PED-01	✓	✓	✓	✓	✓		✓	✓	*
SNRB-01	✓	✓	✓	✓	✓		✓	✓	✓

✓ test performed
 * sample cracked during curing
 ND test not determined

2.1.3 Results and Discussion of Dry FGD By-Product Characterization

2.1.3.1 Chemical Characterization

2.1.3.1.1 Solid Phase Chemical Composition of FGD by-products

Results of the total elemental analyses of standard fly ash samples are presented in Tables 7 to 10. The values reported by OSU are means from a minimum of four replicate measurements obtained by ICP or a minimum of 15 replicate measurements obtained using the GFAA. There was generally excellent agreement between the analytical values measured by OSU and the certified values reported by NIST. Boron analyses were compacted to a standard sample obtained from the Canadian Center for Mineral and Energy Technology (Table 9).

The total concentrations of Al, Ba, Be, Ca, Fe, K, Li, Mg, Mn, Mo, P, S, Si, Sr, V and Zn, in FGD samples were determined by ICP analyses of HF-AR digests, and are listed in Table 11. Values for total S measured with a Leco induction furnace are also presented in Table 11. The total concentrations of As, Cd, Co, Cr, Cu, Ni, Pb, and Se in the FGD by-products were determined by GFAA analyses of the HF-AR digests and are given in Table 12. Total B concentrations in FGD samples were determined by ICP analyses of dissolved $\text{Na}_2\text{H}_2\text{O}_2$ sinter cakes and are presented in Table 13. For all elemental analyses, sample concentrations represent the means of duplicate digestions and analyses. The data in Tables 11, 12, and 13 are grouped according to the type of FGD technology utilized in the coal-fire plants. The categories are Spray Dryer, Duct Inject, LIMB, Fluidized Bed Combustion, which is itself split into Bed ash and Cyclone ash, and Other.

The chemical composition of most samples is dominated by Ca, S, Al, Fe, and Si. This chemistry is consistent with the FGD mineralogy as discussed in section 2.1.3.2.

The values listed as "Means" in Table 11 and 12 represent the means of the concentrations of a given element in all of the FGD samples present within a given sample category. Thus the mean concentration of Al in all FGD samples obtained from Spray Dryer facilities was 5.2 ± 6.8 % wt. This value is typical of many category means reported in Table 11 and 12, in that the means were comparable in size to the standard deviations of the means. This precludes any ranking of FGD technologies in terms of the relative concentrations of any given element. Calculation of means and standard deviations for each individual source, e.g. all OSU-SPD samples, did not result in any decrease in variation. The standard deviations were again comparable in size to the means (data not shown). Apparently there was sufficient variation within the composition of the inputs (coal and/or scrubbing material) and within the operating conditions of each coal-fire facility, to prohibit any calculation of average elemental concentrations for a given FGD technology or a given source of FGD by-products. The one exception to the above general statement was the element B, which decreased in concentration in the FGD-products in the order Spray Dryer > LIMB > cyclone ash from Fluidized Bed Combustion > Duct Injection > fly ash from Fluidized Bed Combustion (Table 13).

Table 7. Elemental composition of NIST standards as measured by ICP analysis of HF-aqua-regia digests and as certified.

	Al	Ba	Be	Ca	Fe	K	Li
	wt%	mg kg ⁻¹	mg kg ⁻¹	wt%	wt%	wt%	mg kg ⁻¹
NIST 2691							
OSU	9.81 ± 0.39	0.66*	NR [†]	18.45 ± 0.32	4.42 ± 0.03	0.34 ± 0.00	43.05 ± 1.15
Certified	10.15 ± 0.24	0.57 ± 0.01	4.62 ± 0.53	18.52 ± 0.51	4.05 ± 0.08	0.34 ± 0.02	NR
NIST 1633							
OSU	15.5 ± 0.4	0.13 ± 0.00	14.24 ± 1.16	1.17 ± 0.03	9.0 ± 0.2	1.84 ± 0.0	185.5 ± 2.2
Certified	14.3 ± 1.0	0.15	12	1.11 ± 0.01	9.4 ± 0.1	1.88 ± 0.0	NR
	Mg	Mn	Mo	P	Si	Sr	V
	wt%	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	wt%	wt%	mg kg ⁻¹
NIST 2691							
OSU	3.26 ± 0.05	0.02 ± 0.00	12.9 ± 2.1	0.54 ± 0.01	14.64 ± 1.65	0.031 ± 0.05	228.7 ± 14.6
Certified	3.12 ± 0.08	0.02	NR	0.51 ± 0.02	6.83 ± 0.1	0.027	NR
NIST 1633							
						mg kg ⁻¹	
OSU	0.49 ± 0.01	178 ± 2	37 ± 3	1771 ± 46	21.6 ± 1.4	814 ± 7	301 ± 17
Certified	0.46 ± 0.01	179 ± 8	29	NR	22.8 ± 0.8	830 ± 30	297 ± 6

*Value not certified by NIST, [†]Value not reported by NIST.

Table 8. Graphite furnace analysis of NIST 1633.

	As	Cd	Co	Cr	Cu	Ni	Pb	Se
	mg kg ⁻¹							
OSU	146±31	1.10±0.10	32±4	191±11	109±6	122±7	73.6±2.0	12.2±
Certified	145±15	1.00±0.15	46*	196±6	118±3	127±4	72.4±0.4	10.3±0.6

*Value not certified by NIST.

Table 9. Concentration of B in standard materials.

Sample	Source	Reported Value	OSU analysis
		mg kg ⁻¹	mg kg ⁻¹
SY-2	CANMET*	85	84 ± 7
SY-3	CANMET	110	100 ± 5

*Canadian Centre for Mineral and Energy Technology.

Table 10. Concentration of Zn in NIST 2691.

Reported Value	OSU analysis
mg Zn kg ⁻¹	mg Zn kg ⁻¹
220 ± 10	267 ± 30

Table 11. Total element content in FGD by-product samples as determined by ICP, Leco, and AA.

Sample	Ag	Al	Ba	Be	Ca	Fe	K
	mg kg ⁻¹	wt%	wt%	mg kg ⁻¹	wt%	wt%	wt%
Spray Dryer							
BAB-LID-01	<0.024	2.9%±0.0%	0.01%±0.00%	9.6 ±0.9	32.6%±0.1%	2.5%±0.0%	0.46%±0.00%
BAB-LID-02	<0.024	2.0%±0.0%	0.01%±0.00%	9.5 ±0.2	24.6%±0.3%	2.4%±0.0%	0.38%±0.02%
BAB-LID-03	<0.024	1.0%±0.0%	0.00%±0.00%	3.2 ±0.1	40.1%±0.7%	1.5%±0.0%	0.19%±0.01%
HST-SPD-01	<0.024	3.7%±0.1%	0.03%±0.00%	2.6 ±0.1	24.6%±0.6%	2.6%±0.0%	0.37%±0.01%
HST-SPD-02	<0.024	5.2%±0.0%	0.04%±0.00%	3.3 ±0.3	21.0%±0.2%	5.1%±0.2%	0.50%±0.00%
HST-SPD-03	<0.024	2.6%±0.0%	0.02%±0.00%	0.7 ±0.0	30.2%±0.4%	1.9%±0.0%	0.26%±0.01%
HST-SPD-04	<0.024	3.0%±0.0%	0.02%±0.00%	1.7 ±0.1	28.6%±0.4%	3.3%±0.0%	0.27%±0.01%
HST-SPD-05	<0.024	3.4%±0.5%	0.03%±0.00%	1.3 ±1.3	21.4%±3.5%	3.0%±0.4%	0.26%±0.07%
NSP-SPD-01	<0.024	8.6%±0.7%	0.24%±0.00%	2.0 ±1.0	17.8%±1.4%	2.1%±0.1%	0.49%±0.07%
OSU-SPD-01	<0.024	2.4%±0.1%	0.01%±0.00%	4.1 ±0.3	27.9%±0.0%	3.2%±0.2%	0.31%±0.03%
OSU-SPD-02	<0.024	1.7%±0.3%	0.01%±0.00%	4.2 ±0.1	31.0%±2.6%	3.8%±1.8%	0.16%±0.01%
OSU-SPD-03	<0.024	1.6%±0.0%	0.01%±0.00%	3.5 ±0.2	33.1%±1.0%	2.3%±0.0%	0.24%±0.01%
OSU-SPD-05	<0.024	2.5%±0.1%	0.01%±0.00%	5.9 ±0.5	28.0%±0.8%	3.3%±0.1%	0.29%±0.00%
Mean		3.1%±1.9%	0.03%±0.1%	4.0 ±2.7	27.8%±5.7%	2.9%±0.9%	0.32%±0.1%
Duct Injection							
BEV-DUC-02	<0.024	4.0%±0.0%	0.01%±0.00%	2.8 ±0.6	31.3%±0.1%	4.7%±0.1%	0.49%±0.01%
BEV-DUC-03	<0.024	3.3%±0.1%	0.01%±0.00%	1.7 ±0.0	34.4%±0.0%	3.5%±0.1%	0.39%±0.01%
BEV-DUC-05	<0.024	6.4%±0.0%	0.02%±0.00%	4.9 ±0.1	20.5%±0.4%	6.4%±0.0%	0.80%±0.01%
BEV-DUC-06	<0.024	4.0%±0.0%	0.02%±0.00%	2.0 ±0.4	31.5%±0.3%	4.0%±0.0%	0.54%±0.00%
BEV-DUC-07	<0.024	6.3%±0.0%	0.02%±0.00%	3.9 ±0.7	21.8%±0.2%	6.2%±0.1%	0.81%±0.00%
BEV-DUC-08	<0.024	6.3%±0.1%	0.02%±0.00%	4.2 ±0.4	19.0%±0.5%	7.3%±0.2%	0.85%±0.01%
EDG-CLS-01	<0.024	10.2%±0.0%	0.04%±0.00%	17.5 ±0.6	11.7%±0.2%	6.5%±0.0%	1.44%±0.01%
Mean		5.8%±2.2%	0.02%±0.00%	5.3 ±4.8	24.3%±7.6%	5.5%±1.3%	0.76%±0.3%

Table 11. continued

Sample	Ag	Al	Ba	Be	Ca	Fe	K
	mg kg ⁻¹	wt%	wt%	mg kg ⁻¹	wt%	wt%	wt%
LIMB							
EDG-LIM-03	<0.024	5.9%±0.1%	0.03%±0.00%	9.2 ±0.1	25.7%±0.6%	5.4%±0.1%	0.81%±0.00%
EDG-LIM-04	<0.024	7.2%±0.0%	0.04%±0.00%	10.8 ±0.3	13.2%±0.2%	7.4%±0.1%	0.97%±0.00%
EDG-LIM-05	<0.024	4.4%±0.0%	0.03%±0.00%	9.0 ±0.0	17.3%±0.4%	6.3%±0.1%	0.47%±0.00%
EDG-LIM-06	<0.024	6.3%±0.0%	0.04%±0.00%	16.6 ±0.3	15.8%±0.2%	8.9%±0.1%	0.67%±0.00%
EDG-LIM-07	<0.024	5.1%±0.0%	0.02%±0.00%	7.8 ±0.0	17.0%±0.2%	6.7%±0.1%	0.56%±0.01%
EDG-LIM-08	<0.024	10.9%±0.1%	0.05%±0.00%	20.7 ±0.2	10.7%±0.2%	6.7%±0.1%	1.86%±0.03%
EDG-LIM-09	<0.024	5.1%±0.0%	0.03%±0.00%	6.0 ±0.3	20.4%±0.2%	5.0%±0.0%	0.70%±0.01%
EDG-LIM-10	<0.024	9.6%±0.1%	0.04%±0.00%	15.3 ±0.3	12.7%±0.0%	5.5%±0.0%	1.46%±0.01%
EDG-LIM-11	<0.024	6.9%±0.0%	0.04%±0.00%	11.0 ±0.1	21.0%±0.0%	7.3%±0.0%	0.93%±0.00%
EDG-LIM-12	<0.024	8.7%±0.1%	0.04%±0.00%	11.9 ±0.2	15.2%±0.1%	8.1%±0.1%	1.34%±0.01%
EDG-LIM-13	<0.024	6.0%±0.1%	0.02%±0.00%	7.7 ±0.5	22.4%±0.4%	8.8%±0.0%	0.72%±0.00%
EDG-LIM-14	<0.024	3.5%±0.0%	0.01%±0.00%	3.3 ±0.1	36.0%±0.7%	5.6%±0.1%	0.40%±0.00%
Mean		6.6%±2.1%	0.03%±0.01%	10.8 ±4.6	18.9%±6.6%	6.8%±1.3%	0.91%±0.42%
Fluidized Bed Combustion							
<i>Bed Ash</i>							
GMC-FLB-01	<0.024	1.4%±0.0%	0.01%±0.00%	5.9 ±0.3	32.7%±0.5%	2.7%±0.1%	0.11%±0.01%
QST-FLB-03	<0.024	1.1%±0.3%	0.00%±0.00%	0.6 ±0.1	41.2%±1.0%	0.8%±0.1%	0.14%±0.06%
TID-FLB-02	<0.024	1.0%±0.0%	0.00%±0.00%	0.0 ±0.6	25.5%±0.2%	1.6%±0.1%	0.08%±0.01%
TID-FLB-04	<0.024	2.8%±0.1%	0.02%±0.00%	1.4 ±0.1	24.1%±1.5%	2.0%±0.1%	0.13%±0.01%
TID-FLB-07	<0.024	1.1%±0.0%	0.00%±0.00%	0.8 ±0.4	24.7%±0.6%	1.8%±0.1%	0.10%±0.02%
TVA-FLB-03	<0.024	0.6%±0.0%	0.01%±0.00%	0.7 ±0.1	39.2%±0.2%	0.7%±0.0%	0.15%±0.01%
Mean		1.3%±0.7%	0.01%±0.01%	1.6 ±2.0	31.2%±7.0%	1.6%±0.7%	0.12%±0.02%

Table 11. continued

Sample	Ag	Al	Ba	Be	Ca	Fe	K
	mg kg ⁻¹	wt%	wt%	mg kg ⁻¹	wt%	wt%	wt%
Fluidized Bed Combustion							
<i>Cyclone Ash</i>							
GMC-FLB-02	<0.024	5.0%±0.0%	0.03%±0.00%	10.7 ±1.2	21.0%±0.4%	10.9%±0.1%	0.65%±0.01%
PED-RCB-01	<0.024	7.5%±0.1%	0.03%±0.00%	14.6 ±0.5	21.2%±0.2%	5.7%±0.0%	1.46%±0.01%
QST-FLB-01	<0.024	2.2%±0.1%	0.01%±0.00%	1.4 ±0.3	22.8%±0.2%	4.4%±0.4%	0.30%±0.01%
QST-FLB-02	<0.024	3.7%±0.1%	0.01%±0.00%	3.2 ±0.3	6.2%±0.4%	5.2%±0.2%	0.45%±0.00%
STA-FLB-01	<0.024	2.8%±0.1%	0.02%±0.00%	4.8 ±0.1	25.2%±0.7%	4.0%±0.1%	0.54%±0.01%
TID-FLB-01	<0.024	3.8%±0.2%	0.01%±0.00%	2.5 ±0.0	17.9%±1.0%	5.8%±0.5%	0.56%±0.02%
TID-FLB-03	<0.024	3.3%±0.2%	0.02%±0.00%	2.6 ±0.9	16.7%±1.0%	5.0%±0.3%	0.50%±0.05%
TID-FLB-06	<0.024	5.8%±0.9%	0.02%±0.01%	6.4 ±1.2	15.3%±0.1%	5.1%±0.2%	0.98%±0.03%
TVA-FLB-01	<0.024	1.3%±0.1%	0.01%±0.00%	1.6 ±0.3	39.1%±2.0%	2.6%±0.1%	0.23%±0.01%
TVA-FLB-02	<0.024	5.0%±0.5%	0.03%±0.01%	7.4 ±0.1	24.4%±0.9%	6.0%±0.1%	0.83%±0.01%
Mean		4.0%±1.7%	0.02%±0.01%	5.5 ±4.1	21.0%±8.0%	5.5%±2.1%	0.65%±0.3%
Other Materials							
GMC-FLB-03	<0.024	2.3%±0.0%	0.02%±0.00%	10.3 ±0.8	31.0%±0.4%	4.3%±0.0%	0.19%±0.00%
OSU-SPD-04	<0.024	10.3%±0.2%	0.03%±0.00%	19.4 ±2.6	2.9%±0.1%	19.7%±0.8%	1.21%±0.01%
OSU-SPD-07	<0.024	8.8%±0.1%	0.02%±0.00%	24.4 ±2.6	0.7%±0.1%	15.1%±1.1%	0.81%±0.02%
OSU-SPD-08	<0.024	12.3%±0.2%	0.03%±0.00%	23.1 ±1.7	0.7%±0.0%	17.6%±0.3%	1.35%±0.00%
OSU-SPD-09	<0.024	9.9%±0.2%	0.03%±0.00%	18.4 ±0.9	0.5%±0.0%	15.2%±0.5%	1.15%±0.00%
OSU-SPD-10	<0.024	1.3%±0.0%	0.01%±0.00%	3.6 ±0.9	37.2%±0.8%	1.2%±0.0%	0.17%±0.00%
TID-FLB-05	<0.024	7.0%±0.4%	0.03%±0.00%	6.7 ±0.6	12.3%±0.2%	4.0%±0.1%	1.26%±0.03%
Mean		7.4%±3.7%	0.02%±0.01%	15.1 ±7.6	12.2%±13.6%	11.0%±6.6%	0.88%±0.4%

Table 11. continued

Sample	Li		Mg	Mn		Mo		P		S (LECO)	S (ICP)
	mg kg ⁻¹		wt%	mg kg ⁻¹		mg kg ⁻¹		mg kg ⁻¹		%	%
Spray Dryer											
BAB-LID-01	56.5 ± 1.7		0.75%±0.01%	253 ± 1		50.2 ± 5.0		409 ± 21		10.2%±0.4%	11.0%±0.0%
BAB-LID-02	31.5 ± 1.2		15.13%±0.06%	116 ± 1		17.7 ± 2.3		242 ± 27		7.7%±0.2%	8.0%±0.7%
BAB-LID-03	15.1 ± 0.3		0.76%±0.02%	252 ± 5		20.1 ± 1.0		322 ± 20		8.2%±0.0%	8.0%±0.1%
HST-SPD-01	31.4 ± 1.1		0.38%±0.01%	64 ± 0		1.7 ± 4.9		745 ± 2		17.0%±0.1%	16.3%±2.5%
HST-SPD-02	38.4 ± 0.8		0.42%±0.00%	92 ± 0		< 0.018		749 ± 24		13.5%±0.1%	12.4%±0.5%
HST-SPD-03	21.7 ± 1.9		0.42%±0.01%	49 ± 0		3.1 ± 2.3		357 ± 21		15.3%±0.0%	14.6%±0.2%
HST-SPD-04	24.1 ± 0.0		0.40%±0.00%	61 ± 0		< 0.018		298 ± 60		14.0%±0.1%	11.5%±0.2%
HST-SPD-05	29.0 ± 3.7		0.41%±0.07%	55 ± 10		10.2 ± 2.9		472 ± 19		16.6%±0.0%	11.8%±2.6%
NSP-SPD-01	90.5 ± 4.6		1.37%±0.15%	501 ± 14		2.2 ± 2.2		1752 ± 16		5.8%±0.1%	4.2%±0.3%
OSU-SPD-01	26.5 ± 1.9		0.81%±0.00%	62 ± 7		7.1 ± 4.0		87 ± 38		7.6%±0.6%	5.0%±0.0%
OSU-SPD-02	20.6 ± 2.8		0.91%±0.04%	43 ± 3		9.2 ± 1.8		21 ± 11		10.7%±0.0%	8.9%±0.3%
OSU-SPD-03	20.2 ± 1.9		0.94%±0.01%	46 ± 1		4.4 ± 2.4		94 ± 7		10.4%±0.1%	8.7%±0.6%
OSU-SPD-05	30.6 ± 1.1		1.01%±0.00%	58 ± 1		8.3 ± 0.3		127 ± 37		10.1%±0.0%	8.2%±0.0%
Mean	33.5 ±19.2		1.82%±3.90%	127 ±128		12.2 ±13.3		437 ± 439		11.3%±3.5%	9.9%±3.4%
Duct Injection											
BEV-DUC-02	57.5 ± 1.2		0.61%±0.01%	149 ± 2		< 0.018		70 ± 43		5.9%±0.1%	4.3%±0.9%
BEV-DUC-03	51.0 ± 0.1		0.54%±0.00%	135 ± 2		1.6 ± 1.0		143 ± 21		6.4%±0.2%	4.9%±0.6%
BEV-DUC-05	96.5 ± 0.9		0.59%±0.01%	113 ± 2		4.2 ± 3.8		204 ± 4		9.8%±0.3%	7.1%±0.7%
BEV-DUC-06	70.9 ± 0.2		0.56%±0.01%	122 ± 1		2.8 ± 4.4		183 ± 15		7.4%±0.2%	6.5%±0.2%
BEV-DUC-07	97.6 ± 1.9		0.59%±0.01%	137 ± 1		8.2 ± 9.1		166 ± 13		8.5%±0.1%	6.7%±0.9%
BEV-DUC-08	106.0 ± 0.4		0.55%±0.02%	132 ± 2		22.9 ±15.9		92 ± 30		9.1%±0.2%	6.1%±0.6%
EDG-CLS-01	94.8 ± 1.1		0.67%±0.01%	143 ± 3		40.0 ± 4.0		679 ± 26		2.4%±0.1%	1.9%±0.1%
Mean	82.1 ±20.3		0.59%±0.00%	133 ± 11		13.3 ±13.9		220 ± 193		7.1%±2.3%	5.4%±1.7%

Table 11. continued

Sample	Li	Mg	Mn	Mo	P	S (LECO)	S (ICP)
	mg kg ⁻¹	wt%	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	%	%
LIMB							
EDG-LIM-03	49.3 ± 1.2	0.39%±0.01%	110 ± 9	19.6 ± 5.8	648 ± 23	2.7%±0.2%	2.6%±0.0%
EDG-LIM-04	65.1 ± 2.5	7.86%±0.06%	136 ± 1	50.2 ±23.8	642 ± 27	3.7%±0.0%	3.1%±0.0%
EDG-LIM-05	43.0 ± 0.2	10.66%±0.31%	139 ± 3	11.7 ± 1.7	243 ± 40	4.2%±0.4%	4.4%±0.0%
EDG-LIM-06	65.2 ± 0.4	9.60%±0.21%	192 ± 1	29.6 ± 3.0	498 ± 21	5.0%±0.0%	4.9%±0.0%
EDG-LIM-07	49.9 ± 2.8	10.56%±0.21%	123 ± 1	7.6 ± 0.1	279 ± 53	5.8%±0.0%	5.7%±0.0%
EDG-LIM-08	89.4 ± 1.3	0.62%±0.02%	241 ± 5	63.7 ± 1.5	1363 ± 16	5.8%±0.0%	1.5%±0.0%
EDG-LIM-09	45.0 ± 0.8	12.66%±0.11%	119 ± 2	22.9 ± 4.3	430 ± 51	1.7%±0.0%	4.0%±0.0%
EDG-LIM-10	72.6 ± 0.5	0.77%±0.01%	306 ± 10	45.1 ± 0.3	1087 ± 11	4.3%±0.1%	2.7%±0.0%
EDG-LIM-11	65.7 ± 1.2	0.55%±0.00%	231 ± 2	15.2 ± 4.2	651 ± 59	3.2%±0.0%	5.9%±0.0%
EDG-LIM-12	62.0 ± 1.3	0.55%±0.00%	170 ± 0	25.8 ± 3.9	863 ± 8	6.0%±0.1%	3.2%±0.0%
EDG-LIM-13	51.7 ± 0.5	0.51%±0.00%	170 ± 1	9.2 ± 0.4	360 ± 3	3.6%±0.0%	5.1%±0.0%
EDG-LIM-14	30.2 ± 2.5	0.60%±0.01%	176 ± 1	5.9 ± 1.1	153 ± 13	5.3%±0.1%	5.8%±0.1%
Mean	57.4 ±15.1	4.61%±4.89%	176 ± 56	25.5 ±17.8	601 ± 344	4.3%±1.3%	4.1%±1.38
Fluidized Bed Combustion							
<i>Bed Ash</i>							
GMC-FLB-01	11.0 ± 0.1	3.95%±0.16%	243 ± 1	25.3 ± 3.5	230 ± 40	14.2%±0.4%	18.3%±0.5%
QST-FLB-03	5.2 ± 1.0	0.38%±0.01%	625 ± 5	< 0.018	235 ± 42	10.5%±0.9%	14.4%±0.8%
TID-FLB-02	11.6 ± 0.9	15.85%±0.19%	63 ± 0	0.5 ± 0.5	94 ± 19	7.7%±0.0%	9.5%±0.1%
TID-FLB-04	20.0 ± 0.6	16.22%±0.09%	93 ± 12	4.8 ± 0.3	89 ± 38	8.5%±0.0%	8.2%±0.8%
TID-FLB-07	14.1 ± 3.3	15.96%±0.71%	125 ± 6	6.6 ± 0.3	59 ± 30	10.3%±0.1%	11.7%±0.0%
TVA-FLB-03	6.5 ± 0.5	2.74%±0.09%	92 ± 4	5.8 ± 0.4	140 ± 3	10.5%±0.1%	13.8%±1.2%
Mean	11.4 ± 4.9	9.18%±6.90%	207 ±196	8.6 ± 9.4	141 ± 69	10.3%±2.1%	12.6%±3.3%

Table 11. continued

Sample	Li	Mg	Mn	Mo	P	S (LECO)	S (ICP)
	mg kg ⁻¹	wt%	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	%	%
Fluidized Bed Combustion							
<i>Cyclone Ash</i>							
GMC-FLB-02	57.2 ± 1.8	3.52%±0.13%	349 ± 9	22.0 ± 7.8	389 ± 7	6.9%±0.3%	7.5%±0.4%
PED-RCB-01	78.7 ± 1.3	3.16%±0.01%	113 ± 1	4.8 ± 2.4	597 ± 32	3.5%±0.1%	3.4%±0.1%
QST-FLB-01	16.5 ± 1.9	0.26%±0.00%	389 ± 31	1.3 ± 3.7	364 ± 9	6.2%±0.2%	6.5%±0.1%
QST-FLB-02	28.1 ± 0.1	0.18%±0.00%	150 ± 6	< 0.018	235 ± 21	2.3%±0.0%	1.5%±0.1%
STA-FLB-01	10.7 ± 0.3	0.60%±0.00%	530 ± 1	1.1 ± 5.3	398 ± 40	6.3%±0.1%	6.3%±0.3%
TID-FLB-01	24.6 ± 1.4	10.78%±0.57%	82 ± 10	5.1 ± 0.3	217 ± 1	4.8%±0.1%	4.7%±0.2%
TID-FLB-03	25.6 ± 1.1	9.79%±1.20%	87 ± 5	6.6 ± 0.7	179 ± 33	5.2%±0.1%	4.7%±0.3%
TID-FLB-06	36.3 ± 6.3	9.37%±0.03%	130 ± 3	6.4 ± 4.0	178 ± 14	5.3%±0.2%	5.1%±0.1%
TVA-FLB-01	10.4 ± 2.8	1.67%±0.07%	107 ± 2	9.8 ± 4.2	140 ± 5	7.1%±0.5%	7.8%±0.7%
TVA-FLB-02	42.7 ± 2.8	1.50%±0.06%	128 ± 3	25.7 ± 6.2	321 ± 24	5.8%±0.1%	5.8%±0.3%
Mean	33.1 ±20.5	4.08%±4.00%	206 ±149	9.2 ± 8.3	302 ± 133	5.3%±1.4%	5.3%±1.8%
Other Materials							
GMC-FLB-03	18.5 ± 1.1	4.45%±0.26%	281 ± 4	24.9 ± 7.5	300 ± 4	11.9%±0.4%	16.1%±1.0%
OSU-SPD-04	133.4 ± 3.1	0.54%±0.01%	199 ± 6	19.2 ± 3.1	225 ± 5	2.5%±0.1%	2.0%±0.1%
OSU-SPD-07	101.3 ± 1.3	0.27%±0.00%	187 ± 1	15.6 ± 0.6	324 ± 29	0.5%±0.0%	0.2%±0.0%
OSU-SPD-08	153.9 ± 0.7	0.42%±0.00%	209 ± 2	14.7 ± 5.0	352 ± 30	1.0%±0.0%	0.7%±0.0%
OSU-SPD-09	123.4 ± 0.6	0.34%±0.00%	170 ± 3	14.1 ± 3.0	384 ± 29	2.1%±0.0%	1.3%±0.1%
OSU-SPD-10	17.7 ± 0.3	0.95%±0.02%	33 ± 3	10.5 ± 5.3	104 ± 46	12.5%±0.1%	11.4%±0.2%
TID-FLB-05	44.6 ± 3.2	6.78%±0.27%	121 ± 1	6.5 ± 1.8	388 ± 33	10.3%±0.2%	11.2%±0.4%
Mean	84.7 ±52.7	1.96%±2.30%	171 ± 72	15.1 ± 5.5	297 ± 94	5.8%±4.9%	6.1%±5.9%

Table 11. continued

Sample	Si	Sr	V	Zn
	wt%	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹
				(ICP & AA)
Spray Dryer				
BAB-LID-01	4.8%± 0.3%	212 ± 0	83.9 ±17.2	*237 ± 1
BAB-LID-02	2.9%± 0.1%	247 ± 2	72.0 ± 4.0	266 ± 83
BAB-LID-03	2.2%± 0.3%	153 ± 2	22.5 ±13.1	*68 ± 8
HST-SPD-01	5.9%± 0.1%	547 ± 10	72.5 ± 2.1	*65 ± 1
HST-SPD-02	8.6%± 0.0%	669 ± 2	82.6 ± 5.1	*52 ± 4
HST-SPD-03	4.4%± 0.1%	430 ± 7	43.4 ±17.0	--
HST-SPD-04	4.8%± 0.1%	426 ± 2	50.8 ± 3.4	*92 ± 6
HST-SPD-05	5.4%± 0.8%	487 ± 63	46.2 ±20.3	*87 ± 10
NSP-SPD-01	13.7%± 0.7%	3166 ± 125	66.3 ± 1.6	*88 ± 23
OSU-SPD-01	4.0%± 0.0%	255 ± 10	26.2 ±13.5	*52 ± 20
OSU-SPD-02	2.5%± 0.3%	240 ± 12	30.5 ± 5.6	*125 ± 7
OSU-SPD-03	2.6%± 0.0%	257 ± 5	33.1 ± 5.8	*90 ± 4
OSU-SPD-05	3.5%± 0.2%	258 ± 3	50.7 ± 2.7	69 ± 1
Mean	5.0%± 3.0%	565 ± 765	52.3 ±21.1	108 ± 68
Duct Injection				
BEV-DUC-02	7.5%± 0.1%	306 ± 6	69.6 ± 7.0	99 ± 28
BEV-DUC-03	6.5%± 0.3%	286 ± 1	42.4 ±13.0	--
BEV-DUC-05	11.7%± 0.1%	378 ± 3	114.4 ± 9.8	154 ± 7
BEV-DUC-06	8.0%± 0.3%	378 ± 4	54.3 ± 9.6	63 ± 17
BEV-DUC-07	11.9%± 0.1%	358 ± 3	98.1 ±18.5	--
BEV-DUC-08	12.2%± 0.1%	540 ± 12	99.2 ±15.8	117 ± 53
EDG-CLS-01	18.2%± 0.3%	313 ± 3	144.7 ±19.0	*289 ± 18
Mean	10.8%± 3.7%	367 ± 79	89.0 ±33.1	124 ± 75

Table 11. continued

Sample	Si	Sr	V	Zn
	wt%	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹
				(ICP & AA)
LIMB				
EDG-LIM-03	10.2%± 0.1%	314 ± 3	102.7 ± 3.0	*210 ± 69
EDG-LIM-04	12.5%± 0.0%	783 ± 0	106.3 ± 18.9	123 ± 10
EDG-LIM-05	7.0%± 0.1%	993 ± 34	76.5 ± 2.7	116 ± 33
EDG-LIM-06	9.4%± 0.0%	663 ± 9	126.3 ± 2.5	*227 ± 71
EDG-LIM-07	7.8%± 0.2%	555 ± 2	92.3 ± 5.4	133 ± 36
EDG-LIM-08	19.3%± 0.2%	388 ± 5	192.0 ± 4.6	*469 ± 3
EDG-LIM-09	9.4%± 0.1%	952 ± 11	67.0 ± 17.0	*131 ± 38
EDG-LIM-10	16.8%± 0.7%	367 ± 3	154.6 ± 1.3	*457 ± 70
EDG-LIM-11	11.4%± 0.3%	350 ± 2	123.4 ± 1.8	*190 ± 64
EDG-LIM-12	16.3%± 0.1%	360 ± 2	120.2 ± 2.8	*253 ± 46
EDG-LIM-13	10.7%± 0.1%	313 ± 3	89.4 ± 2.4	104 ± 28
EDG-LIM-14	6.6%± 0.1%	297 ± 7	40.9 ± 19.7	*86 ± 4
Mean	11.4%± 3.9%	528 ± 247	107.6 ± 38.5	208 ± 119
Fluidized Bed Combustion				
<i>Bed Ash</i>				
GMC-FLB-01	3.4%± 0.2%	173 ± 5	34.5 ± 1.5	*45 ± 3
QST-FLB-03	2.5%± 0.7%	895 ± 29	18.5 ± 8.5	*108 ± 11
TID-FLB-02	2.0%± 0.1%	98 ± 1	-17.8 ± 3.7	--
TID-FLB-04	2.1%± 0.3%	111 ± 9	41.6 ± 1.0	*245 ± 7
TID-FLB-07	2.7%± 0.0%	121 ± 2	-13.3 ± 3.0	*109 ± 37
TVA-FLB-03	2.4%± 0.1%	453 ± 6	26.2 ± 8.0	95 ± 19
Mean	2.5%± 0.5%	308 ± 289	15.0 ± 8.7	119 ± 66

Table 11. continued

Sample	Si	Sr	V	Zn
	wt%	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹
				(ICP & AA)
Cyclone Ash				
GMC-FLB-02	9.3%± 0.0%	214 ± 5	83.0 ±14.1	*184 ± 1
PED-RCB-01	13.9%± 0.3%	487 ± 5	141.5 ±10.8	*182 ± 7
QST-FLB-01	4.4%± 0.2%	511 ± 15	26.2 ± 9.4	*122 ± 29
QST-FLB-02	6.6%± 0.3%	216 ± 3	49.4 ± 9.5	5 ± 0
STA-FLB-01	8.3%± 0.5%	492 ± 4	59.1 ±10.4	101 ± 14
TID-FLB-01	7.7%± 0.4%	138 ± 8	17.1 ± 1.6	*69 ± 26
TID-FLB-03	6.7%± 0.6%	133 ± 7	60.2 ± 5.9	*74 ± 17
TID-FLB-06	35.0%±25.0%	170 ± 5	70.9 ±29.7	*136 ± 17
TVA-FLB-01	3.4%± 0.2%	471 ± 8	63.6 ±12.0	126 ± 26
TVA-FLB-02	26.0%±17.0%	592 ± 17	116.9 ± 7.4	--
Mean	12.1%± 9.8%	342 ± 173	68.8 ±35.9	111 ± 58
Other Materials				
GMC-FLB-03	4.3%± 0.2%	200 ± 0	107.5 ±13.8	*83 ± 35
OSU-SPD-04	16.0%± 0.6%	388 ± 10	126.7 ±11.2	*389 ± 1
OSU-SPD-07	12.1%± 0.0%	371 ± 33	156.2 ±21.4	55 ± 10
OSU-SPD-08	17.4%± 0.4%	404 ± 0	190.6 ±13.5	234 ± 8
OSU-SPD-09	15.2%± 0.5%	420 ± 0	152.3 ±12.7	99 ± 15
OSU-SPD-10	2.1%± 0.3%	256 ± 7	23.3 ±13.7	*128 ± 15
TID-FLB-05	30.4%±14.7%	206 ± 3	99.4 ±24.3	*150 ± 9
Mean	13.9%± 9.4%	321 ± 89	122.3 ±49.7	163 ±102

Table 12. Total trace element content in FGD by-product samples as determined by graphite furnace AA.

Sample	As (mg/kg)	Cd (mg/kg)	Co (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Se (mg/kg)
<u>Duct Injection</u>								
BEV-DUC-02	8.0 ± 0.5	1.1 ± 0.1	20.0 ± 5.6	29.8 ± 0.6	14.5 ± 6.4	33.9 ± 2.8	9.5 ± 0.7	7.5 ± 1.7
BEV-DUC-03	9.4 ± 0.8	1.5 ± 0.1	15.0 ± 0.7	35.6 ± 11.2	29.4 ± 7.8	27.7 ± 3.7	8.5 ± 0.7	6.7 ± 1.4
BEV-DUC-05	16.5 ± 0.6	1.8 ± 0.8	27.5 ± 3.2	52.0 ± 2.7	25.1 ± 6.3	49.6 ± 5.0	21.0 ± 0.0	17.2 ± 0.9
BEV-DUC-06	15.2 ± 2.8	4.2 ± 2.6	13.4 ± 0.1	29.9 ± 6.0	44.8 ± 3.2	27.7 ± 4.6	16.5 ± 2.1	15.2 ± 2.8
BEV-DUC-07	23.0 ± 3.1	2.7 ± 2.0	20.1 ± 0.6	55.2 ± 3.5	35.4 ± 2.8	37.5 ± 0.4	15.0 ± 1.4	12.6 ± 0.7
BEV-DUC-08	18.3 ± 3.2	1.3 ± 0.0	21.0 ± 0.7	52.4 ± 2.7	37.8 ± 4.1	38.3 ± 0.7	14.5 ± 2.1	11.2 ± 2.3
EDG-CLS-01	378.4 ± 60.5	2.4 ± 0.1	71.8 ± 1.3	89.3 ± 7.7	91.3 ± 2.7	152.5 ± 2.8	121.0 ± 1.4	18.8 ± 2.7
Mean	67.0 ± 137.4	2.1 ± 1.1	27.0 ± 20.3	49.2 ± 20.8	39.8 ± 24.7	52.5 ± 44.7	29.4 ± 40.6	12.7 ± 4.6
<u>Spray Dryer</u>								
BAB-LID-01	103.6 ± 0.2	4.0 ± 0.8	20.8 ± 1.5	42.7 ± 2.2	73.21 ± 18.0	58.9 ± 10.9	109.5 ± 12.0	23.0 ± 3.0
BAB-LID-02	165.5 ± 4.0	2.3 ± 0.5	14.7 ± 1.8	31.7 ± 12.0	37.3 ± 5.1	48.3 ± 6.4	56.5 ± 0.7	15.5 ± 2.0
BAB-LID-03	87.9 ± 8.8	40.7 ± 0.1	8.0 ± 0.6	56.3 ± 20.4	48.7 ± 4.9	31.2 ± 1.1	139.0 ± 5.7	14.4 ± 1.9
HST-SPD-01	17.9 ± 2.5	1.1 ± 0.2	14.7 ± 0.7	29.6 ± 4.8	15.9 ± 3.2	26.6 ± 2.5	20.0 ± 1.4	8.9 ± 1.6
HST-SPD-02	16.6 ± 2.0	1.4 ± 0.6	20.2 ± 0.3	37.3 ± 6.5	27.7 ± 5.2	33.3 ± 0.1	21.5 ± 3.5	8.2 ± 1.8
HST-SPD-03	13.3 ± 0.9	4.7 ± 2.6	9.4 ± 1.5	23.5 ± 4.8	14.9 ± 4.6	22.5 ± 0.4	13.5 ± 3.5	7.2 ± 2.8
HST-SPD-04	9.6 ± 0.7	1.2 ± 0.1	12.0 ± 0.9	20.1 ± 4.5	39.1 ± 21.4	19.5 ± 0.8	15.0 ± 0.0	4.9 ± 1.2
HST-SPD-05	14.3 ± 0.1	1.1 ± 0.2	13.8 ± 0.2	27.5 ± 0.7	18.8 ± 7.3	22.6 ± 4.0	17.5 ± 2.1	8.0 ± 0.7
NSP-SPD-01	6.9 ± 0.0	1.5 ± 0.2	15.6 ± 4.3	29.2 ± 3.7	53.9 ± 1.6	31.5 ± 1.0	38.5 ± 3.5	5.7 ± 2.0

Table 12. continued

Sample	As (mg/kg)	Cd (mg/kg)	Co (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Se (mg/kg)
Spray Dryer continued...								
OSU-SPD-01	26.1 ± 0.6	1.2 ± 0.2	13.2 ± 1.6	24.2 ± 13.3	13.3 ± 7.0	24.4 ± 7.0	6.5 ± 0.7	7.9 ± 0.2
OSU-SPD-02	35.1 ± 2.8	1.6 ± 0.3	13.8 ± 6.3	11.4 ± 3.1	16.3 ± 6.1	12.4 ± 1.3	19.0 ± 2.8	10.4 ± 0.1
OSU-SPD-03	43.2 ± 4.8	1.2 ± 0.8	9.6 ± 1.7	13.0 ± 1.3	18.5 ± 0.9	17.6 ± 0.8	24.1 ± 0.1	9.1 ± 0.4
OSU-SPD-05	33.2 ± 4.4	1.1 ± 0.1	18.7 ± 0.2	22.3 ± 6.3	22.3 ± 2.1	27.9 ± 0.5	18.5 ± 0.7	7.6 ± 0.4
Mean	44.1 ± 47.1	4.9 ± 10.8	14.2 ± 4.0	28.4 ± 12.1	30.8 ± 18.6	29.0 ± 12.6	38.4 ± 40.5	10.1 ± 4.9
<u>LIMB</u>								
EDG-LIM-03	201.6 ± 13.9	2.5 ± 1.3	60.9 ± 11.4	49.5 ± 4.4	44.7 ± 17.1	78.3 ± 2.5	57.0 ± 4.2	16.9 ± 0.6
EDG-LIM-04	144.0 ± 0.9	2.0 ± 0.8	38.8 ± 3.4	68.0 ± 12.3	50.1 ± 1.4	80.0 ± 15.5	55.0 ± 0.0	15.0 ± 0.5
EDG-LIM-05	142.5 ± 13.7	1.9 ± 0.8	33.8 ± 3.6	34.4 ± 6.4	36.2 ± 0.4	63.1 ± 4.9	38.5 ± 4.9	14.3 ± 0.3
EDG-LIM-06	276.4 ± 47.3	2.3 ± 0.5	52.8 ± 10.9	56.6 ± 3.8	58.9 ± 19.8	91.8 ± 0.1	66.0 ± 8.5	22.3 ± 0.4
EDG-LIM-07	93.6 ± 14.9	2.2 ± 0.3	24.2 ± 3.8	41.1 ± 4.5	40.5 ± 6.0	54.7 ± 2.1	40.5 ± 2.1	12.6 ± 1.0
EDG-LIM-08	368.4 ± 33.8	3.2 ± 0.0	90.7 ± 26.9	85.2 ± 10.7	80.2 ± 6.5	156.0 ± 0.9	138.5 ± 9.2	16.8 ± 2.2
EDG-LIM-09	99.1 ± 9.5	1.5 ± 0.0	25.8 ± 1.2	39.7 ± 1.4	30.8 ± 2.4	53.3 ± 6.3	31.0 ± 2.8	9.5 ± 0.4
EDG-LIM-10	386.3 ± 27.0	3.8 ± 1.4	78.9 ± 21.9	68.4 ± 9.5	85.8 ± 22.8	125.2 ± 3.2	108.0 ± 4.2	22.1 ± 1.2
EDG-LIM-11	168.4 ± 18.1	1.7 ± 0.4	38.5 ± 5.2	56.3 ± 3.3	47.6 ± 12.5	75.8 ± 5.1	55.5 ± 7.8	17.1 ± 1.2
EDG-LIM-12	176.2 ± 9.0	1.6 ± 0.2	60.7 ± 14.2	64.0 ± 6.2	50.3 ± 11.9	107.1 ± 6.6	68.5 ± 4.9	13.7 ± 1.3
EDG-LIM-13	113.8 ± 17.4	1.3 ± 0.4	27.8 ± 3.4	45.4 ± 7.9	33.1 ± 9.0	50.3 ± 0.8	35.5 ± 6.4	13.9 ± 0.4
EDG-LIM-14	55.1 ± 2.8	1.0 ± 0.0	14.8 ± 1.1	28.0 ± 4.0	21.0 ± 8.0	31.1 ± 1.3	16.0 ± 0.0	8.1 ± 1.3
Mean	185.5 ± 106.3	2.1 ± 0.8	45.6 ± 23.4	53.1 ± 16.5	48.3 ± 19.2	80.6 ± 35.2	59.2 ± 34.2	15.2 ± 4.3

Table 12. continued

Sample	As (mg/kg)	Cd (mg/kg)	Co (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Se (mg/kg)
<u>Fuidized Bed Combustion</u>								
<i>Bed Ash</i>								
GMC-FLB-01	80.8 ± 7.0	1.7 ± 0.6	27.3 ± 5.1	21.7 ± 5.7	23.1 ± 2.7	58.2 ± 5.9	6.5 ± 0.7	4.6 ± 1.7
QST-FLB-03	213.2 ± 22.9	< 0.5	5.7 ± 0.2	12.4 ± 3.9	28.3 ± 19.9	32.8 ± 5.0	9.5 ± 0.7	3.8 ± 0.3
TID-FLB-02	49.7 ± 1.3	1.6 ± 0.3	3.8 ± 1.7	11.7 ± 3.3	15.6 ± 1.8	18.2 ± 1.6	9.1 ± 0.1	3.3 ± 0.0
TID-FLB-04	46.7 ± 0.7	3.9 ± 2.7	8.5 ± 1.9	17.5 ± 0.6	912.9 ± 13.5	21.2 ± 3.9	28.0 ± 4.0	2.3 ± 0.1
TID-FLB-07	52.2 ± 2.3	< 0.5	3.9 ± 0.5	12.5 ± 4.1	16.5 ± 3.5	16.4 ± 2.4	5.0 ± 0.0	3.7 ± 0.5
TVA-FLB-03	5.4 ± 1.6	1.9 ± 0.2	4.4 ± 0.3	25.3 ± 3.1	63.9 ± 3.9	51.0 ± 5.1	9.5 ± 0.7	4.1 ± 1.3
Mean	74.7 ± 72.0	2.3 ± 1.1	8.9 ± 9.2	16.9 ± 5.7	176.7 ± 361.1	33.0 ± 17.8	11.3 ± 8.4	3.6 ± 0.8
<i>Cyclone/Fly Ash</i>								
GMC-FLB-02	66.9 ± 1.2	2.1 ± 0.9	51.6 ± 1.3	40.7 ± 3.4	80.6 ± 4.8	103.4 ± 2.2	33.0 ± 1.4	7.2 ± 2.7
PED-RCB-01	23.0 ± 1.8	1.6 ± 0.3	29.2 ± 2.4	72.3 ± 7.4	56.1 ± 19.7	48.6 ± 4.9	100.0 ± 8.5	16.4 ± 0.7
QST-FLB-01	127.0 ± 8.9	< 0.5	14.5 ± 0.4	15.1 ± 2.9	19.4 ± 3.4	28.3 ± 4.2	18.0 ± 1.4	3.87 ± 0.5
QST-FLB-02	146.7 ± 22.7	< 0.5	19.1 ± 2.8	31.4 ± 2.0	19.2 ± 1.9	37.0 ± 0.8	25.0 ± 1.4	3.5 ± 0.9
STA-FLB-01	10.5 ± 2.0	5.9 ± 0.2	11.3 ± 0.9	31.8 ± 1.8	19.3 ± 5.7	35.2 ± 7.0	13.0 ± 4.2	7.4 ± 0.9
TID-FLB-01	78.8 ± 7.2	1.1 ± 0.2	18.4 ± 0.9	56.7 ±	36.1 ± 8.5	95.8 ± 4.3	27.5 ± 1.2	2.7 ± 0.5
TID-FLB-03	75.0 ± 3.5	1.9 ± 0.7	15.3 ± 0.5	36.9 ± 9.0	52.5 ± 13.1	52.1 ± 21.4	16.0 ± 3.5	5.6 ± 0.5
TID-FLB-06	67.8 ± 2.5	2.1 ± 0.3	18.8 ± 0.4	47.0 ± 5.1	31.7 ± 8.3	44.6 ± 6.6	51.5 ± 7.8	3.9 ± 0.6
TVA-FLB-01	5.2 ± 0.2	3.5 ± 1.9	7.1 ± 0.5	16.4 ± 2.6	16.1 ± 2.1	21.8 ± 4.3	10.5 ± 4.9	6.8 ± 0.8
TVA-FLB-02	35.3 ± 1.9	6.9 ± 0.4	20.7 ± 0.5	41.7 ± 8.8	33.0 ± 3.6	48.0 ± 0.8	39.0 ± 18.4	9.9 ± 3.2
Mean	63.6 ± 47.1	3.1 ± 2.1	20.6 ± 12.4	39.0 ± 17.3	36.4 ± 20.9	51.5 ± 27.1	33.4 ± 26.6	6.7 ± 4.1

Table 12. continued

Sample	As (mg/kg)	Cd (mg/kg)	Co (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Se (mg/kg)
Other Materials								
BEV-DUC-01	37.3 ± 1.4	1.5 ± 0.3	30.8 ± 6.6	65.1 ± 8.7	42.5 ± 3.6	54.0 ± 4.5	25.5 ± 0.7	16.3 ± 0.4
GMC-FLB-03	111.0 ± 4.9	1.8 ± 0.0	29.0 ± 0.8	33.6 ± 5.5	26.0 ± 4.2	77.4 ± 1.1	11.0 ± 1.4	7.2 ± 2.6
OSU-SPD-04	9.6 ± 1.1	1.1 ± 0.1	46.9 ± 1.8	105.8 ± 16.8	64.6 ± 8.6	83.4 ± 10.3	18.5 ± 0.7	3.0 ± 0.4
OSU-SPD-07	5.9 ± 0.5	0.8 ± 0.1	61.6 ± 20.1	80.6 ± 2.9	68.8 ± 17.4	81.5 ± 4.2	18.0 ± 4.2	4.1 ± 1.1
OSU-SPD-08	11.0 ± 0.5	1.0 ± 0.6	69.3 ± 3.2	137.1 ± 3.0	1487.2 ± 11.3	99.4 ± 2.6	20.5 ± 3.5	4.1 ± 1.1
OSU-SPD-09	18.4 ± 2.4	< 0.5	52.6 ± 7.5	100.9 ± 0.4	258.6 ± 30.8	77.7 ± 0.5	29.0 ± 2.8	5.1 ± 0.6
OSU-SPD-10	45.9 ± 7.9	1.8 ± 0.2	13.8 ± 0.0	11.4 ± 4.4	24.4 ± 3.5	33.2 ± 4.2	29.0 ± 0.0	19.6 ± 3.6
TID-FLB-05	219.3 ± 7.8	4.1 ± 0.1	23.3 ± 0.7	79.9 ± 7.2	33.0 ± 4.2	61.0 ± 2.0	92.0 ± 4.2	5.1 ± 0.7
Mean	57.3 ± 73.9	1.7 ± 1.1	40.9 ± 19.6	76.6 ± 40.1	250.6 ± 505.6	71.0 ± 20.6	30.4 ± 25.6	8.1 ± 6.3

Table 13. Total boron content of FGD by-products.

Sample	B		Sample	B	
	mg kg ⁻¹			mg kg ⁻¹	
<u>Duct Injection</u>			<u>LIMB</u>		
BEV-DUC-02	158 ±	1	EDG-LIM-03	297 ±	13
BEV-DUC-03	153 ±	6	EDG-LIM-04	389 ±	3
BEV-DUC-05	281 ±	5	EDG-LIM-05	320 ±	2
BEV-DUC-06	196 ±	3	EDG-LIM-06	524 ±	29
BEV-DUC-07	259 ±	4	EDG-LIM-07	399 ±	11
BEV-DUC-08	245 ±	17	EGD-LIM-08	364 ±	5
EDG-CLS-01	460 ±	9	EGD-LIM-09	334 ±	12
			EDG-LIM-10	501 ±	6
Mean	240 ±	82	EDG-LIM-11	386 ±	5
			EDG-LIM-12	315 ±	8
			EDG-LIM-13	442 ±	12
			EDG-LIM-14	233 ±	20
<u>Spray Dryer</u>					
BAB-LID-01	948 ±	12			
BAB-LID-02	509 ±	8	Mean	374 ±	82
BAB-LID-03	360 ±	0			
HST-SPD-01	418 ±	7	<u>Fluidized Bed Combustion</u>		
HST-SPD-02	386 ±	8	<i>Bed Ash</i>		
HST-SPD-03	345 ±	6			
HST-SPD-04	303 ±	19	GMC-FLB-01	302 ±	57
HST-SPD-05	405 ±	1	QST-SPD-03	115 ±	14
OSU-SPD-01	292 ±	14	TID-FLB-02	100 ±	1
OSU-SPD-02	374 ±	15	TID-FLB-04	127 ±	9
OSU-SPD-03	315 ±	8	TID-FLB-07	157 ±	2
OSU-SPD-05	368 ±	14	TVA-FLB-03	68 ±	2
Mean	418 ±	177	Mean	145 ±	82

Table 13. continued

Sample	B mg kg ⁻¹		Sample	B mg kg ⁻¹	
			<u>Fluidized Bed Combustion</u>		
			<i>Cyclone/fly ash</i>		
<u>Other Materials</u>			GMC-FLB-02	492 ±	1
			PED-RCB-01	375 ±	18
BEV-DUC-01	240 ±	6	QST-FLB-01	147 ±	8
GMC-FLB-03	461 ±	16	QST-FLB-02	204 ±	3
OSU-SPD-04	275 ±	24	STA-FLB-01	525 ±	6
OSU-SPD-07	464 ±	10	TID-FLB-01	169 ±	3
OSU-SPD-08	341 ±	25	TID-FLB-03	171 ±	4
OSU-SPD-09	310 ±	5	TID-FLB-06	208 ±	3
OSU-SPD-10	345 ±	3	TVA-FLB-01	117 ±	4
TID-FLB-05	164 ±	2	TVA-FLB-02	387 ±	9
Mean	319 ±	96	Mean	280 ±	151

Table 14 contains proposed ceiling concentrations for ten elements in land-applied sewage sludge. Whereas it must be recognized that the geochemical forms of metals in sewage sludge are undoubtedly dissimilar to those in FGD, the 503 regulations represent an accepted level for the application of potentially hazardous metals to soils and thus can serve in a comparative way, in assessing the suitability of land application of FGD. Additionally, it is likely that some eventual uses of FGD will include additions to sewage sludge to form lime-stabilized materials. Thus comparisons of FGD to the metal limits established in the 503 regulations is of value. By making this comparison we do not mean to imply that FGD by-products should be regulated at the same levels as sewage sludge. All of the FGD by-products analyzed in the present study met the Part 503 criteria for Cd, Cr, Cu, Pb, Ni, Se and Zn. One sample, EDG-LIM-08, exceeded the value for Mo, and 26 out of 56 samples (46% of all of the FGD by-products) exceeded the limit for As. In general, the greatest As concentrations were present in the FGD by-products from the LIMB process. The OSU laboratories did not have the facilities to determine the solid-phase concentrations of Hg in the samples of FGD by-product. Thus, no comparison can be made between the total Hg content of the FGD by-products and the regulatory limits listed in Table 14, for sewage sludge. Nevertheless, the low concentrations of dissolved Hg measured in the toxic characteristic leaching procedure extractions (section 2.1.3.1.2) suggest that the FGD by-products pose little threat with regards to Hg-contamination.

The acid insoluble residues result from solubilizing and washing out the reaction products and unspent sorbent in FGD samples and provide a measure of the fly ash fraction of the samples. Chemical analyses of acid residues from the Ohio FGD by-products showed this fraction was dominated by Al, Fe, and Si. This chemistry is consistent with the mineralogy of fly ash. Total trace element concentrations of the acid insoluble residues varied between sources and samples suggesting a dependency on coal composition and on operating conditions within a given coal-fire facility. Plots of total elemental concentrations versus the weight fraction of acid insoluble residue (Fig. 1 to 7, and Fig. D1 to D18, Appendix D) suggest a preferential partitioning of many of the elements. Elements showing partitioning primarily into the fly ash were Al, As (Fig. 1 and 2), and also Ba, Be, Co, Cr, Cu, Fe, K, Li, Mn, Ni, P, Pb, Si, and V. In contrast, Ca, S (Fig. 3 and 4), and Mg showed an inverse relationship to the concentration of acid insoluble residue. This is to be expected since Ca and Mg are intentionally introduced as sorbents to reduce SO₂ emissions. Increases in the acid insoluble residue resulted in dilution of the Ca and Mg materials and a corresponding decrease in S content. Intermediate elemental partitioning was exhibited by B, Cd (Fig. 5 and 6), Mo, Se and Sr, indicating these elements occur in both the acid soluble and insoluble fractions. This is not surprising since these elements are known to occur in fly ash and as contaminants of limestone.

The data above suggest many of the elements regulated by EPA for solid waste materials, reside primarily in the fly-ash fraction of FGD by-products. Support for this contention can be found by comparing the elemental concentrations in the whole FGD by-products, to those present in the acid insoluble residue. Figures 7 to 11 show greater concentrations of As, Cr, Cu, Ni and Pb in the acid insoluble residue than in

Table 14. Pollutant ceiling concentrations for land application of sewage sludge*.

Pollutant	Concentration
	mg kg ⁻¹
Arsenic	75
Cadmium	85
Chromium	3000
Copper	4300
Lead	840
Mercury	57
Molybdenum	75
Nickel	420
Selenium	100
Zinc	7500

*US Environmental Protection Agency

the whole FGD by-products (for samples OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04). The same trend was observed for Al, Ba, Be, Co, Fe, K, Li, Mn, P, and V. Cadmium, Mo and Se (Fig. 12 to 14) and Sr were in near equivalent concentrations in the whole FGD by-products and the acid insoluble residues of the same samples. (See Fig. D19 to D29, Appendix D for elements not shown here.) In contrast, Ca, Mg and S were concentrated in the whole FGD by-product (Fig. 15 to 17) as was previously noted.

From a regulatory perspective, it appears that the FGD by-products examined in the present study can be characterized as clean materials. The only exception to this is the high As content present in 46% of the samples. However, it should be noted that the data in Fig. 2 and 7 strongly suggest that the majority of the As is present in the fly ash fraction of these materials. Therefore, FGD technologies can actually be considered to dilute the As in the ash. Thus, regulation of As in FGD by-products in the same way as As is regulated in fly ash seems reasonable.

Fig. 1. Concentration of Al versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. 2. Concentration of As versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. 3. Concentration of Ca versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. 4. Concentration of S versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. 5. Concentration of B versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. 6. Concentration of Cd versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. 7. Concentration of As in the fly ash fraction (acid insoluble residue) versus the concentration of As in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 8. Concentration of Cr in the fly ash fraction (acid insoluble residue) versus the concentration of Cr in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 9. Concentration of Cu in the fly ash fraction (acid insoluble residue) versus the concentration of Cu in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 10 Concentration of Ni in the fly ash fraction (acid insoluble residue) versus the concentration of Ni in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 11. Concentration of Pb in the fly ash fraction (acid insoluble residue) versus the concentration of Pb in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 12. Concentration of Cd in the fly ash fraction (acid insoluble residue) versus the concentration of Cd in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 13. Concentration of Mo in the fly ash fraction (acid insoluble residue) versus the concentration of Mo in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 14. Concentration of Se in the fly ash fraction (acid insoluble residue) versus the concentration of Se in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 15. Concentration of Ca in the fly ash fraction (acid insoluble residue) versus the concentration of Ca in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 16. Concentration of Mg in the fly ash fraction (acid insoluble residue) versus the concentration of Mg in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. 17. Concentration of S in the fly ash fraction (acid insoluble residue) versus the concentration of S in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

2.1.3.1.2 Leaching Analysis (ASTM and TCLP)

Analytical results for ASTM and TCLP leachates of the five Ohio samples and GMC-FLB-03 (the samples selected for more detailed study) are given in Tables 15 and 16, respectively. Data for all ASTM analyses are provided in Appendix D, Table D2. Leachates were dominated by S (primarily as SO_4^{2-}), Ca, and OH^- (as indicated by high pH). The TCLP leachates for the TID-FLB-03 and -04 samples were also high in Mg, reflecting the use of dolomite as a sorbent in the pressurized fluidized bed process.

The leachate pH (both ASTM and TCLP) for several samples was above the Resource Conservation and Recovery Act (RCRA) limit of 12 for toxic waste. These high pH levels result from the presence of unspent CaO and $\text{Ca}(\text{OH})_2$ sorbents in these samples. These leachates were obtained on fresh samples, however upon aging and exposure to moisture and atmospheric or soil CO_2 the CaO and $\text{Ca}(\text{OH})_2$ will carbonate to form calcite (CaCO_3) and pH will decrease to around 8.3.

The relatively high total dissolved solids (TDS) and SO_4^{2-} resulted primarily from the dissolution of CaSO_4 , and were higher with TCLP acid extraction than with ASTM water extraction. However, TDS and SO_4^{2-} were below the levels for Class III residual wastes proposed by the Ohio EPA for ASTM water leachate (7500 mg/kg for each). With the exception of EDG-LIM-14, sulfite (SO_3^{2-}) was found only in leachates from duct injection and spray dryer samples (those FGD processes which occur under more reducing conditions of low temperature and high relative humidity). Also even though total sulfur in duct injection and spray dryer samples was as high or higher than in the LIMB and FBC samples, total leachate sulfur for these samples tended to be much lower than in the LIMB and FBC samples. This is because much of the S in the duct injection and spray dryer samples is present as calcium sulfite (CaSO_3) which is 20 times less soluble than calcium sulfate (CaSO_4), the predominant S salt in LIMB and FBC samples. Thus a smaller fraction of the total sample S was dissolved during leaching of duct injection and spray dryer samples compared to the LIMB and FBC samples.

Concentrations of the eight RCRA metals (Ag, As, Ba, Cd, Cr, Hg, Pb, and Se) were below drinking water standards for both ASTM and TCLP leachates (Table 17). Concentrations of other trace metals in the ASTM and TCLP leachates were also generally very low for all samples. The low solubility of these metals can be accounted for by the fact that most of them are associated with the relatively insoluble mineral (fly ash) portion of the FGD matrix, rather than the more soluble fraction consisting of unspent sorbent and SO_2 reaction products. (See section 2.1.3.1.1 for additional discussion.)

Table 15. ASTM water leachate results for 6 dry FGD by-products.

Constituent ^a (mg L ⁻¹)	BEV-DUC -02	OSU-SPD -03	EDG-LIM -14	TID-FLB -03	TID-FLB -04	GMC-FLB -03
pH	12.22	12.26	12.14	11.42	11.77	12.01
TDS ^b	2910	3520	4830	3140	5150	4830
Ag	<0.005	<0.005	<0.005	<0.005	<0.005	0.007
Al	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
As ^c	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
B	2.33	5.15	3.93	0.83	0.21	1.01
Ba	0.136	0.292	0.231	0.166	0.202	0.310
Be	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Ca	1070	1190	1840	844	1140	1540
Cd ^c	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Co	0.01	0.01	0.01	0.02	<0.01	<0.01
Cr	0.026	<0.011	<0.011	<0.011	<0.011	<0.011
Cu	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007
Fe	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Hg ^d	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
K	3.9	21.7	1.6	21.7	3.4	1.8
Li	0.15	0.08	0.05	0.13	<0.03	0.04
Mg	<0.04	<0.04	0.07	0.19	0.09	0.06
Mn	<0.053	<0.053	<0.053	<0.053	<0.053	<0.053
Mo	0.073	0.091	0.101	0.033	0.035	0.183
Na	4.8	3.5	1.1	8.3	1.3	2.5
Ni	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
P	<0.092	<0.092	<0.092	<0.092	<0.092	<0.092
Pb	<0.001	0.012	<0.001	<0.001	<0.001	<0.001
S	127	201	740	654	642	638
Sb	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
Se ^c	0.021	<0.005	<0.005	<0.005	<0.005	<0.005

Table 15. continued.

Constituent ^a (mg L ⁻¹)	BEV-DUC -02	OSU-SPD -03	EDG-LIM -14	TID-FLB -03	TID-FLB -04	GMC-FLB -03
Si	<0.07	0.13	0.12	1.26	0.34	0.20
Sr	2.56	2.35	2.58	0.66	0.61	1.04
V	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Zn	<0.006	0.007	<0.006	<0.006	<0.006	<0.006
Cl ⁻ ^e	42.2	40.5	54.4	7.9	3.2	19.9
F ⁻ ^e	4.0	2.5	3.4	2.8	2.3	2.9
SO ₃ ²⁻ ^e	23.2	35.7	31.3	<1.0	<1.0	<1.0
SO ₄ ²⁻ ^e	233	444	1870	1700	1570	1480

^a All elemental analyses by ICP unless otherwise noted

^b Total dissolved solids

^c Analyses by GFAA

^d Analyses by cold vapor generation and GFAA, conducted by Burgess and Niple, Columbus, OH

^e Analyses by ion chromatography

Table 16. TCLP acetic acid leachate results for 6 dry FGD by-products.

Constituent ^a (mg L ⁻¹)	BEV-DUC -02	OSU-SPD -03	EDG-LIM -14	TID-FLB -03	TID-FLB -04	GMC-FLB -03
pH	11.95	11.98	12.01	9.58	9.61	12.12
TDS ^b	11840	12050	13790	12870	11980	13670
Ag	<0.024	<0.024	<0.024	<0.024	<0.024	0.024
Al	0.20	0.20	0.20	0.12	0.14	0.22
As ^c	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
B	2.165	4.668	3.455	0.767	0.543	9.028
Ba	0.159	0.348	0.250	0.141	0.141	0.693
Be	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Ca	3132	3224	3858	1383	1741	3694
Cd ^c	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Co	<0.014	0.016	0.017	0.026	0.017	<0.014
Cr	0.028	0.009	0.007	0.011	<0.005	<0.005
Cu	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013
Fe	<0.029	<0.029	<0.029	<0.029	<0.029	<0.029
Hg ^d	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
K	3.5	22.1	1.3	21.1	3.0	1.5
Li	0.15	0.09	0.04	0.18	0.07	0.04
Mg	<0.04	0.05	0.07	1351.8	881.5	0.21
Mn	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Mo	0.059	0.088	0.103	0.025	0.031	0.208
Na	4.86	3.64	1.32	9.82	1.67	2.62
Ni	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
P	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
Pb	0.001	0.017	0.005	<0.001	<0.001	0.002
S	132	206	582	979	737	492
Sb	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24
Se ^c	0.004	0.004	0.005	<0.001	0.001	0.005

Table 16. continued.

Constituent (mg L ⁻¹)	BEV-DUC -02	OSU-SPD -03	EDG-LIM -14	TID-FLB -03	TID-FLB -04	GMC-FLB -03
Si	0.10	0.14	0.10	0.33	0.31	0.25
Sr	3.38	2.96	2.55	1.21	0.83	1.33
V	0.022	<0.019	0.021	0.022	0.024	0.056
Zn	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Cl ^e	43.6	45.5	67.8	19.6	28.5	38.0
SO ₃ ^{2-e}	41.6	23.4	43.2	<1.0	<1.0	<1.0
SO ₄ ^{2-e}	236	460	1460	2800	2270	1430

^a All elemental analyses by ICP unless otherwise noted^b Total dissolved solids^c Analyses by GFAA^d Analyses by cold vapor generation and GFAA, conducted by Burgess and Niple, Columbus, OH^e Analyses by ion chromatography

Table 17. Comparison of ASTM and TCLP leachates with RCRA primary drinking water limits.

Element	ASTM Water Leachate		TCLP acid leachate		RCRA primary drinking water limit
	mean	range	mean	range	
-----mg kg ⁻¹ -----					
Ag	<0.005	<0.005-0.007	<0.024	<0.024	0.05
As	<0.005	<0.005	<0.005	<0.005	0.05
Ba	0.223	0.136-0.310	0.289	0.141-0.693	1.0
Cd	<0.001	<0.001	<0.003	<0.003	0.01
Cr	<0.011	<0.011-0.026	0.011	<0.005-0.028	0.05
Hg	<0.0002	<0.0002	<0.0002	<0.0002	0.002
Pb	<0.001	<0.001-0.012	0.005	<0.001-0.017	0.05
Se	<0.005	<0.005-0.021	0.003	<0.001-0.005	0.01

2.1.3.1.3 Paste pH, Total Neutralizing Power, Available Lime, and Thermal Reactivity

All FGD by-products, regardless of the process employed, are highly alkaline with mean pH values exceeding 11.7 (Table 18). Mean pH values for the various processes (11.7 to 12.3) and the range of observed values within each type of FGD process varied only slightly. The only exceptions were TID-FLB-01, TID-FLB-03, and TID-FLB-06 in the "Cyclone Ash" group which yielded slightly lower pH values (9.9 to 10.5). This suggests that FGD by-product pH is primarily dependent on the sorbent used with the particular FGD process is of secondary importance. The lower mean pH value and wider range reported for the "other" category is a result of the inclusion of non FGD samples (i.e. bottom and economizer ashes, siftings etc.). The high pH values of most FGD samples is due to the presence of oxides and hydroxides of Ca and Mg (see section 2.1.3.4). It is expected that when these by-products are exposed to moisture and atmospheric and soil CO₂ the oxides and hydroxides will be converted carbonates by carbonation reaction, thus lowering the pH to around 8.3.

Total neutralizing power (TNP), expressed as percent CaCO₃ equivalency (CCE), ranged from 11.8 to 97.7 (Table 18), with an overall mean of 55%. The great majority of the FGD by-product samples (80%) fell in the much narrower range of 39 to 71 % CCE. The spray dryer process grouping had the highest mean CCE, and the fluidized bed boiler had the lowest mean CCE (with the exception of the "other" grouping which included non-FGD samples). The high mean CCE for the spray dryer group partially results from 2 unusually high CCE values (BAB-LID-02, & 03).

The sources of alkalinity in the samples vary according to the FGD technology and sorbents used and include CaO, Ca(OH)₂, CaCO₃, Ca,Mg(CO₃), and MgO (see section 2.1.3.4). Available lime (measures both CaO and Ca(OH)₂), and thermal reactivity (measures heat evolution from hydration of CaO) results (Table 18) varied widely both within and among the sample groupings, but also give an indication of the different sources of alkalinity in the FGD by-products. Overall, it is clear that FGD by-products contain sufficient acid neutralizing potential to warrant their use as alkaline amendments in acid soils and spoils. The generally very fine particle size of these by-products (see section 2.1.3.3), as well as the more reactive chemical species contained in some of the by-products (CaO, CaOH, MgO), suggests that the FGD by-products will react very rapidly to neutralize soil or spoil acidity.

Table 18. Paste pH, calcium carbonate equivalent (CCE), available lime, and thermal reactivity of FGD by-product samples.

Sample	pH	CCE		Available lime	Thermal Reactivity
		%	range	%CaO, Ca(OH) ₂	
Duct Injection					
BEV-DUC-02	12.04	71.6	±1.1	33.2	0.4
BEV-DUC-03	12.01	70.7	±0.5	33.5	
BEV-DUC-05	12.20	44.7	±6.8	9.8	
BEV-DUC-06	12.18	63.3	±1.4		
BEV-DUC-07	12.30	51.8	±0.2		
BEV-DUC-08	12.09	43.6	±0.4		
EDG-CLS-01	12.47	27.1	±0.2		
BUR-SNR-01		45.8	±0.3	3.6	
Mean	12.18	52.3		25.5	0.4
Spray Dryer					
BAB-LID-01	12.31	62.0	±0.1		
BAB-LID-02	12.44	97.7	±3.0		
BAB-LID-03	12.05	92.1	±1.0		
HST-SPD-01	11.83	54.2	±1.4	0.8	0
HST-SPD-02	12.35	46.3	±0.9	1.3	0
HST-SPD-03	12.41	66.7	±1.3	7.0	0
HST-SPD-04	12.42	68.1	±0.6	7.6	0
HST-SPD-05	12.28	53.8	±2.0	1.7	0
NSP-SPD-01	12.51	41.6	±1.0	2.9	0.8
OSU-SPD-01	12.00	66.7	±0.6	13.6	0.3
OSU-SPD-02	12.25	64.5	±0.6	22.3	1.0
OSU-SPD-03	12.54	64.7	±0.6	24.1	1.1
OSU-SPD-05	12.42	68.9	±1.4		
Mean	12.29	65.2		9.0	0.4
LIMB					
EDG-LIM-03	12.10	60.6	±0.5	29.0	12.7
EDG-LIM-04	12.12	55.3	±0.7		

Table 18. continued

Sample	pH	CCE		Available Lime	Thermal Reactivity
		%	range	%CaO, Ca(OH) ₂	
EDG-LIM-05	12.37	66.7	±0.3		
EDG-LIM-06	12.16	61.6	±0.4	12.3	4.8
EDG-LIM-07	12.10	74.8	±10.5	12.3	
EDG-LIM-08	12.27	19.7	±0.5		
EDG-LIM-09	12.23	85.8	±0.4		
EDG-LIM-10	12.50	22.1	±0.2		
EDG-LIM-11	12.45	35.0	±0.4		
EDG-LIM-12	12.39	27.7	±0.4		
EDG-LIM-13	12.49	42.5	±0.3		
EDG-LIM-14	12.51	59.4	±0.4		
Mean	12.31	50.9		17.9	8.8
Fluidized Bed Combustion					
<i>Bed Ash</i>					
GMC-FLB-01	12.39	39.5	±1.5		
QST-FLB-03	12.58	65.4	±5.9	38.4	6.0
TID-FLB-02	11.18	75.2	±1.7	2.6	
TID-FLB-04	12.20	60.0	±5.5		
TID-FLB-07	12.25	62.8	±0.8		
TVA-FLB-03	12.52	69.1	±2.1	28.4	
Mean	12.19	62.0		23.1	6.0
<i>Cyclone/Fly Ash</i>					
GMC-FLB-02	12.48	39.2	±0.5		
PED-RCB-01	12.30	53.0	±3.5	10.1	3.4
QST-FLB-01	12.60	11.8	±0.2		
QST-FLB-02	12.58	12.5	±0.3		
STA-FLB-01	12.32	50.0	±0.8	19.0	

Table 18. continued

Sample	pH	CCE	Available Lime	Thermal Reactivity
		%	%CaO, Ca(OH) ₂	
TID-FLB-01	9.90	69.4 ± 1.5	2.3	
TID-FLB-03	10.46	60.3 ± 0.7		
TID-FLB-06	10.09	56.0 ± 0.5		
TVA-FLB-01	12.45	72.4 ± 2.8		
TVA-FLB-02	12.33	51.3 ± 2.8	18.0	
Mean	11.75	47.6	12.4	3.4
Other				
GMC-FLB-03	12.52	37.7 ± 2.1		
OSU-SPD-04	12.20			
OSU-SPD-07	7.58	-1.0 ± 0.3		
OSU-SPD-08	6.90	1.9 ± 0.7		
OSU-SPD-09	5.16	1.8 ± 0.6		
OSU-SPD-10		61.1 ± 1.3	16.2	
TID-FLB-05	8.92	33.2 ± 4.2		
Rockport C		39.0 ± 0.9	1.8	2.3
Mean	8.88	24.8	9.0	2.3

2.1.3.1.4 Long-term Equilibrium Studies

All six FGD samples chosen for the long-term equilibration study exhibited rapid equilibration with soluble salts (for complete report of data see Table D3, Appendix D). Little or no change occurred in specific conductance after 1 d of reaction time. Most samples showed little net change in solution pH over the 112 d reaction time. The exceptions to this were samples TID-FLB-04 and TID-FLB-MIX, both of which showed a decline in pH over time. The high pH values present in all of the samples indicates that little to no recarbonation of lime occurred during this study. The final solution pH values ranged from a high of 12.1, to a low of 9.9. The lower pH values in the TID samples was likely due partial recarbonation of the lime and the presence of dolomite. The higher pH values in the other samples reflect incomplete recarbonation of the lime present in most of the FGD materials. This likely resulted from the limited amount of time that the sample tubes were left open to the atmosphere. Nonetheless, the amount of gas exchange with the atmosphere was sufficient to prevent the samples from becoming anaerobic. In fact, an increase in solution Eh was observed in all samples over the total equilibration time of 112 d. The solution Eh values after 1 d of equilibration, ranged from a low of 101 mv (TID-FLB-05) to a high of 183 mv (EDG-LIM-14). By 112 d, the lowest solution Eh value was 189 mv (OSU-SPD-03) and the highest value was 304 mv (TID-FLB-03).

The concentration of dissolved Ca in EDG-LIM-14, rapidly declined from 0 to 36 days, remained roughly constant through 70 days, and then decreased again to a low at 112 d (Fig. 18). Similar results were observed for all other samples except TID-FLB-04, which showed a rapid increase in Ca solubility followed by a plateau at 20 to 70 days, and again a subsequent decline to a low at 112 days (Fig. 19). TID-FLB-04 is a sample of the bed ash. The average particle size was much coarser than that of the other materials used in this long-term equilibration study. It is also likely that the higher temperatures in the pressurized burner resulted in greater calcining of the particle surfaces. Both of these factors would lead to different dissolution rates of the particles of FGD-by-product, and may have contributed to the different behavior of dissolved Ca in TID-FLB-04.

Table 19 contains values of log SI for selected solids after 56 and 112 days, for each sample of FGD by-product used in this study. Values of log SI > 0 indicate that the sample solutions were supersaturated with respect to the specified mineral, indicating that precipitation of this solid could have occurred. Values of log SI < 0 indicate undersaturation with respect to a given solid, generally precluding its precipitation. At 56 days, all samples, except BEV-DUC-02, were near equilibrium with gypsum, and highly supersaturated with respect to ettringite (Table 19). No ettringite was detected by XRD at this sampling time (Table 20). Upon further aging to 112 days, the SI values for gypsum showed little change while those for OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, and TID-FLB-04 were all near equilibrium or less supersaturated with respect to ettringite. One sample, EDG-LIM-14 did contain XRD-detectable ettringite at 112 days (Table 20). Both the XRD data and the SI values

indicate that Ca weathering reactions in EDG-LIM-14 resulted in the interim precipitation of gypsum as a major Ca-phase. This caused the rapid decrease and then plateau in dissolved Ca observed from 21 to 70 days, and likely also was responsible for the minimum in total dissolved S concentrations measured at the 36 day sampling time (Fig. 20). Conversion of gypsum to ettringite with longer reaction time caused the decline in dissolved Ca concentration, and the subsequent release of S to solution (Fig. 18 to 20). The exact weathering scenarios may be somewhat different in the other FGD products, but the geochemical modeling suggests that in the absence of more significant recarbonation, the final reaction product, ettringite will form in all of the samples with the exception of TID-FLB-03 and TID-FLB-MIX. The latter two samples had significantly lower solution pH values and this likely inhibited ettringite formation.

Boron and Mo generally exhibited short-term increases in solution concentration followed by decreases in solubility with increasing reaction time (Fig. 21 and 22). Saturation Index calculations indicated both elements were extremely undersaturated (in excess of 2 log units) with respect to likely solid phases (data not shown). It is possible that the depletion of these ions from solution may have resulted from incorporation into an ettringite-like phase.

Whereas, at both time points, the geochemical modeling suggests that the solutions are near equilibrium with anhydrite, it is unlikely that this phase is present because all of these samples were well hydrated and anhydrite was not detected by XRD (Table 20). All samples were found to be supersaturated with calcite, which was confirmed by XRD (with the exception of BEV-DUC-02). There was good agreement between the SI values and the XRD analyses, with respect to the presence and absence of portlandite, but several minor phases predicted by the geochemical modeling (barite, celestite and strontianite) were not detected by XRD (Table 19 and 20). Since the total concentrations of Ba and Sr were low, relative to Ca, it is possible that these phases were not present in sufficient quantity to be detected by XRD.

The results of this long-term equilibration study (XRD and SI) suggest that "closed" (incomplete recarbonation with atmospheric CO₂), alkaline weathering conditions will lead to interim formation of gypsum and portlandite, followed by conversion of gypsum to ettringite. Such conditions may occur if FGD by-products are placed in confined settings such as road embankments or if they are used in active surface-mine reclamation where they could be buried as a discrete layer, at depth.

Table 19. Values of log SI for selected solids after 56 and 112 days of equilibration of FGD suspensions.

Mineral	FGD source					
	OSU-SPD-03		EDG-LIM-14		TID-FLB-04	
	BEV-DUC-02		TID-FLB-03		TID-FLB-Mixed	
56 days						
Anhydrite	-0.22	-2.35	-0.03	0.03	-0.05	0.04
Barite	1.46	-0.53	1.11	1.36	0.82	2.31
Brucite	2.01	1.56	1.78	0.79	2.70	0.51
Calcite	1.69	1.89	1.73	1.22	1.51	1.46
Celestite	-0.52	-2.50	-0.20	-0.59	-0.96	-0.59
Dolomite	-1.42	-1.30	-1.09	-0.62	-0.89	-0.37
Ettringite	17.45	14.11	21.53	29.90	20.36	29.98
Gypsum	-0.21	-2.34	-0.02	0.04	-0.04	0.05
Portlandite	0.97	0.81	0.49	-1.98	0.77	-2.03
Strontianite	0.34	0.70	0.51	-0.45	-0.44	-0.22
112 days						
Anhydrite	-0.24	-2.24	0.10	0.03	0.07	0.01
Barite	1.19	0.14	1.19	1.31	0.66	1.27
Brucite	-5.46	-5.41	-5.52	-2.37	-5.49	-1.75
Calcite	1.10	1.09	1.00	0.66	0.89	0.83
Celestite	-0.61	-2.40	-0.06	0.43	-0.95	-0.55
Dolomite	-8.36	-8.19	-8.54	-1.54	-8.78	-1.59
Ettringite	4.24	-0.83	7.03	-3.48	5.16	-1.88
Gypsum	-0.23	-2.23	0.11	0.04	0.08	0.02
Portlandite	-0.75	-0.87	-0.81	-5.33	-0.76	-4.34
Strontianite	-0.32	-0.12	-0.21	0.01	-1.18	-0.78

Table 20. FGD mineral phases detected by X-ray after 56 and 112 days of equilibration.

Mineral	FGD Source				
	OSU-SPD-03		EDG-LIM-14		TID-FLB-04
		BEV-DUC-02		TID-FLB-03	
56 Days					
Anhydrite	nd	nd	nd	nd	nd
Barite	nd	nd	nd	nd	nd
Brucite	nd	nd	nd	*	*
Calcite	*	nd	*	*	•
Celestite	nd	nd	nd	nd	nd
Dolomite	nd	nd	nd	*	nd
Ettringite	nd	nd	nd	nd	nd
Gypsum	nd	nd	*	*	*
Hemihydrate	•	*	nd	nd	nd
Periclase	nd	nd	nd	*	*
Portlandite	*	*	*	nd	nd
Strontianite	nd	nd	nd	nd	nd
112 days					
Anhydrite	nd	nd	nd	nd	nd
Barite	nd	nd	nd	nd	nd
Brucite	nd	nd	nd	•	*
Calcite	•	nd	*	*	*
Celestite	nd	nd	nd	nd	nd
Dolomite	nd	nd	nd	*	nd
Ettringite	nd	nd	*	nd	nd
Gypsum	nd	nd	nd	*	*
Hemihydrate	*	*	nd	nd	nd
Periclase	nd	nd	nd	*	•
Portlandite	*	•	•	nd	nd
Strontianite	nd	nd	nd	nd	nd

Fig. 18. Effect of reaction time on the concentration of dissolved Ca in EDG-LIM-14.

Fig. 19. Effect of reaction time on the concentration of dissolved Ca in TID-FLB-04.

Fig. 20. Effect of reaction time on the concentration of dissolved S in EDG-LIM-14.

Fig. 21. Effect of reaction time on the concentration of dissolved B in BEV-DUC-02.

Fig. 22. Effect of reaction time on the concentration of dissolved Mo in OSU-SPD-03.

2.1.3.2 Mineralogical Characterization

2.1.3.2.1 X-ray diffraction

Mineralogical analyses of the dry FGD by-products were initiated with the identification of crystalline phases using X-ray diffraction. A qualitative identification of all phases was essential in order to reliably interpret other forms of data leading to mineral quantification. Representative X-ray diffraction patterns from all six forms of by-product are presented in Figures 23 to 28. Patterns such as these provided "fingerprints" of the crystalline phases present, however proportions of various constituents in a samples could only be estimated from the relative peak intensities (Table 21). In addition, X-ray amorphous phases, such as the glass associated with fly ash, were not readily detected in such heterogeneous samples.

The X-ray diffraction results showed that scrubber residues from duct injection, spray dryer and coolside processes were similar and consisted primarily of Ca(OH)_2 (portlandite) and $\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$ (calcium sulfite hemihydrate) (Figures 23 to 25). The former is derived from the use of excess sorbent and the latter is the primary product of sorbent reaction with SO_2 -laden flue gas via:

Both phases are indicative of low reaction temperatures in the range of 150 to 200°C. The coolside sample and those duct injection samples produced by re-cycle of the FGD by-product (BEV-DUC 05, 07 and 08) showed more evidence of the mineral phases typically associated with fly ash (e.g., glass, quartz, mullite, hematite and magnetite).

Most of the LIMB by-products contained significant amounts of CaO (lime), CaSO_4 (anhydrite), and CaCO_3 (calcite) (Table 21, Figure 26). In the LIMB process, the sorbent is injected directly into the upper portion of a suspension-fired boiler at temperatures ranging from 1100 to 1260°C. At these temperatures, the sorbent calcines to form CaO which then reacts with SO_2 and O_2 in the flue gas to form CaSO_4 . If a dolomitic sorbent is used, MgO (periclase) may also be a product of the calcination process (Table 21). The presence of portlandite and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) in some samples indicates partial re-hydration of the FGD by-product. Likewise, CaCO_3 reflects re-carbonation of Ca(OH)_2 by reaction of Ca(OH)_2 with atmospheric CO_2 .

Analyses of both bed and cyclone ashes from the Tidd facility indicated that in addition to CaSO_4 , the bed ashes were enriched with CaCO_3 , CaO and MgO. These latter two minerals were derived by calcination of dolomite [$\text{CaMg}(\text{CO}_3)_2$] sorbent at temperatures ranging between 815 and 870°C (Table 21, Figure 27). The cyclone ashes were similar in composition but contained more unspent sorbent and CaSO_4 and less MgO (Table 21, Figure 28). Comparable results were obtained for samples from the GMC plant in Pontiac, MI.

Table 21. Crystalline phases¹ detected by X-ray diffraction

Sample	Major Minerals ²	Minor Minerals ²
BEV-DUC-02	P, H	Q, F
BEV-DUC-03	P, H	C, Q
BEV-DUC-05	P, H	F, M, Q, U
BEV-DUC-06	P	Q, F
BEV-DUC-07	P, H	F, Q, U
BEV-DUC-08	P, H	F, Q, U
OSU-SPD-01	C, P, H	F, M, Q, U
OSU-SPD-02	P, H	C, F, Q, U
OSU-SPD-03	P, H	C, F, Q, U
OSU-SPD-05	P, H	C, F, M, U
OSU-SPD-10	P, H	Q, U
EDG-CLS-01	Q, P, H	C, F, M, U
EDG-LIM-03	L, C, A, P	F, M, Q, U
EDG-LIM-04	R, C, A	Q, F, M, U, L
EDG-LIM-05	B, P, L, A, C, G, R	Q, M, F, U
EDG-LIM-06	R, A, L, C	F, M, Q, U, P
EDG-LIM-07	R, A, C, L	P, F, M, Q, U
EDG-LIM-08	L, Q, A, C	P, F, M, U
EDG-LIM-09	R, L, A, C	P, Q, F, M, U
EDG-LIM-10	A, Q, L, C	P, U, F, M
EDG-LIM-11	A, C, L	P, Q, F, M, U
EDG-LIM-12	L, A, Q, C	F, M, U
EDG-LIM-13	L, A, C	F, M, Q, P, U
EDG-LIM-14	L, A, C	P, F, M, Q, U
TID-FLB-01	D, A, R, C	Q, F
TID-FLB-02	C, A, R	L, Q
TID-FLB-03	D, A, R, C	Q, F
TID-FLB-04	R, A, C	L, Q
TID-FLB-05	D, A, Q	F, L, U
TID-FLB-06	D, A, P, Q, C	F, L
TID-FLB-07	A, R, C	L, Q
GMC-FLB-02	A, L, F, Q	C
GMC-FLB-03	A, L, P	Q, F, C

¹

A = Anhydrite (CaSO_4)
 B = Brucite [$\text{Mg}(\text{OH})_2$]
 D = Dolomite [$\text{CaMg}(\text{CO}_3)_2$]
 H = Hemihydrate ($\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$)
 L = Lime (CaO)
 U = Mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$)
 P = Portlandite [$\text{Ca}(\text{OH})_2$]

C = Calcite (CaCO_3)
 G = Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)
 F = Hematite (Fe_2O_3)
 M = Magnetite (Fe_3O_4)
 R = Periclase (MgO)
 Q = Quartz (SiO_2)

² Listed in order of estimated abundance.

Fig. 23. Representative X-ray diffraction pattern for Beverly Duct Injection samples.

Fig. 24. Representative X-ray diffraction pattern for Ohio State University Spray Dryer samples.

Fig. 25. X-ray diffraction pattern from the Edgewater Coolside sample.

Fig. 26. Representative X-ray diffraction pattern for Edgewater LIMB samples.

Fig. 27. Representative X-ray diffraction pattern for Tidd PFBC Bed Ash samples.

Fig. 28. Representative X-ray diffraction pattern for Tidd PFBC Cyclone Ash samples.

2.1.3.2.2 Mineral "quantification"

Mineralogical analyses are normally semiquantitative, at best, because it is difficult to obtain reference minerals that closely match the physical, chemical and structural characteristics of the sample materials. Furthermore, in the present study no single analytical technique was adequate for "quantifying" the full range of mineral phases present in the dry FGD by-products. Therefore to obtain a measure of quantification, data from multiple procedures were used, whenever possible, to support or verify the analytical procedure of choice.

Thermal analysis was found to be an excellent tool for quantifying those compounds that were susceptible to phase transitions with heating. Standard reference materials were used to develop a basic understanding of the thermal reactivity of each phase, but the thermal characteristics of the FGD by-products were never identical to standard specimens. Variations in thermal behavior resulted from differences in particle size, crystallinity and the presence of other phases. Spiked samples, selective dissolution, X-ray diffraction analysis, and the technical literature were used to guide interpretations. Representative thermogravimetric and differential thermal analysis (TGA/DTA) results are reproduced in Figures 29 to 33.

A 12% stoichiometric weight loss, resulting from the dehydroxylation of $\text{Ca}(\text{OH})_2$ to form CaO , was used to quantify the portlandite ($\text{Ca}(\text{OH})_2$) content of relevant samples (e.g., Figure 29). In the FGD by-products studied, this thermal event occurred over the temperature range of 375 to 500°C and could be defined with little interference from other thermal transitions. Most FGD samples contained some portlandite, but the highest amounts occurred in the OSU spray dryer (10 to 30 wt%) and the Beverly duct injection (5 to 40 wt%) samples (Table 22). The effect of re-cycle in the Beverly samples was clearly evidenced by reduced quantities of $\text{Ca}(\text{OH})_2$ in the recycle samples (BEV-DUC-05, 07 & 08) as compared to non-recycle samples (BEV-DUC-02, 03 & 06).

The contents of $\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$ were determined by weight loss associated with the evolution of water over a temperature range of 300 to 370°C (Figures 29 and 30). This compound was restricted to samples from the low temperature, high humidity FGD processes, namely, spray dryer (SPD), coolside (CLS), and duct injection (DUC) (Table 22). It was present at slightly elevated levels where recycle was employed.

Reference specimens of CaSO_4 (anhydrite) were thermally stable over the temperature range and experimental conditions employed. Decomposition, however, was observed in most of the FGD by-products containing anhydrite. Contents of anhydrite were calculated using the stoichiometry shown in Figures 31 and 33 and weight losses observed in the range of 850 to 1050°C were in good agreement with total elemental analysis of S. Because a limited number of anhydrite-bearing samples did not exhibit a weight loss in this range (Figure 33), the CaSO_4 contents reported in Table 22 were calculated from total S. In general, the highest quantities of CaSO_4 were associated with the PFBC bed ashes.

The content of either CaCO_3 or $[\text{CaMg}(\text{CO}_3)_2]$ could readily be determined by the weight loss associated with CO_2 evolution. Although calcination temperatures varied from 600 to 850°C, the analysis was straightforward when only one of the two carbonate phases was present. Optical calcite was also used as a thermal standard for instrument calibration. The recovery from multiple thermogravimetric analyses was $99.43 \pm 0.74\%$. In materials containing both calcite and dolomite (e.g., TID-FLB-O3, Figure 32), the weight loss event resulting from dolomite decomposition was not completed prior to the onset of CaCO_3 decay. In these samples, calcite and dolomite were quantified using the gasometric Chittick technique. Variable amounts of calcite were present in all samples, and dolomite occurred whenever it was employed as a sorbent (Table 22).

Both CaO and MgO are thermally inert phases and could not be measured by thermogravimetric analysis. Consequently, the CaO contents (Table 22) were determined by first allocating elemental Ca from total chemical analyses to all other Ca species present in the samples and then converting the remaining Ca to CaO. Periclase (MgO) commonly occurred in those samples where dolomite was used as an absorbent. When both periclase and dolomite were present, the latter was quantified by using the Chittick apparatus, and a corresponding amount of Mg was allocated based on a 1:1 Mg to Ca ratio. The remaining Mg was assigned to MgO. The resulting values (Table 22) were in good agreement with the relative abundance of these phases as estimated from X-ray diffraction peak intensities.

Fly ash contents of the FGD by-products were highly variable, ranging from 10 to 79 wt% (Table 22). Although fly ash was a significant component of most samples, it was often "hidden" in XRD patterns from whole by-product specimens. No attempt was made to quantify the fly ash mineralogy; however, X-ray diffraction analyses of the acid-insoluble residues showed that all were composed of glass, quartz (SiO_2), hematite (Fe_2O_3), mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$) and a magnetic phase with the characteristics of partially oxidized magnetite (Fe_3O_4). A representative X-ray diffraction pattern from the fly ash component of EDG-LIM-14 is shown in Figure 34.

Table 22. Semiquantitative mineralogy of FGD by-products^a

Sample	Fly Ash	Calcite (CaCO ₃)	Lime (CaO)	Portlandite [Ca(OH) ₂]	Anhydrite (CaSO ₄)	CaSO ₃ ·0.5H ₂ O	Dolomite [CaMg(CO ₃) ₂]	Periclase (MgO)	Total
----- % (wt/wt) -----									
BEV-DUC-02	28	9		38		21			96
BEV-DUC-03	23	12		40		24			99
BEV-DUC-05	46	8		10		33			97
BEV-DUC-06	30	4		36		26			96
BEV-DUC-07	46	8		11		29			94
BEV-DUC-08	48	5		5		28			86
OSU-SPD-01	29	33		10		29			101
OSU-SPD-02	18	18		28		31			95
OSU-SPD-03	21	17		29		31			98
OSU-SPD-05	28	15		22		28			93
OSU-SPD-10	12	15		27		44			98
EDG-CLS-01	71	13		5		7			96
EDG-LIM-03	49	22	12	10	11				104
EDG-LIM-04	57	16		4	14			16 ^c	107
EDG-LIM-05	35	15		9	21 ^b			23 ^d	104
EDG-LIM-06	48	10	5	3	21			16	103
EDG-LIM-07	42	14	4	2	24			18	104
EDG-LIM-08	79	7	7	2	7				102
EDG-LIM-09	38	14	10	4	18			21	105
EDG-LIM-10	71	8	6	3	13				101
EDG-LIM-11	51	10	10	5	25				101
EDG-LIM-12	67	9	8	3	15				102
EDG-LIM-13	52	14	11	5	22				104
EDG-LIM-14	30	15	28	5	25				103
TID-FLB-01	33	9			20		31	11	104
TID-FLB-02	10	29	4		36			26	105
TID-FLB-03	32	12			22		25	12	103
TID-FLB-04	10	27	4	1	36			27	105
TID-FLB-05	40	3			46		17	4	110
TID-FLB-06	40	13			22		17	18	110
TID-FLB-07	11	17	6		47			26	107
GMC-FLB-02	49	3	12		31				95
GMC-FLB-03	19	1	21	3	51			7	102

^a Determined by a combination of thermal, chemical and gasometric techniques.^b Includes 11% CaSO₄·2H₂O.^c Includes 10% Mg(OH)₂.^d Includes 19% Mg(OH)₂.

Fig. 29. Representative thermograms for Beverly Duct Injection samples.

TGA Event	Reaction	DTA Peak (°C)
A	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O} \rightarrow \text{CaSO}_3 + 0.5\text{H}_2\text{O}$	349
B	$\text{Ca}(\text{OH})_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$	438
C	$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$	738

Fig. 30. Representative thermograms for Ohio State Spray Dryer samples.

Fig. 31. Representative thermograms for Edgewater LIMB samples.

TGA Event	Reaction	DTA Peak (°C)
A	$\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$	443
B	$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$	814

Fig. 32. Representative thermograms for Tidd PFBC Bed Ash samples.

TGA Event	Reaction	DTA Peak (°C)
A	$\text{MgCa}(\text{CO}_3)_2 \rightarrow \text{MgO} + \text{CaO} + 2\text{CO}_2$	822
	$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$	
B	$\text{CaSO}_4 \rightarrow \text{CaO} + \text{SO}_3$	996

Fig. 33. Representative thermograms for Tidd PFBC Cyclone Ash samples.

Fig. 34. Representative X-ray diffraction pattern for fly ash component of FGD by-products.

2.1.3.3 Physical Characterization

Particle size analysis indicated that all fly ash materials were very fine with those from the duct injection, spray dryer and lime injection process having in excess of 80% by weight finer than 0.025 mm effective diameter (Table 23). The fly ash particles from the fluidized bed process were somewhat coarser as compared with the other processes. Bed ash materials were, as expected, very coarse averaging 1.4% by weight finer than 0.25 mm effective diameter (Table 23). Uniformity coefficients (C_u , section 2.1.2.3.1) less than approximately 2 are indicative of very uniform particle size distributions. As such, FGD particles from all processes with the exception of the fluidized bed fly ash were quite uniform. The fluidized bed fly ash, on the other hand, contained a wide range of particle sizes.

Particle densities from the spray dryer, lime injection, and fluidized bed fly ash were similar ranging from 2.5 to 2.7 g cm⁻³, while those from the duct injection process were somewhat less and the bed ash from the fluidized bed process had somewhat greater particle densities (Table 24). Specific surface areas corresponded with particle size data with the duct injection, spray dryer and lime injection processes having larger surface areas (Table 24). The surface area of the fluidized bed fly ash was intermediate and the bed ash was low corresponding to the large size of these particles.

After compaction at 25 psi, bulk densities of the FGD materials from the duct injection, spray dryer and lime injection processes were surprisingly low, having values less than 1.0 g cm⁻³ (62.4 lbs/ft³) (Table 25). The fluidized bed process produced identical bulk densities regardless of whether the source was bed or fly ash, and these were significantly higher (1.3 g cm⁻³) as compared with the other processes.

Table 26 presents experimental variables required as inputs for fitting the Van Genuchten equation (section 2.1.2.3.5) to the water retention data. Table 27 gives the values of the fitted variables (α and n) and the r value indicating the goodness of fit. In general, the Van Genuchten equation provided an excellent description of the water retention data with mean r values exceeding 0.97. Again, the bed ash showed expected deviation in its water retention properties as compared with the other materials. The bed ash had a low saturated water content, a high α value and a low n value. The high mean α value (and exceedingly large S.D.) for the spray dryer process was the result of the OSU-SPD-01 sample. If this sample was eliminated, the resulting mean α value for this process was 3.01 MPa⁻¹, a value much closer to the other fly ash samples.

The saturated hydraulic conductivities were lognormally distributed and therefore a log₁₀ transform was applied to the results for a given sample prior to further analysis (Table 28). Initial hydraulic conductivity values roughly corresponded with the particle size results where the bed ash exhibited much higher conductivities as compared with samples from the other processes. Also, within the duct injection, spray dryer and lime injection groupings, the finer lime injection material had the lowest hydraulic conductivity. The low values for the fluidized bed fly ash did not

correspond with this material's intermediate particle size. This, however, is explained by the high bulk density for this material as compared with the other fly ash samples. All FGD samples exhibited a decrease in hydraulic conductivity after aging for 7 days. This is explained by the cementation that occurred in these samples over time.

Five individual FGD samples were selected for a more detailed examination. These samples were BEV-DUC-02, EDG-LIM-14, OSU-SPD-03, TID-FLB-03 and TID-FLB-04. The results from these samples as well as the S.D. from within sample replication are given in Figs. 35 to 43. The results from these individual samples corresponded to those observed for the means for the respective processes.

Table 23. Mean percent finer than 0.025 mm (except where noted) and uniformity coefficients for the dry FGD materials grouped by process.

Sample Grouping	Percent Finer	S.D.	Uniformity Coefficient	S.D.
Duct Injection ^a	81.7	2.3	1.80	0.14
Spray Dryer ^b	83.2	5.1	1.83	0.20
Lime Injection ^c	90.7	11.5	2.38	0.58
Fluidized Bed ^d	1.36 ^f	0.73	1.97	0.27
Bed Ash				
Fluidized Bed ^e	56.3	2.6	11.76	2.30
Fly Ash				

^a EDG-CLS-01, BEV-DUC-02, 03, 05, 06, 07^b OSU-SPD-01, 02, 03, 05^c EDG-LIM-03 to 14^d TID-FLB-02, 04, 07^e TID-FLB-01, 03, 06^f percent finer than 0.25 mm

Table 24. Mean particle density and specific surface area for the dry FGD materials grouped by process.

Sample Grouping	Particle Density	S.D.	Specific Surface Area	S.D.
	g cm ⁻³		m ² g ⁻¹	
Duct Injection ^a	2.41	0.04	9.34	4.44
Spray Dryer ^b	2.51	0.11	9.49	3.82
Lime Injection ^c	2.65	0.21	7.48	2.33
Fluidized Bed ^d	2.92	0.11	1.28 ^f	0.65 ^f
Bed Ash				
Fluidized Bed ^e	2.70	0.21	6.50	3.41
Fly Ash				

^a EDG-CLS-01, BEV-DUC-02, 03, 05, 06, 07, 08^b BAB-LID-01 to 03, HST-SPD-01 to 05, NSP-SPD-01, OSU-SPD-01, 02, 03, 05^c EDG-LIM-03 to 14^d GMC-FLB-01, QST-FLB-03, TID-FLB-02, 04, 07, TVA-FLB-03^e GMC-FLB-02, PED-RCB-01, QST-FLB-01, 02, STA-FLB-01, TID-FLB-01, 03, 06, TVA-FLB-01, 02^f excluding GMC-FLB-01 and QST-FLB-03

Table 25. Mean compression index and bulk density for the dry FGD materials grouped by process.

Sample Grouping	Compression Index	S.D.	Bulk Density	S.D.
			g cm ⁻³	
Duct Injection ^a	0.047	0.006	0.79	0.07
Spray Dryer ^b	0.030	0.009	0.63	0.02
Lime Injection ^c	0.039	0.010	0.91	0.08
Fluidized Bed ^d	0.026	0.001	1.29	0.06
Bed Ash				
Fluidized Bed ^e	0.033	0.002	1.29	0.06
Fly Ash				

^a EDG-CLS-01, BEV-DUC-02, 03, 05, 06, 07^b OSU-SPD-01, 02, 03, 05^c EDG-LIM-03 to 14^d TID-FLB-02, 04, 07^e TID-FLB-01, 03, 06

Table 26. Mean saturated and residual water contents for the Dry FGD materials grouped by process.

Sample Grouping	Saturated Water Content	S.D.	Residual Water Content	S.D.
	m ³ m ⁻³		m ³ m ⁻³	
Duct Injection ^a	0.59	0.17	0.14	0.07
Spray Dryer ^b	0.79	0.05	0.20	0.08
Lime Injection ^c	0.68	0.08	0.18	0.08
Fluidized Bed ^d	0.40	0.04	0.04	0.01
Bed Ash				
Fluidized Bed ^e	0.52	0.01	0.11	0.03
Fly Ash				

^a EDG-CLS-01, BEV-DUC-02, 03, 05, 06, 07^b OSU-SPD-01, 02, 03, 05^c EDG-LIM-03 to 14^d TID-FLB-02, 04, 07^e TID-FLB-01, 03, 06

Table 27. Mean α , n , and r values from fitting the Van Genuchten equation to water retention data from the Dry FGD materials grouped by process.

Sample Grouping	α	S.D.	n	S.D.	r	S.D.
	MPa^{-1}					
Duct Injection ^a	2.00	0.64	2.36	0.26	0.99	0.01
Spray Dryer ^b	28.0	43.4	2.48	0.86	0.97	0.02
Lime Injection ^c	2.63	0.82	3.09	0.76	0.99	0.01
Fluidized Bed ^d	85.7	78.3	1.46	0.09	0.97	0.01
Bed Ash						
Fluidized Bed ^e	2.26	0.79	2.34	0.71	0.98	0.02
Fly Ash						

^a EDG-CLS-01, BEV-DUC-02, 03, 05, 06, 07

^d TID-FLB-02, 04, 07

^b OSU-SPD-01, 02, 03, 05

^e TID-FLB-01, 03, 06

^c EDG-LIM-03 to 14

Table 28. Mean $\log_{10}$ saturated hydraulic conductivity from initial testing and after 7 days for the Dry FGD materials grouped by process.

Sample Grouping	Initial Conductivity	S.D.	7 Day Conductivity	S.D.
	$\log_{10} \text{ cm s}^{-1}$		$\log_{10} \text{ cm s}^{-1}$	
Duct Injection ^a	-2.88	1.68	-3.53	2.01
Spray Dryer ^b	-2.43	1.17	-3.06	1.22
Lime Injection ^c	-4.15	0.26	-5.43	0.46
Fluidized Bed ^d	-0.50	0.66	-1.15	0.39
Bed Ash				
Fluidized Bed ^e	-3.68	1.15	-4.15	1.66
Fly Ash				

^a EDG-CLS-01, BEV-DUC-02, 03, 05, 06, 07

^d TID-FLB-02, 04, 07

^b OSU-SPD-01, 02, 03, 05

^e TID-FLB-01, 03, 06

^c EDG-LIM-03 to 14

Fig. 35. The percent of particles finer than 0.025 mm effective diameter and the uniformity coefficient for FGD samples BEV-DUC-02, EDG-LIM-14, OSU-SPD-03, TID-FLB-03 and TID-FLB-04. Fineness results for the bed ash sample TID-FLB-04 are expressed as the percent finer than 0.25 mm effective diameter.

Fig. 36. The particle density and specific surface areas for FGD samples BEV-DUC-02, EDG-LIM-14, OSU-SPD-03, TID-FLB-03 and TID-FLB-04.

Fig. 37. The bulk density and compression index for FGD samples BEV-DUC-02, EDG-LIM-14, OSU-SPD-03, TID-FLB-03 and TID-FLB-04.

Fig. 38. The water retention data and fitted Van Genuchten curve for FGD sample BEV-DUC-02.

Fig. 39. The water retention data and fitted Van Genuchten curve for FGD sample EDG-LIM-14.

Fig. 40. The water retention data and fitted Van Genuchten curve for FGD sample OSU-SPD-03.

TID-FLB-03

Fig. 41. The water retention data and fitted Van Genuchten curve for FGD sample TID-FLB-03.

TID-FLB-04

Fig. 42. The water retention data and fitted Van Genuchten curve for FGD sample TID-FLB-04.

Fig. 43. The initial and 7 day saturated hydraulic conductivities for FGD samples BEV-DUC-02, EDG-LIM-14, OSU-SPD-03, TID-FLB-03 and TID-FLB-04.

2.1.3.4 Engineering Characterization

2.1.3.4.1 Optimum Moisture Content and Density

The compaction of each FGD sample was performed by applying a specified amount of energy to specified volume of material at a known initial moisture content. The compaction was conducted at several initial moisture contents for each FGD sample and the final sample density was recorded as a function of moisture content. Moisture content is defined as the ratio of the weight of the water to the weight of the solids. Figures 44 to 46 show the range of moisture-density curves obtained using the Standard Proctor compaction method. Note that for each material tested, a unique maximum density was identified. This maximum density and the moisture content at which it was achieved are defined as the optimum density and moisture (water) content.

For all FGD samples the moisture-density curve slopes are small (Fig. 44 to 46, Table 29) indicating that the range of moistures over which optimum density can be obtained is fairly broad. Thus the maximum density is not particularly sensitive to slight variations in the water content in the vicinity of optimum. With the exception of TID-FLB samples, all the FGD by-products would be considered light weight materials, i.e. compacted densities lower than those of a typical natural soil. Both these observations have some impact on the suitability of an FGD by-product as a replacement for natural soil in an embankment. The fact that compaction near the optimum can still result in in-place densities close to the maximum value means that taking special care to achieve precisely optimum conditions in the field is probably not necessary. Light weight fills impose smaller loads on the natural soils upon which they are placed, resulting in less settlement in the underlying soils and less likelihood that the loaded soils will fail.

Fig. 44. Moisture content - density relationships for the Coolside and LIMB samples.

Fig. 45. Moisture content - density relationships for the OSU and Tidd samples.

Fig. 46. Moisture content - density relationships for the EPRI High Sulfur Test Center, PEDCO, Beverly, and SNRB samples.

Table 29. Optimum moisture content and density for FGD samples.

Sample ID	Optimum Density	Optimum Moisture Content
	g cm ⁻³	%
CLS-01	1.100	32
LIM-06	1.200	43
LIM-07	1.120	48
LIM-08	1.300	28
LIM-09	1.055	50
LIM-10	1.069	43
LIM-11	1.019	50
LIM-12	1.118	42
LIM-13	1.042	45
LIM-14	0.789	40
OSU-01	0.909	50
OSU-02	0.833	68
OSU-03	0.845	63
OSU-11	1.056	40
HST-01	0.974	53
HST-03	0.881	65
HST-05	0.933	50
BEV-05	1.132	42
BEV-06	1.084	40
TID-1/2 60%/40%	1.807	18
TID-1/2 50%/50%	1.815	18
TID-3/4 40%/60%	1.830	18
TID-05	1.359	35
TID-06	1.582	25

Table 29. continued

Sample ID	Optimum Density	Optimum Moisture Content
	g cm ⁻³	%
PED-01	1.272	35
SNRB-01	1.146	35

2.1.3.4.2 Strength and Compressibility

The engineering properties of a geotechnical material are strongly influenced by the density of the tested sample. Therefore, it is oftentimes convenient to record these properties as a function of the material density. Although any consistently reproducible density could be chosen for the design density, we chose the Standard Proctor as defined in ASTM Standard D-698 (Table 5) as our reference condition. Therefore, all our laboratory tests on FGD samples were compacted at (or in some particular cases near) the optimum moisture content and density. The specification of the Standard Proctor optimum moisture content and density was made because it is the most common way to relate the laboratory densities to field conditions, and this density can be readily achieved in the field by virtually all construction contractors using conventional highway equipment.

Sample strength (unconfined compressive strength) corresponds to the largest stress measurement recorded during the test. In most tests this value occurred when the sample failed rapidly (fractured). Some samples, usually those that had not been cured, did not fracture. In these cases, strength was taken to be the value of stress recorded over an extended stress range (typically 0.02%).

Sample stiffness is determined by recording the rate of stress increase as a function of axial strain (the slope of the stress-strain curve). Figures 47 through 50 illustrate the experimental procedure by presenting the results of four tests performed on four different FGD materials. The sample identified as TID 3/4 (a mixture of 40% bottom ash and 60% cyclone ash) demonstrated high strength values, reaching an average unconfined compressive strength of approximately 1300 lb/in², which is approaching half the strength of conventional concrete. The values for the other three FGD materials shown are substantially lower, ranging between 50 lb/in² and 240 lb/in². Figures 51 through 55 present in graphical form the results of all unconfined compression tests we performed in this phase of the project. As can be seen in these figures, the strengths of all the FGD samples were higher after 28 days than immediately after being compacted. As a class, FGD materials possessed high strengths when compared with the clay sample (Fig. 55), although some variability in the strength is apparent, particularly in the 7 and 28 day strengths. Table 30 summarizes the strength and stiffness measurements and the densities of the tested samples. Clearly the FGD materials as a class possess strengths considerably in excess of what would be required in a structural fill.

Fig. 47. Unconfined compression test results for compacted Tidd 3/4 samples at 0, 7, and 28 days.

Fig. 48. Unconfined compression test results for compacted LIM 14 samples at 0, 7, and 28 days.

Fig. 49. Unconfined compression test results for compacted OSU 11 samples at 0, 7, and 28 days.

Fig. 50. Unconfined compression test results for compacted BEV 05 samples at 0, 7, and 28 days.

Fig. 51. Average unconfined compressive strengths: Tidd by-product.

Fig. 52. Average unconfined compressive strengths: Coolside and LIMB by-products.

Fig. 53. Average unconfined compressive strengths: LIMB by-product.

Fig. 54. Average unconfined compressive strengths: EPRI High Sulfur Test Center, Beverly, and SNRB by-products.

Fig. 55. Average unconfined compressive strengths: OSU spray dryer by-product and reference clay.

Table 30. Unconfined compressive strength for FGD samples.

Sample ID	Optimum Density g cm ⁻³	Unconfined Compressive Strength (psi)		
		0	7	28
CLS-01	1.100	28.7	50.3	410.0
LIM-06	1.200	103.0	179.0	518.0
LIM-07	1.120	95.0	163.5	485.0
LIM-08	1.300	33.4	154.0	872.0
LIM-09	1.055	47.1	200.0	267.0
LIM-10	1.069	34.3	63.6	268.0
LIM-11	1.019	33.0	72.4	298.0
LIM-12	1.118	56.8	122.0	202.0
LIM-13	1.042	58.1	72.4	246.0
LIM-14	0.789	28.4	44.3	60.8
OSU-01	0.909	24.6	22.0	52.1
OSU-02	0.833	42.4	37.4	71.2
OSU-03	0.845	43.5	38.0	51.0
OSU-11	1.056	66.7	57.9	87.8
HST-01	0.974	18.3	25.4	54.8
HST-03	0.881	15.8	12.7	34.0
HST-05	0.933	31.9	45.0	107.0
BEV-05	1.132	36.3	53.8	240
BEV-06	1.084	38.0	63.0	111
TID-1/2 60%/40%	1.807	ND	568	ND
TID-1/2 50%/50%	1.815	52.7	680	2202
TID-3/4 40%/60%	1.830	28.4	1103	1290
TID-05	1.359	31.8	206	238
TID-06	1.582	104.5	1129	1532
PED-01	1.272	77.1	1148	1294
SNRB-01	1.146	12.8	104.7	72.9

ND not determined

A limited number of one-dimensional compressibility tests were conducted according to ASTM D2435 (Table 5) on samples of selected FGD by-product. This test was performed to provide the design engineer with the material parameters necessary to make estimates of the amount of settlement that could take place within the embankment when the FGD was loaded. A load settlement curve obtained for an Edgewater LIMB sample (Fig. 56) shows the decrease in pore volume (void ratio) as a function of applied load. Although the void ratio (i.e. volume of void space divided by the volume occupied by the solid portion) was high, which was typical of most of the FGD materials studied, the amount of compression during loading was small. A one-dimensional test conducted on a compacted Tidd sample (Fig. 57) indicates the initial void ratio was much lower than in the LIMB samples, and the compressibility, as measured by the slope of the stress vs. void ratio curve, was observed to be less than that measured in the EDG-LIM-06 sample. The above results were obtained for samples immediately after compaction. The results of compressibility tests performed on three Edgewater LIMB samples that had been allowed to cure for more than 400 days (Fig. 58 to 59) show that the void ratio vs. applied stress curve is similar to that seen in Figure 55 for the previously tested LIMB sample. However, the compressibility is less indicating an increase in stiffness accompanies curing (aging). A summary of these results compared to typical values of the same compressibility parameters for a soft and a stiff clay (Table 31) clearly suggests that the FGD materials are much less compressible than typical natural materials that might be used for embankment fill.

Fig. 56. One dimensional compression of a compacted LIMB sample 0 days after compaction.

Fig. 57. One dimensional compression of a compacted Tidd sample 0 days after compaction.

Fig. 58. One dimensional compression of a compacted LIMB sample 425 days after compaction.

Fig. 59. One dimensional compression of a compacted LIMB sample 425 days after compaction.

Fig. 60. One dimensional compression of a compacted LIMB sample 404 days after compaction.

Table 31. One dimensional compression tests on FGD samples.

Sample ID	Initial Density	Elapsed Time to Test	Coefficient of Compression	
	(g cm ⁻³)	(days)	Initial (C _c)	Reload (C _r)
LIM-06	1.200	0	0.051	0.004
TID-3/4	1.830	0	0.011	0.005
LIM-07	1.120	425	0.026	0.002
LIM-08A	1.300	425	0.042	0.004
LIM-08B	1.055	404	0.015	0.002
Soft Clay ¹			0.200	
Stiff Clay ¹			0.300	

¹ Soil Mechanics 2nd Edition, by T.H. Wu, 1981, p.10

2.1.3.4.3 Permeability

Since the strength and compressibility tests previously described have clearly shown that the scope of potential applications of the compacted FGD by-product could be quite broad, other properties that may ultimately determine the actual range of engineering uses for this material were explored. For this reason, a program of laboratory permeability tests was initiated. Results indicated that permeability is indeed an important parameter since, for the range of samples and conditions tested, the coefficient of permeability varies by a factor of more than 16,000.

The measured coefficients of permeability for each type of by-product tested, as a function of the amount of time elapsed from sample preparation to the measurement, revealed a general trend toward lower permeabilities with increasing time (Fig. 61 to 65). The FGD process used to generate the FGD materials, however, has a more important role in the determination of actual permeability than does the curing time. As a class of materials, the spray dryer samples had the highest permeabilities with values ranging from 3.6×10^{-5} cm/sec (OSU-01 at 0 days) to 1.5×10^{-6} cm/sec (OSU-SPD-03 at 28 days). The Tidd samples (pressurized fluidized bed combustion) had permeabilities ranging between 1.7×10^{-5} cm/sec (TID-FLB-06 at 0 days) to 9.1×10^{-10} cm/sec (TID-FLB-3/4 at 28 days) and were the least permeable. Table 32 lists all of the permeability tests performed and the measured permeability coefficient for each sample.

Fig. 61. Permeability coefficients: Tidd and PEDCO by-products.

Fig. 62. Permeability coefficients: Coolside and LIMB by-products.

Fig. 63. Permeability coefficients: LIMB by-product.

Fig. 64. Permeability coefficients: EPRI High Sulfur Test Center, Beverly, and SNRB by-products.

Fig. 65. Permeability coefficients: OSU spray dryer by-product and reference clay.

Table 32. Coefficient of permeability for FGD samples.

Sample ID	Optimum Density	Permeability Coefficient (cm s ⁻¹) at curing time (days)		
		0	7	28
	g cm ⁻³			
EDG-CLS-01	1.100	3.2x10 ⁻⁵	1.9x10 ⁻⁵	3.5x10 ⁻⁷
EDG-LIM-06	1.200	7.2x10 ⁻⁶	8.4x10 ⁻⁷	9.8x10 ⁻⁸
EDG-LIM-07	1.120	6.6x10 ⁻⁶	5.6x10 ⁻⁷	1.4x10 ⁻⁷
EDG-LIM-08	1.300	4.8x10 ⁻⁶	1.3x10 ⁻⁶	1.3x10 ⁻⁷
EDG-LIM-09	1.055	9.0x10 ⁻⁶	3.7x10 ⁻⁷	*
EDG-LIM-10	1.069	1.0x10 ⁻⁵	1.9x10 ⁻⁶	•
EDG-LIM-11	1.019	1.3x10 ⁻⁶	9.0x10 ⁻⁷	3.5x10 ⁻⁷
EDG-LIM-12	1.118	1.4x10 ⁻⁶	7.4x10 ⁻⁷	1.4x10 ⁻⁷
EDG-LIM-13	1.042	5.8x10 ⁻⁶	2.8x10 ⁻⁶	9.9x10 ⁻⁷
EDG-LIM-14	0.789	2.1x10 ⁻⁵	2.4x10 ⁻⁵	5.9x10 ⁻⁶
OSU-SPD-01	0.909	3.6x10 ⁻⁵	1.6x10 ⁻⁵	7.6x10 ⁻⁶
OSU-SPD-02	0.833	1.7x10 ⁻⁶	ND	ND
OSU-SPD-03	0.845	7.4x10 ⁻⁶	7.7x10 ⁻⁶	1.5x10 ⁻⁶
OSU-SPD-11	1.056	4.2x10 ⁻⁶	3.9x10 ⁻⁶	2.7x10 ⁻⁶
HST-SPD-01	0.974	2.6x10 ⁻⁵	8.6x10 ⁻⁶	7.1x10 ⁻⁶
HST-SPD-03	0.881	1.3x10 ⁻⁵	9.2x10 ⁻⁶	4.5x10 ⁻⁶
HST-SPD-05	0.933	3.2x10 ⁻⁵	3.6x10 ⁻⁶	4.3x10 ⁻⁶
BEV-DUC-05	1.132	6.2x10 ⁻⁶	3.1x10 ⁻⁶	7.2x10 ⁻⁷
BEV-DUC-06	1.084	2.7x10 ⁻⁶	1.0x10 ⁻⁶	2.5x10 ⁻⁷
TID-FLB-1/2 60%/40%	1.807	1.8x10 ⁻⁶	*	*
TID-FLB-1/2 50%/50%	1.815	9.4x10 ⁻⁶	3.2x10 ⁻⁸	4.7x10 ⁻⁹
TID-FLB-3/4 40%/60%	1.830	1.9x10 ⁻⁶	5.8x10 ⁻⁸	9.1x10 ⁻¹⁰
TID-FLB-05	1.359	ND	ND	ND
TID-FLB-06	1.582	1.7x10 ⁻⁵	2.6x10 ⁻⁶	1.3x10 ⁻⁶

Table 32. continued

Sample ID	Optimum Density	Permeability Coefficient (cm s^{-1}) at curing time (days)		
	g cm^{-3}	0	7	28
PED-RCB-01	1.272	1.7×10^{-5}	6.3×10^{-6}	*
BUR-SNR-01	1.146	5.1×10^{-5}	1.4×10^{-5}	3.4×10^{-6}

* sample cracked during curing

ND not determined

2.1.3.4.4 Swelling

Long term laboratory swell tests were conducted on 16 samples taken from four different power plants (Table 33). The materials included in the swell tests are illustrative of the range of by-products studied in the other portions of the laboratory program.

Figures 66 through 69 show the change in volume as a function of time for four specimens, one from each of the FGD processes investigated. Note that in each specimen, two distinct swelling episodes are apparent. The first episode occurred almost immediately after the water was supplied to the specimen. This corresponds to the time period during which naturally occurring soils typically experience the greatest volume increase. In natural soils, swelling is a result of hydration reactions and it is likely that the volume increases observed during the first days in the FGD by-product can be explained in a similar fashion, e.g. the hydration of lime (CaO) to portlandite (Ca(OH)_2), and anhydrite (CaSO_4) to hemihydrate ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$). The second episode of swelling usually began after ten or more days had elapsed.

Table 34 lists the swelling tests completed to date and the number of days each sample has been observed. Because the possibility of swelling would have such a profound effect on the choice of FGD for use in an embankment, we are continuing to study the swelling phenomenon in the laboratory in Phase 2 and are attempting to associate the occurrence of swell with evidence of mineralogical changes in the samples.

Table 33. Swelling test samples.

Sample	Power Plant	Process	Replicates
CLS-01	Edgewater	Coolside	A, B, C*
LIM-06	Edgewater	LIMB	
LIM-07	Edgewater	LIMB	
LIM-08	Edgewater	LIMB	A, B*
LIM-10	Edgewater	LIMB	A, B
LIM-14	Edgewater	LIMB	A, B
OSU-03	OSU	Spray Dryer	A, B, C
HST-05	EPRI High S Test Center	Spray Dryer	
TID-3/4	TIDD	PFBC	

* Sample cured for seven days prior to start of swelling test

Table 34. Summary of swelling test results.

Sample	Duration of Swell Test	Swell
	days	%
CLS-01A	543	13.2
CLS-01B	169	11.1
CLS-01C	64	0.12
LIM-06	544	1.02
LIM-07	425	2.46
LIM-08A	425	9.60
LIM-08B	404	1.31
LIM-10A	423	5.90
LIM-10B	184	3.20
LIM-14A	246	69.3
LIM-14B	184	12.0
OSU-03A	423	1.97
OSU-03B	272	2.56
OSU-03C	82	1.60
HST-05	243	0.58
TID-3/4	267	0.87

Fig. 66. Swelling vs. time: Coolside by-product.

Fig. 67. Swelling vs. time: LIMB by-product.

Fig. 68. Swelling vs. time: OSU spray dryer by-product.

Fig. 69. Swelling vs. time: Tidd by-product.

2.2 Economic Analyses

2.2.1 Overview

The primary objectives of Phase 1 economic analyses have been (1) to develop the basic methodological framework for estimation of the financial and economic or social benefits and costs for FGD by-product recycling or disposal, and (2) to gather data not forthcoming from the technical tasks of the project so that preliminary runs can be made of our economic models. An extensive literature review, site visits and interviews, and considerable interaction with professional peers resulted in some refinements of the original objectives, major development of appropriate conceptual models and some preliminary data collection and model estimation.

2.2.1.1 Materials Balance

Flue gas desulfurization (FGD) by-products are one of the many residuals of production and consumption activities prevalent in a contemporary society. Specifically, FGD by-products result from the post-combustion "scrubbing" of flue gases in coal burning facilities. As the gross national product (GNP) or value of goods and services of a society grows so does the variety and volume of FGD and other residuals.

Raw materials are extracted from the environment, are processed in the production sector (that is, converted into consumer goods), and then--at least in part--are passed on to the household sector. The materials returning to the environment from the household sector are wastes or residuals. They are the unwanted by-products of the consumption activities of households. Similarly, not all of the material inputs that enter the production sector are passed on to the household sector. These are the wastes or residuals from production. Thus, there is a flow of residuals from both the production and consumption sectors back to the environment.

If the environment's capacity to absorb or assimilate wastes or residuals were unlimited, there would be no pollution problem and waste management would be a non-issue. However, the assimilative capacity of the environment is limited. One such limit results from the conflict or competition with other services provided by the environment such as human habitat, amenities, and materials inputs to the economic system. Many of these services provide significant economic benefits even though they may not be currently or directly priced in markets.

The materials balance model and the notion of a service-producing environment provide critical insights for the proper management of wastes or residuals. Examples suggested by Freeman *et al.* (1973) include (1) identification of the full range of technical options, (2) recognition of the interdependency among the various kinds of residual flows, (3) illumination of the relationships among population growth, economic growth and pollution, and (4) emphasis in public environmental institutions on broad jurisdiction over air, water, and land pollution, and over major physical systems such as river basins.

With increasing evidence of wastes or residuals exceeding the assimilative capacity of various environmental "sinks", it is important to first identify the major technical

alternatives for either reducing wastes or altering assimilative capacity. Examples include the following:

1. Reducing the rate of throughput of materials and energy by reducing production, increasing the efficiency of production, converting residuals to new products or recycling them as inputs, or by changing the composition of economic activities so that lesser amounts of residuals are produced. The three alternative uses proposed for FGD by-products all involve recycling or conversion to new products.
2. Biologically, chemically, or mechanically treating or changing the residual to a more benign form for discharge to the environment.
3. Altering the time and place of residuals discharge.
4. Man-made investments to increase the residual assimilative capacity of the environment such as dams to store water for dispensing heavy waste loads and paddle wheels to augment the natural supplies of dissolved oxygen.

2.2.1.2 Social Costs and Benefits

Social costs and benefits -- or gains and losses -- from an economic perspective refer to the aggregation of individual producer and consumer measures of full willingness to accept or pay compensation. Individual preferences count in the determination of social benefits and costs and are weighted by income or, more narrowly, by market power. Since most policy changes involve economic gainers and losers, economists have developed the concept of potential Pareto improvement (PPI) to add up gains and losses to get net benefits. Simply stated, the concept holds that any policy change is a PPI or an increase in economic efficiency if at least one individual is better off after all losers are compensated to their original (or before the policy change) income positions. The compensation need not actually occur but must be possible (Dasgupta and Pearce, 1978).

These measures of social costs and benefits are not fully reflected in current market prices (thus the "social" terminology), such as the price of electricity resulting from coal-fired power generation, for several reasons. First, there are consumers willing to pay more and producers willing to sell for less than prevailing market or regulated prices. They receive what economists call consumer and producer surpluses. Second, technological externalities in coal-fired electric power generation exist to the extent that, external to the production and consumption of the resulting electricity, individuals experience uncompensated real economic losses or gains. Examples include air and water pollution, lake acidification from the combustion of coal, and adjacent property value losses from strip mining of coal. Finally, there may be willingness to pay to keep future economic options such as sport and commercial fishing open or to maintain plant or animal species threatened by water or air pollution. These externalities are not reflected in the market price of electricity.

Figure 70 illustrates both the concepts of economic surplus and technological externalities. One might think of P as the market price for a kilowatt of electricity based on the intersection of marginal private cost (from the power plants perspective or accounting stance) of coal-fired production with demand. Thus, for example, at

Technological Externality Defined (Dasgupta & Pearce 1978)

1. Necessary Condition

Physical interdependence of production
and/or utility functions

2. Sufficient Condition

Not fully priced or compensated

S = marginal private (e.g. power plant) cost function

S' = marginal social (e.g. air shed) cost function

D = demand or marginal benefit function

Q = output quantity

P = price unit of output

Fig. 70. Concepts of economic surplus and technological externalities.

market price P consumer surplus is equal to area PEC and producer surplus is equal to area PEA .

The fact that sulfur emissions from coal burning electric power plants appear to cause aquatic and forestry economic losses, the fact that strip mining of coal can lead to health and safety hazards as well as destruction of habitat and lower surrounding property values, and the possible global warming implications of CO_2 emissions from coal combustion for electric power all suggest the presence of uncompensated technological externalities. Stated another way, output Q exceeds the assimilative capacity of the environment. These external or social costs are internalized into the cost of producing coal-fired electricity and are represented by S' (i.e. the marginal social cost function). Price P' represents the price per kilowatt that would prevail if these external costs were included at output Q' . Price P^* represents the marginal social cost at output Q . The shaded area $BE'EA$ represents the net loss in producer and consumer surpluses from the presence of these uncompensated externalities.

The foregoing is a static analysis and does not show the adjustments that might occur over time due to, for example, a tax on or a subsidy for electricity equal to the distance between P and P^* . The willingness to pay to keep future options open or to maintain plant or animal species is also not shown in Figure 70. However, if a proposed stripmine site impacts an endangered species for which considerable willingness to pay exists, it could result in the development of a higher cost alternative site which in turn would further increase the marginal social cost function in Figure 70.

A rapidly growing empirical economic literature (see, for example, Hufschmidt *et al.*, 1983, Pearce and Turner, 1990, and V. Kerry Smith, 1993) has evolved from the foregoing conceptual concerns. The following major subsets are relevant to coal-fired electricity production:

1. Market values in related external markets. These values may be reflected in agricultural or forest crops damaged from air pollution, reduced maintenance and private re-routing costs from highway embankment stabilization, replacement costs such as electricity generation from biomass or natural gas, restoration or clean-up costs such as the liming of acidified lakes to return pH to normal levels, and monitoring and treatment costs of contaminated groundwater. For example, analysis by Hitzhusen and Nyamaah (1984) of private re-routing costs from the closure or weight limit posting of bridges in rural Ohio found that a repaired bridge resulted in much larger private savings than the public cost relative to public repair costs. This would suggest the possibility of relatively large economic benefits from the stabilization of highway embankments using FGD by-products. As a second example, Sweden (as well as several northeastern states in the U.S.) is spending several million dollars per year on a very modest program to apply lime to a few of many acidified lakes. This is an attempt to reintroduce fish and other aquatic life presumably lost when coal combustion produced acid rain. The Swedes claim acid rain originates primarily from their European neighbors to the south, an example of a transnational externality.
2. Surrogate market measures. These include willingness to incur travel costs to use or avoid a particular natural resource or environmental service, impacts

(hedonic) on property values from the decrease or increase in the quality of a particular environmental service, reduction of landscape utility from strip mining, and wage differentials reflecting desirable or undesirable environmental attributes of a particular location impacted by water, air or visual pollution. For example, a travel cost analysis was done by Mullen and Menz (1985) on the economic effect of acidification damage in the Adirondack fishery to fisherman from New York State. The financial loss due to reduced travel and expenditures by fishermen to the Adirondack lakes for fishing exceeded \$1 million per year in 1976 values.

3. Direct surveys. These include surveys of willingness to pay for gain, or willingness to avoid loss of goods and services such as loss of visibility from air pollution or loss of sport fishing and related industries due to the impact of acid rain. Originally called hypothetical evaluation, this methodology is now known as contingent valuation and includes much concern for various forms of strategic behavior of respondents. Bidding and trade-off games are used to elicit the responses of willingness to accept and willingness to pay compensation. For example, Brookshire et al. (1976) used pictures of three alternative levels of visibility related to smokestacks and emissions from a proposed coal fired power plant in Lake Powell, Arizona. To elicit willingness to pay measures from respondents for these aesthetic damages or losses, an entrance fee to Lake Powell was used as the instrument to collect bids. The estimated aggregate bids ranged from \$400,000 to \$700,000 per year, not a trivial sum.

For a more detailed development of these concepts, see the attached paper by Hitzhusen presented at the ENVIROTECH conference in Vienna, Austria, April 23, 1992 (Appendix E) and the earlier mentioned publications by Hufschmidt et al., Pearce and Turner, and Smith.

2.2.2 Analysis of Agricultural Lime Demand and Supply Relationships

Limestone has a long history of use in agriculture. Agricultural lime, commonly termed aglime, is usually in the form of ground or crushed limestone. Its importance to agriculture is recognized by its being considered as a fertilizer, a soil conditioner, and as a soil amendment for correcting soil acidity and improving productivity.

There is a great disparity between the need for and actual use of agricultural lime even though there are proven benefits associated with its application. The returns on investment in agricultural limestone are very high if properly used at its recommended rates. Even though lime efficiency has been proven, U.S. farmers have decreased their use of lime. Factors contributing to a drop in aglime usage include government policy changes (decrease in government cost share for the purchase of lime used), and changes in farmers' cropping systems (shift away from crop rotations that include a legume forage). The supply of agricultural lime also has been affected by low profit margins for agricultural lime producers, seasonal demand for agricultural lime, the difficulties in its storage by producers, and the additional costs incurred from crushing operations to produce a very fine agricultural lime material.

2.2.2.1 Research Objective

Our objective was to estimate demand and supply relationships that can best explain the observed variation in the usage of agricultural limestone in Ohio. The purpose of the demand equation is to quantify the sensitivity of farmers' demand for agricultural lime with respect to alternative factors such as prices of farm products, agricultural lime, and other inputs. The supply equation is used to estimate the effect of agricultural lime price, prices of key inputs such as transportation and fuel, and prices of non agricultural lime products on agricultural lime supplies.

2.2.2.2 Data Collection

This study concentrates on the demand and supply sides of agricultural lime in the State of Ohio. The data and the sources of data collected for the purpose of the present study consist of the following:

- The quantity of agricultural lime sales in short tons: Annual Report on Ohio Mineral Industries, Ohio Division of Geological Survey, Ohio Department of Natural Resources, 1955-1989. The assumption made here is that the quantity of agricultural lime sold by Ohio producers is the same as the quantity used in agriculture by Ohio farmers.
- The price of ground limestone in Ohio in dollars per ton: Annual Summary of Agricultural Prices, U.S. Department of Agriculture, 1960-1989 and the part from 1955-1960 was obtained from the archives of price paid by farmers from the Ohio Historical Library.
- The price of industrial lime: series LIME, the U.S. Department of the Interior, Bureau of Mines 1963-1990.
- Ohio net farm income (in millions of dollar): Ohio Farm Income Series, Ohio Agricultural Research and Development Center, Wooster, Ohio, 1955-1960. The part of the data from 1955 to 1960 was also obtained from the Ohio Historical Library.
- The index of prices received by farmers for all crops, and index of prices paid by farmers for fertilizer: the Economic Report of the President, Council of Economic Advisors, 1990.
- The index of prices paid by farmers on items used for production: Annual Summary of Agricultural Prices, publication from the U.S. Department of Agriculture, 1990.

All prices are expressed in real terms, deflated by the producer price index for intermediate goods with 1982 as the base year. Ohio net farm income is deflated by the gross national product implicit price deflator (base year = 1982). The data used to estimate the demand equation for agricultural lime are from 1955 to 1989. Data to estimate supply are from 1963 to 1989 because of the unavailability of data on industrial lime production from 1955 to 1962.

2.2.2.2.1 Industry Structure in the United States

The agricultural lime industry is a subsector of a larger lime industry and the crushed stone industry. The United States is the largest producer of crushed stone among the market economy countries. In 1989, total production of crushed stone reached 1.2 billion short tons of which 75 % was limestone and dolomite. Agricultural lime accounted for 2 % of total limestone production and 6 % of total dolomite production. Of the 1989 total U.S crushed stone production, 74 % was obtained from two major geographic areas, the south and the middle west. In the United States, limestone is produced in all states except Delaware, Louisiana, New Hampshire, and North Dakota.

The 1989 crushed dolomite output was reported in 27 states by 92 companies at 136 quarries. Of the 49 million tons of crushed dolomite consumed, 6 % was used as agricultural lime.

The United States is self sufficient in crushed stone of which agricultural lime is a part. Production of limestone meets all domestic demand.

2.2.2.2.2 Market Structure of Agricultural Limestone

The agricultural lime industry is characterized by its low unit value. Agricultural limestone is a material of low price at the point of production. Transportation costs, however, substantially increase price at the point of delivery. Consequently, agricultural lime generally is produced near its marketable area and points of use, and the industry is mostly concentrated in high demand areas.

The limestone industry is highly competitive and characteristically serves local or regional markets as a result of an abundance of mineral deposits. Factors affecting production are mainly labor, equipment, energy, water, and compliance with environmental and safety regulations. These factors affect the cost of production which can vary with the natural formation of deposits, their geographic locations, and the quality and kind of product. The closer the markets are to the supply areas, the more significant the advantage to producers. Therefore, local production even though impure or of lower grade is more economical to farmers than purchasing higher quality material from distant markets at a higher cost. Most producers of agricultural lime are relatively small and face competition from large companies producing agricultural lime as a joint product of limestone or industrial lime production.

Limestone and dolomite were produced or sold by 80 companies at 122 operations in 54 Ohio counties during 1990. Total sales of limestone and dolomite were 52.7 million short tons from which 37.2 % was the contribution of 5 counties (Erie, Franklin, Wyandot, Ottawa, and Sandusky). The 1990 reported sales of agricultural crushed and broken limestone accounted for 3 % of total limestone sales in the state (Ohio Department of Natural Resources).

Agricultural limestone producers, which are mainly crushed stone producers, face some problems related to environmental regulations, transportation costs, and marketing programs. Location of firms and processing quarries near suburban areas make air pollution from the crushing operation a major problem in the crushed stone industry. On the marketing side, in addition to the competition of the fertilizer industry, little effort has been made to promote the sale of agricultural limestone.

2.2.2.2.3 Method of Estimation

A simultaneous system of equations, estimated by a two-stage regression technique, was used to estimate factors influencing demand and supply of agricultural lime. Because demand and supply are believed to be determined simultaneously, the two stage least squares estimation technique was applied. This is to avoid the bias and inconsistency associated with ordinary least squares estimators. Indeed, ordinary least squares estimation is inappropriate when there is joint determination between two or more dependent variables. The following assumptions were made:

- demand and supply (quantity and price) of agricultural lime are simultaneously determined and the use of agricultural lime can be affected by economic factors that affect the supply as well as the demand side.
- the price of agricultural lime is determined with regard to economic phenomena related to its manufacturing, processing, and marketing situations. Price is considered as an endogenous variable.

2.2.2.3 Results

Two functional forms were used to estimate the model. One form involved the use of linear equations and the other form used was a logarithmic transform of these linear equations and is called a double-log linear regression model. The model that offers the better explanation of the demand and supply of agricultural lime is the double-log linear regression model and only results from this model are presented. The equations from the two stage least squares estimation process are as follows:

2.2.2.3.1 Demand and Supply Estimates

Demand Equation

$$\begin{aligned} \log(QAL) = & -1.9417 - 0.101 \log(PAL) + 1.176 \log(IPP) + \\ & (-1.639) \quad (-0.271) \quad (4.764) \\ & 0.118 \log(NFI) - 0.677 \log(IIP) + 0.539 D \\ & (1.992) \quad (-3.730) \quad (3.251) \end{aligned}$$

$$R^2 = 0.77, \text{ adjusted } R^2 = 0.73$$

Supply Equation

$$\begin{aligned} \log(\text{QAL}) = & 0.1468 + 0.646 \log(\text{PAL}) - 0.014 \log(\text{PIL}) - \\ & (0.063) \quad (1.557) \quad (-0.025) \\ & 2.234 \log(\text{ITR}) - 0.349 \log(\text{IFU}) + 2.264 \log(\text{IME}) \\ & (-2.932) \quad (-1.179) \quad (2.712) \end{aligned}$$

$$R^2 = 0.58, \text{ adjusted } R^2 = 0.48$$

wherein

QAL = quantity of agricultural limestone
 PAL = price of agricultural limestone
 IPP = index of price received by farmers
 NFI = real Ohio net farm income for crops
 IIP = index of price paid for farm inputs
 D = government program variable (0 = no government program,
 1 = government program)
 PIL = real price of industrial lime
 ITR = price index for transportation equipment
 IFU = price index for fuel
 IME = price index for material used in manufacturing

The number in parenthesis is the t-statistic. The use of the t-statistic is very common in the case of Ordinary Least Squares estimators and Two Stages Least Squares Estimators. It is a computed number for each parameter estimate in the regression. The most common use of the t-statistic is in testing hypotheses and creating interval estimates, and to infer the level of significance of the parameters of the estimated regression, e.g., each number in parenthesis indicates how the parameter in question is significantly different from zero.

Considering the demand side, in terms of explanatory power, the squared coefficient of determination (R^2) is very high (0.77) indicating that 77 % of the variation in demand for agricultural lime is explained by the model. Also, the coefficient of determination (R^2) in the supply estimation is 0.58 and indicates that the model has an appreciable explanatory power.

The estimated demand and supply relationships identify the contribution of individual factors (say price of agricultural lime) in explaining the variations in the quantity of agricultural lime demanded or supplied, holding all other variables constant.

The demand price of agricultural lime is inelastic (-0.101). In this case, inelasticity implies that demand is relatively insensitive to price changes. There is a negative association between the price of agricultural lime and its purchase by farmers. As

agricultural lime price increases by 1%, quantity demanded by farmers decreases by 0.101%. Lime usage proves to be income inelastic (0.118) but highly elastic with respect to crop prices paid to farmers (1.176). That is, a 1% increase in net farm income increases quantity demanded by 0.118 %, while a 1% increase in crop prices increases quantity demanded of agricultural lime by 1.176%. On the other hand, lime application in agriculture is inversely related to prices of other farm production inputs, and a 1% increase in the price of items used for production (IIP) decreases the demand for agricultural lime by 0.68%. Last, on the demand side, cost share conservation programs have had a significant positive effect on agricultural lime usage.

The supply price of agricultural limestone is also considered inelastic (0.646). That is, agricultural lime producers respond to a 1 % increase in agricultural lime price by increasing agricultural lime production by only 0.646 %. An inverse relationship between prices of industrial lime and the supply of agricultural lime is noted. That is, increasing industrial lime prices result in slightly lower agricultural lime supplies. One % increase in prices of transportation equipment and fuel leads respectively to a drop of 2.23 and 0.34 % in lime supply. However, 1 % increase in material handling equipment price increases agricultural lime supply by 2.264%.

From the results of this econometric model of agricultural lime supply and demand relationships, the price elasticity of demand is 0.10, and a rise in the price of agricultural lime, holding everything constant, has only a small direct effect on its use. However, the use of agricultural lime is affected by prices of other farm inputs, by net farm income, and by crop prices. An elasticity of supply of 0.64 roughly means that a 10% increase in price of agricultural lime would lead producers to increase supply by 6%.

The industry appears to be capable of readily increasing supply in response to agricultural lime price increases. This analysis supports the comment by William L. Carter, NCSA's President, who mentioned at the 1980 National Limestone Conference that the crushed stone industry is able to meet the demand side for agricultural lime in a range between 30 million tons and 90 million tons, which are respectively the historic annual use of agricultural lime and the estimated annual need for lime in agriculture.

2.2.2.4 Summary and Implications

Agricultural lime is a product of both the crushed stone industry and lime industry. It is a material of low price per ton at point of production. However, due to its bulk, transportation costs constitute a considerable part of its price at points of delivery. Because of high transportation costs and the abundance of limestone deposits in the United States, agricultural limestone is marketed within small geographic areas and not transported large distances.

Agricultural limestone has experienced a declining market in agriculture even though the benefits from its application are well documented. A two stage model was used to analyze the demand and supply forces of this input market. A double-log

linear regression model was used to estimate these relationships. This model shows that the demand for lime is inelastic with respect to its price. Its use also is affected by the prices of other agricultural inputs used in production. The quantity of agricultural lime supplied is also inelastic with respect to its price. It is affected by various factors of production such as transportation and fuel costs, which have an inverse relationship with respect to lime supply.

FGD by-product promises to be an effective substitute for agricultural lime, and characteristics of the agricultural lime market will affect FGD by-product use. This new product will be entering a highly competitive market. If it is to be used in agriculture, it will have to replace agricultural lime. Agricultural limestone producers stand to lose market opportunities with the introduction of FGD by-products, even though limestone producers would probably gain an even bigger market if coal burners are retrofitted with scrubbers. However, the agricultural lime market constitutes a relatively small share of total sales in the limestone industry.

Table 35. Price paid by farmers for ground limestone in dollars per ton.

Year	Actual Price	Real Price 1982 = 100
1955	4.20	14.70
1956	4.34	14.65
1957	4.46	14.71
1958	4.57	15.03
1959	4.62	15.00
1960	4.66	15.12
1961	4.67	15.25
1962	4.75	15.52
1963	4.74	15.43
1964	4.76	15.45
1965	4.60	14.74
1966	4.65	14.53
1967	4.50	13.91
1968	4.60	13.93
1969	4.60	13.48
1970	4.90	13.84
1971	4.50	12.23
1972	4.20	10.90
1973	4.50	10.61
1974	5.70	10.85
1975	6.40	10.03
1976	5.00	8.21
1977	7.64	11.72
1978	8.30	11.94
1979	8.90	11.35
1980	9.67	10.70
1981	10.50	10.64
1982	10.90	10.90
1983	10.30	10.23
1984	10.60	10.24
1985	12.10	11.75
1986	12.60	12.71
1987	12.70	12.51
1988	12.90	12.04
1989	12.70	11.33

Source: USDA, Series of Annual Summary Agricultural Prices.

Table 36. Agricultural limestone sales report of crushed and broken limestone in Ohio.

Year	Total Quantity (Million Short Tons)
1955	2.2743
1956	2.2457
1957	2.3517
1958	1.8303
1959	1.9289
1960	2.1023
1961	2.0835
1962	1.9514
1963	2.1918
1964	2.1534
1965	1.9355
1966	2.1328
1967	2.0458
1968	1.8775
1969	1.5918
1970	1.5082
1971	1.6251
1972	1.1956
1973	1.5852
1974	1.7353
1975	1.8918
1976	2.1893
1977	1.4211
1978	1.4293
1979	1.3039
1980	1.7585
1981	1.3928
1982	1.2034
1983	1.1183
1984	1.6756
1985	1.2342
1986	1.0787
1987	1.3070
1988	1.4923
1989	1.5621

Source: Ohio Division of Geological Survey, ODNR, series: Annual Report on Ohio Mineral Industries.

Table 37. Ohio farm income.

Year	Actual Total Net Farm Income (Million \$)	Deflated Total Net Farm Income (Million \$)
1955	368.50	1352
1956	369.30	1314
1957	309.00	1062
1958	375.20	1263
1959	374.70	1232
1960	326.70	1057
1961	369.60	1185
1962	333.40	1045
1963	323.30	998
1964	322.80	981
1965	397.10	1174
1966	552.30	1578
1967	385.90	1074
1968	422.80	1121
1969	411.90	1035
1970	404.50	963
1971	418.90	943
1972	564.80	1215
1973	778.20	1572
1974	727.30	1347
1975	711.90	1200
1976	644.00	1021
1977	640.00	951
1978	655.40	908
1979	886.80	1128
1980	611.90	714
1981	310.40	330
1982	476.40	476
1983	120.50	116
1984	915.90	850
1985	867.00	782
1986	819.00	720
1987	956.20	814
1988	766.60	632
1989	823.30	652

Source: OARDC, Wooster, Ohio, Ohio Farm Income Series.

Table 38. Price indices: I.

Year	Transportation	Processed Fuel	Capital Equipment	Material and Components for Manufacturing	Unit Labor Cost
1955	34.30	15.80	27.40	30.50	27.40
1956	36.30	16.30	29.50	32.00	28.90
1957	37.90	17.20	31.30	32.70	30.00
1958	39.00	16.20	32.10	32.80	30.60
1959	39.90	16.20	32.70	33.30	30.80
1960	39.30	16.60	32.80	33.30	31.80
1961	39.20	16.80	32.90	32.90	31.90
1962	39.20	16.70	33.00	32.70	32.20
1963	38.90	16.60	33.10	32.70	32.10
1964	39.10	16.20	33.40	33.10	32.40
1965	39.20	16.50	33.80	33.60	32.60
1966	39.20	16.80	34.60	34.30	33.80
1967	39.80	16.90	35.80	34.50	34.80
1968	40.90	16.50	37.00	35.30	36.50
1969	41.70	16.60	38.30	36.50	39.10
1970	43.30	17.70	40.10	38.00	41.80
1971	45.70	19.50	41.70	38.90	43.20
1972	47.00	20.10	42.80	40.40	44.60
1973	47.40	22.20	44.20	44.10	47.30
1974	51.40	33.60	50.50	56.00	52.90
1975	57.60	39.40	58.20	61.70	57.10
1976	61.20	42.30	62.10	64.00	60.30
1977	65.20	47.70	66.10	67.40	64.10
1978	70.00	49.90	71.30	72.00	68.90
1979	75.80	61.60	77.50	80.90	76.70
1980	83.10	85.00	85.80	91.70	85.10
1981	94.60	100.60	94.60	98.70	92.20
1982	100.00	100.00	100.00	100.00	100.00
1983	102.20	95.40	102.80	101.20	100.90
1984	104.10	95.70	105.20	104.10	102.80
1985	106.40	92.80	107.50	103.30	105.60
1986	109.10	72.70	109.70	102.20	108.80
1987	111.70	73.30	111.70	105.30	111.60
1988	113.10	71.20	114.30	113.20	114.50
1989	116.10	76.50	118.70	118.20	119.00

Source: The Economic Report of the President, Council of Economic Advisors, 1990.

Table 39. Price indices: II.

Year	Items Used for Production	Fertilizer Price Index	Prices Paid to Farmers
1955	28.30	40.00	53.00
1956	28.20	39.00	54.00
1957	29.00	40.00	52.00
1958	29.80	40.00	52.00
1959	30.00	39.00	51.00
1960	29.90	39.00	51.00
1961	30.00	40.00	52.00
1962	30.50	40.00	54.00
1963	30.80	39.00	55.00
1964	30.50	39.00	55.00
1965	31.20	39.00	53.00
1966	32.20	39.00	55.00
1967	32.40	38.00	52.00
1968	32.90	36.00	52.00
1969	34.30	33.00	50.00
1970	35.40	33.00	52.00
1971	37.40	35.00	56.00
1972	39.50	36.00	60.00
1973	47.80	39.00	91.00
1974	54.30	64.00	117.00
1975	59.60	83.00	105.00
1976	63.10	71.00	102.00
1977	65.30	69.00	100.00
1978	70.90	69.00	105.00
1979	81.10	75.00	116.00
1980	90.20	93.00	125.00
1981	96.40	100.00	134.00
1982	100.00	100.00	121.00
1983	99.70	95.00	128.00
1984	101.60	99.00	138.00
1985	98.60	94.00	120.00
1986	94.20	86.00	107.00
1987	96.40	82.00	106.00
1988	102.80	90.00	124.00
1989	108.10	95.00	134.00

Source: USDA, Annual Summary Agricultural Prices, 1990; and The Council of Economic Advisors, 1990.

2.2.3 Representative Farm Preliminary Analysis of FGD as Agronomic Lime Substitute

This section reports on a preliminary analysis of FGD by-product as an agricultural lime substitute. This required making a farm level comparison of current agricultural liming practices with those of the proposed substitute. In order to make this comparison, representative farms were depicted and alternative liming practices were developed for these farms. A typical farm was constructed for each of two geographic regions, the northwest and northeast quadrants of the state (Figure 71).

The northeast and northwest regions account for 60 % of the agricultural lime usage in Ohio: 34 % of Ohio lime is used in the northwestern region, and 26 % in the northeastern region. These regions also represent extremes in market conditions for agricultural lime and FGD by-product. In contrast to the northeast region, the northwest region tends to have higher soil pH, lower agricultural lime application rates, closer distances to limestone quarries, and farther distances to potential FGD sources. Given these characteristics, the northwest region would appear to present weaker market opportunities for the FGD by-product than would the northeastern region. Farm types in the northwestern region of Ohio generalize to the southwestern region, and in the northeastern region to the southeastern region, reasonably well.

2.2.3.1 Farm Selection

Using the Ohio Farm Household Longitudinal Study (1990), a representative farm for each geographic region was constructed. The Ohio Farm Household Longitudinal Survey is a stratified sample, which is representative of Ohio farm households. Thus, mean farm size and agricultural practices for farms in the sample should be representative of average farming practices within these regions.

The boundaries for each region are shown in Figure 71. As illustrated by the crops grown on these representative farms, land use differs between these two regions (Figures 72 and 73). In the northwest, corn and soybeans are grown on almost 80 percent of the cropland, compared to about 60 percent in the northeast. Hay is an important crop in the northeast, but it is grown on a relatively small proportion of the cropland in the northwest.

2.2.3.2 Agricultural Lime Use

Agricultural lime application rates are estimated using the average soil pH and average lime test indexes (LTI) for each region (OARDC). From this information, suggested lime application rates are estimated assuming a pH of 7.0 is desired (Table 40). These suggested or recommended rates of application for the representative farms are lower than farmers actually apply. For example, from 1986-91, farmers annually spent about \$0.07 per acre on agricultural lime in the northwest and about \$0.18 per acre in the northeast, which is in sharp contrast to the \$6 to \$12 per acre agricultural lime costs projected in these budgets. However, application rates used in

Fig. 71. Map of Ohio depicting quadrants used in liming study. The number in each count is the average annual sale of agricultural lime for that county.

Composition of Avg. Farm

Northeast Region-- 246 total ac.

Fig. 72. Composition of an average farm in the Northeast Region of Ohio (total area = 246 acres).

Composition of Avg. Farm

Northwest Region-- 471 total ac.

Fig. 73. Composition of an average farm in the Northwest Region of Ohio (total area = 471 acres).

Table 40. Lime usage and cost on representative Northwestern and Northeastern Ohio farms.

Crop	Acres	Lime to pH 7.0 (T/A)	Tons Required	Freight \$/Acre	Application \$/Acre	Total Cost	Amortized 5 Yrs @ 8%
Northwest Sector							
Corn	169.68	1.40	237.55	18.20	4.9	3919.54	981.67
Soybean	200.91	1.40	281.28	18.20	4.9	4641.04	1162.38
Wheat	82.34	1.40	115.27	18.20	4.9	1902.03	476.38
Hay	18.15	1.40	25.41	18.20	4.9	419.26	105.01
Total	471.08		659.51			10881.88	2725.44
Cost per Acre						23.10	5.79
Avg. Soil pH: 6.49							
Avg. Lime Test Index: 68.35							
Northeast Sector							
Corn	111.20	2.40	266.88	39.60	8.4	5337.50	1336.81
Soybean	36.24	2.40	86.97	39.60	8.4	1739.42	435.65
Wheat	23.08	2.40	55.39	39.60	8.4	1107.79	277.45
Hay	75.37	2.40	180.90	39.60	8.4	3617.95	906.14
Total	245.89		590.13			11802.67	2956.06
Cost per Acre						48.00	12.02
Avg. Soil pH: 6.20							
Avg. Lime Test Index: 67.62							

this analysis reflect the maximum economic potential for agricultural lime and FGD by-product.

For each representative farm, agricultural lime costs were estimated from telephone conversations with individuals who provide liming services. Estimates quoted for wholesale lime are about \$5.00 per ton for both regions. Lower transportation costs of agricultural lime to the northwest reflects the fact that northwest Ohio farms are in closer proximity to limestone quarries than are farms in the northeastern part of the state. Transportation costs are \$8 per ton for the northwest region and \$11.50 per ton for the northeast region. Spreading costs are expected to be the same for both regions and are estimated at \$3.50 per ton. Again, the source of these cost estimates is agricultural lime dealers. It is assumed that liming occurs on average every five years, thus total lime costs have been amortized over their expected life at an 8 percent interest rate.

Due to higher soil pH in the northwestern region, lime application rates are lower for the representative farm in the northwest than for the one in the northeast (Table 40). The amortized lime cost per acre also is lower on the northwest farm (\$5.79 per acre) than on the northeast farm (\$12.02), due to these lower application rates and to the lower costs of transporting agricultural lime from quarries to farms.

The results of the agricultural lime budget suggest that although the two regions differ with respect to lime cost per ton, farm size, and composition of crops grown, the total costs associated with liming on the two farms are not substantially different. Total agricultural liming cost for the typical farm in the northwest is estimated to be \$10,882 and the northeast to be \$10,671. Amortizing these costs over a five year life expectancy yields an annual cost of about \$2,725 and \$2,956 for the northwest and northeast regions, respectively.

2.2.3.3 FGD By-Product Use

The use of FGD by-product as a substitute for agricultural lime is estimated in the same manner, with the only differences being the cost of the product and the quantity applied. For this preliminary analysis, we have assumed there is no charge for FGD by-product material at its source. The only costs incurred by users are associated with transportation of the product to the application site and its application. It is also assumed that the by-product is 60% as effective as agricultural lime in total neutralizing power (TNP) and has physical properties similar to agricultural lime. If actual field testing during Phase 2 of this project finds otherwise, these preliminary estimates will be revised. With these assumptions more product must be applied to achieve desired results. Specialized equipment may also be required for transportation and application, but per ton transportation and application costs are assumed to be similar for the FGD by-product and lime.

Transportation costs are estimated to be \$0.10 per ton per mile. It is estimated that 100 miles are traveled from the FGD source to the representative farm in this region at an average cost of about \$10 per ton. The northeast region tends to be closer to the source of the by-product, and a 30 mile distance is used to estimate the

average cost of transportation in this region, or about \$3 per ton. Application cost per ton is expected to be the same for the FGD by-product as for agricultural lime, and a \$3.50 per ton application cost is assumed.

The results of our estimates show that the total cost of using FGD by-product as a lime substitute for the northwestern farm are \$14,838 and for the northeastern farm is \$6,393 (Table 41). Amortizing these costs over a five year period at 8 percent interest provides an estimated annual cost of \$3,716 and \$1,601 for the northwestern and northeastern farms, respectively. Total costs associated with the by-product as an agricultural lime substitute are substantially less for the northeast region and substantially higher for the northwest region, relative to agricultural lime (Figures 74 and 75). This cost difference is primarily a function of the reduced costs associated with transporting the by-product shorter distances in the northeast region.

2.2.3.4 Implications for FGD By-Product Use

This preliminary comparison of representative farms illustrates potential problems in marketing FGD by-product in agricultural markets. First, the potential market for FGD by-product in agriculture is limited since it is to serve as a substitute for agricultural lime. While agricultural lime is used widely, demand for the product is unlikely to grow dramatically in the future. Second, both agricultural lime and FGD by-product are bulky materials, and transportation is the most important component of their total cost. Since total neutralizing power of FGD by-product is less than that of agricultural lime, use of FGD by-product requires relatively more bulk to be hauled and spread. Third, FGD by-product's use on agricultural land may be feasible on cropland near its source (electric power plants); however, it may not be economically competitive with agricultural lime on cropland distant from its source.

Electric utilities might find it feasible to subsidize FGD by-product use in agriculture to avoid incurring landfilling costs. If the power plant were to bear all or a major part of the transportation costs, FGD by-product might be competitive with agricultural lime over most of Ohio.

Analysis of the southeastern and southwestern regions of Ohio is needed and more precise estimates for all regions of Ohio will be possible when actual field data are available in Phase 2.

Table 41. FGD by-product usage and cost on representative Northwestern and Northeastern Ohio farms.

Crop	Acres	Lime to pH 7.0 (T/A)	Tons Required	Freight \$/Acre	Application \$/Acre	Total Cost	Amortized 5 Yrs @ 8%
Northwest Sector							
Corn	169.68	2.33	395.91	23.33	8.17	5344.83	1338.65
Soybean	200.91	2.33	468.79	23.33	8.17	6328.70	1585.06
Wheat	82.34	2.33	192.12	23.33	8.17	2593.68	649.60
Hay	18.15	2.33	42.35	23.33	8.17	571.73	143.19
Total	471.08		1099.18			14838.93	3716.50
Cost per Acre						31.50	7.89
Avg. Soil pH: 6.49							
Avg. Lime Test Index: 68.35							
Northeast Sector							
Corn	111.20	4.00	444.79	12.00	14.00	2891.15	724.11
Soybean	36.24	4.00	144.95	12.00	14.00	942.19	235.98
Wheat	23.08	4.00	92.32	12.00	14.00	600.05	150.29
Hay	75.37	4.00	301.50	12.00	14.00	1959.72	490.83
Total	245.89		983.56			6393.11	1601.20
Cost per Acre						26.00	6.51
Avg. Soil pH: 6.20							
Avg. Lime Test Index: 67.62

Fig. 74. Cost per acre of aglime vs. FGD in Northeast Ohio.

Fig. 75. Cost per acre of aglime vs. FGD in Northwest Ohio.

2.2.4 Property Value Impacts from Landfilling and Stripmine Reclamation

During Phase 1 of this project two preliminary hedonic pricing models have been identified as appropriate for estimating extra-market effects as inputs in the economic optimization models. The hedonic pricing model is a well-established statistical technique which is used not only in environmental economic analysis but has also been widely adopted in the fields of urban and regional planning and real estate analysis. Because of the wide acceptance of the methodology, we have chosen the hedonic pricing model as one of our primary tools for estimating the social costs and benefits associated with use of FGD by-products.

First, a model which quantifies willingness to pay by individuals for mitigation of an environmental disamenity, as in the case of landfilling, will be specified. This model is based on landfill operations within Franklin County, and a significant amount of data have been collected thus far. Second, a model which estimates adjacent property value and downstream sediment impacts on areas in which many abandoned stripmines now exist will be specified.

The need for two models arises from the particular problem which FGD by-product presents. At present it is difficult to estimate the capacity and feasibility of existing abandoned and active surface coal mines needing reclamation to assimilate FGD by-product. This lack of reliable information necessitates estimation of not only the positive impact of reclamation of mines, but also of the disamenity effect of landfilling FGD waste. In addition, further implications specific to the rural mine reclamation study may exist with respect to sedimentation and acid mine drainage.

The theoretical basis of the hedonic model is to calculate "consumers' surplus", or economic benefit. Consumers' surplus is simply the amount which consumers are willing to pay above the market price for a good which was illustrated earlier in Figure 70. Although consumers' surplus is an abstract notion, it is possible to estimate a demand curve for a commodity econometrically and calculate consumers' surplus as the total area under the demand curve. In the case of a landfill or strip mine, we use the amount that an individual is willing to pay to be *located away* from a landfill. This is done by observing market prices of real estate transactions in areas around landfills and stripmines while statistically controlling confounding factors such as individual income, presence of additional neighborhood amenities and disamenities, as well as the characteristics of the property itself. In short, economic theory suggests that we should observe *lower* real estate transaction prices closer to landfills or stripmines, once confounding factors have been controlled for in the model.

Statistically rigorous estimation of the demand equation is essential in establishing willingness to pay. It is from the demand equation that consumers' surplus calculations will be made which in turn will become inputs into the optimization model. Estimation of the demand equation will be made simultaneously with the supply equation using a generalized linear regression model. The precise functional forms of the demand and supply equations will be established by rigorous statistical tests. The

supply equation is made up of many of the same variables as the demand equation, and the only difference is in the factors which influence shifts in supply and demand.

2.2.4.1 Model 1

During Phase 1, significant progress was made in preliminary specification of a conceptual model of demand and supply for a study area in Franklin County which includes four landfill sites. Refinement and actual estimation of the model will take place in Phase 2. The Franklin County landfill sites were chosen for the model prototype in order to minimize costs associated with data collection and to expedite estimation. In addition, Franklin County landfills are located in marginal urban areas, i.e. areas where farms, and industrial and residential uses are adjacent to one another and involve disposal of municipal as well as demolition and construction wastes.

2.2.4.1.1 Demand equation estimation

The model specifies a demand equation as follows:

$$f(p) = g(x, y, z, d) + e$$

where $f(p)$ is a function (usually logarithmic) of the real (adjusted for inflation) price of housing, x represents a vector of housing and property characteristics, y represents a vector of neighborhood demographic characteristics, and z is likewise a vector of neighborhood amenities and disamenities. The variable, d , is a set of parameters which shift demand for residential housing and is determined outside of the system, and e is a statistical error term.

In our model, housing and property characteristics are comprised of such items as number of rooms, square footage of the structure, number of bathrooms, presence of air-conditioning, fireplaces and garages, lot size, number of outbuildings, and age of structure. Neighborhood demographics include average age, racial composition and average annual income. Another common measure of neighborhood quality is the quality of local school systems. Neighborhood amenities can generally be found in parks and shopping centers, and commuting distance is also often included in models of this nature. Factors which can degrade neighborhood quality are the presence of high air pollution, airports, freeways, industry, and high crime rates.

We have identified two major variables associated with landfills which we will investigate in our model: distance from landfills, and life expectancy of landfills. The landfill life expectancy variable attempts to capture the effect which "distance in time" plays in affecting willingness to pay. It is expected that distance from a landfill, both spatially and temporally will be inversely related to real estate prices. Finally, the vector d of housing demand shift variables is generated by population changes, mortgage interest rates, real personal income and tax benefits.

The supply equation included in the system is differentiated from the demand

equation by the variables which shift housing supply. In the housing market there are two distinctly different types of suppliers: 1) sellers of existing housing (homeowners), and 2) producers of new housing (construction firms). In the market of existing housing, supply is shifted by vacancy rates, and in the new housing market, supply is additionally affected by factor prices such as the cost of money, the cost and availability of land, and the cost of construction materials.

2.2.4.1.2 Data

Data has been collected via three major electronic databases: 1990 census block data, 1990 census block group data, and 1990 real estate transaction data. These databases provide us with the necessary data for calculating specific variables necessary for the estimation process. Variables which are in the process of being created from both the electronic databases and other sources are described briefly below.

Landfills: We have been informed by interviews with the Central District Office of the Ohio EPA that landfill operations in Central Ohio fall into three major categories: 1) toxic waste landfills, 2) sanitary landfills which are a source of methane emission, and 3) demolition dumps which accept the relatively more benign materials which are the by-product of construction.

The four study areas in Franklin County initially will include 3 mile radii around 4 landfill sites: Gahanna, a sanitary landfill with a life expectancy of 1 year; Grove City, a sanitary landfill with a life expectancy of 10 years; Alum Creek, an area with a combination of sanitary landfills and demolition dumps which have been closed for 14 years (life expectancy, -14 years); and Obetz, a demolition dump site closed for 6 years (life expectancy, -6 years). Our assumption at present is that demolition dumps approximate the profile of an FGD landfill site, although we have also initially included sanitary sites in our study until the FGD sites can be more thoroughly characterized. The purpose of including closed landfills in the study is to try to capture the full impact of the presence of a landfill *throughout time*.

Housing Price and Property Characteristics: We have obtained an electronic database of 1990 residential real estate transactions from the City of Columbus Development Department, Planning Division. The purpose of choosing 1990 data is that it can be matched with the most recent Census data which will be used to control for demographic and other factors. Included with each transaction are variables that describe the transaction price, size of the structure, lot size, presence of air conditioning, garages and fireplaces, age of structure, number of rooms and bathrooms and census identification and school district data. Since sales of housing take place in all 12 months of 1990, transaction prices will be "deflated" by the monthly Consumer Price Index for Urban Dwellers (Standard & Poor's Corp, 1992). Each residence is then identified on a map, and its study area identified. Finally, the distance from the landfill is measured and entered as

a variable on the database.

Neighborhood Demographics: Variables on average age and income within a census block group as well as racial distribution at census block level have been calculated from raw data available from an electronic version of 1990 Census micro data.

Dummy variables for the different school districts in the sample are used to capture school quality and differential taxation effects on housing prices. Crime statistics are being collected from the various municipalities involved and will be used at community level as a measure of neighborhood quality.

Housing Demand Shift Variables: A monthly index of average effective mortgage rates for the period under study will be used (US Dept. of Commerce, 1990). The loan rate is an average of all conventional mortgage loans based on an annual effective rate. Population growth variables of changes in census tract population from the 1980 to 1990 census will be used to proxy demand shifts caused by population growth (City of Columbus, OH, Department of Development).

Real income growth and tax benefit variables at the local Columbus SMSA level are still being sought for inclusion in the estimation.

Housing Supply Shift Variables: Building permit data (US Dept. of Commerce, 1990) at the Columbus SMSA level have been obtained. Assuming that the average time to construct a new residence is six months, the data will be used at six month lags.

Cost of raw materials will be proxied by a national composite construction price index, the Construction Cost Index (US Dept. of Commerce, 1990). The raw materials index will be used monthly with a six month lag period.

Land availability has been collected as raw data on land and water acreage at the census block level. The land and water acreage variables will be combined with real estate data to create a measure of land available for new construction. Housing unit vacancy rates are also part of the census block data set and will be used as shift variables for the supply of existing housing.

2.2.4.1.3 Analysis

A system of simultaneous regression models will be estimated using the SAS statistical programming language Model procedure. (SAS Institute, Inc., 1988) Once the demand equation has been satisfactorily determined, we will calculate consumer surplus for various distance increments from the landfill sites. Consumer surplus related to landfill life expectancy will also be calculated. The consumer surplus estimates will then be used as inputs to the linear programming economic optimization model.

2.2.4.2 Model 2

Work on our second model, although begun during Phase 1, will be done primarily in Phase 2. We plan to include rural study sites which will be adjacent to abandoned surface mines in eastern Ohio. We feel a more pervasive environmental disamenity may exist in the case of a strip mine than is the case with a landfill, due to such problems as sedimentation and acid runoff. In contrast, landfills are probably more contained in their effects. Thus, each rural study area will likely cover a larger geographic area than the study areas for Model 1. Our study sites will be located within the Muskingum Watershed Conservancy District, and will consist of at least four lakes; two of the lakes will be in an area where adjacent abandoned mines have a negative environmental impact. We hypothesize that real estate prices (and possibly recreation values) within a wide area will be depressed not only by the more immediate impact of an abandoned mine's presence but by the cumulative effects of sedimentation downstream from the mine as well.

2.2.4.2.1 Data

Housing Price and Property Characteristics: Unlike the urban data already collected, rural data are not available in any known electronic format. As a result, data collection from county auditors' records will be necessary, requiring travel to the county seats of the study areas. In addition, all data collected will require hand input into a database. A second problem associated with the rural data is the infrequency of transactions, plus the additional factor of differential land use (i.e., villages vs. farms).

Demographic Variables: Statewide 1990 Census tract data may be used to estimate these important variables. Other sources are under investigation.

Property Demand and Supply Shift Variables: These variables will be similar to those used in Model 1, but data sources have not yet been identified.

2.2.4.3 Summary

Consumer surplus estimations are to be made from two different study areas comprising four landfills in Franklin County, and at least four lakes in a watershed in eastern Ohio which is impacted by abandoned strip mines. Based on future estimates of assimilative capacity of strip mines, land use applications, and highway embankment stabilization, weights will be developed for the hedonic price estimates. The weights, once established, will allocate net benefits derived from the different schemes for recycling FGD by-product, and will then be used as inputs into the economic optimization models discussed in the next section.

2.2.5 Financial and Economic Optimization Models of Options

The models being developed present a means of determining the most appropriate use of the FGD by-product under normal conditions. Given the objective of minimizing costs, the models determine the optimal use of the FGD by-products produced in Ohio from both the power plant (financial) and societal (economic) perspectives.

The alternative options (destinations) for the FGD by-product are assumed to be agricultural use as a lime substitute on cropland, coal surface reclamation use as a topsoil amendment, landfill disposal, and other unspecified uses (e.g., highway embankment stabilizing material). Sources of the by-product are the power plants that are likely to be considering dry scrubbing processes for controlling sulfur emissions. The models assume that all quantities of FGD by-product produced by the power plants must be used in one of these options.

2.2.5.1 Transportation Problem

Transportation costs will be determined using a transportation model that has its origin in industrial logistics. A product is to be distributed from sources, which in this case are the power plants, to destinations, which are the alternative use locations. The total number of tons of FGD by-product material produced at each plant and the capacity of each destination to receive the material are assumed to be known. The objective is to distribute the material at the least cost.

To formulate the problem mathematically, the following terms are defined:

a_i = number of tons available at source (power plant) i , $i = 1, 2, \dots, m$;

b_j = maximum number of tons required at each destination j (use location), $j = 1, 2, \dots, n$;

c_{ij} = unit processing, transportation, and application cost from source i to destination j ($i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$).

It is assumed that the sum of total production available is equal to the sum of total product use at all locations; that is,

$$\sum a_i = \sum b_j.$$

The amounts shipped from each source (power plant) to each destination (use location) are the decision variables or

x_{ij} = number of tons annually shipped from source i to destination j .

The transportation problem is formulated as follows:

$$\text{minimize } z = \sum \sum c_{ij} x_{ij} \quad (1)$$

subject to:

$$\sum x_{ij} = a_i \quad (i = 1, 2, \dots, m), \quad (2)$$

$$\sum x_{ij} \leq b_j \quad (j = 1, 2, \dots, n), \quad (3)$$

$$x_{ij} \geq 0 \quad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (4)$$

Expression (1) represents the minimization of total distribution cost, assuming a linear cost structure for shipping, processing, and applying the FGD by-product. Equation

(2) states that the amount being shipped from source i to all possible destinations should be equal to the total availability, a_i , at that source. Equation (3) indicates that the amounts being shipped to destination j from all possible sources should be less than or equal to some maximum usage, b_j , at that destination. Equation (4) specifies that each decision variable, x_{ij} , must be greater than or equal to zero.

2.2.5.2 Example

A simple example helps illustrate the problem. Assume there are two power plants producing FGD by-product: Shadyside and Marietta, Ohio. Annual production of FGD by-product is assumed to be 436,000 tons from Shadyside and 233,000 tons from Marietta. Alternative destinations for the by-product include its use as an agricultural lime substitute in Belmont, Monroe, Noble, and Washington Counties, where maximum annual demand is projected at 4,900, 370, 398, and 1,963 tons, respectively. Alternatively, the by-product could be used as a soil amendment in surface mine reclamation in Belmont, Noble, and Washington Counties, the maximum annual use is projected to be 267,000, 332,000, and 6,000 tons, respectively. If not shipped to these locations for use as an agricultural lime substitute on cropland or as a soil amendment for reclamation (or embankment stabilizer for highways), then the material is to be landfilled.

The unit distribution costs from each plant to each destination, the quantities of material available at the two sources, and the potential demand in each county for agricultural and reclamation use (Table 42) serve as inputs into a standard computer algorithm ("Lindo"). The algorithm then determines the optimum distribution of FGD by-products from our two example sources to the final destinations (Fig. 76). The minimum distribution costs for the two plants total \$4,464,100. Shadyside distributes 4,900, 400, and 400 tons in Belmont, Monroe, and Noble Counties, respectively, on cropland. For reclamation of surface mines, 267,000 tons are distributed in Belmont County and 100,000 tons in Noble County. Also, Shadyside landfills 67,300 tons.

Marietta distributes 2,000 tons in Washington County on cropland, and the remainder is used in reclamation, 232,000 in Noble County and 6,000 in Washington County. Nothing is landfilled from Marietta.

This example illustrates trade-offs in an optimal distribution network of FGD by-product among all power plants. Each power plant distributes the by-product to relatively low-cost and abundant surface mine reclamation land that is nearby. Then nearby agricultural land receives the by-product, rather than the more distant surface mines to be reclaimed. Finally, the high cost option, landfilling, is used as a last resort. Another use, such as using the dry FGD by-product for stabilizing road embankments, would be economical at each power plant if it costs less than \$27.50 per ton, the estimated cost of landfilling.

Table 42. Unit production and shipping costs (example).

Destinations	Power Plants		Destination Potential Use (max.)
	Shadyside	Marietta	
Lime Substitute	(\$/ton)	(\$/ton)	(tons)
Belmont	4.50	8.50	4,900
Monroe	5.50	7.00	400
Noble	7.00	7.00	400
Washington	8.50	4.50	2,000
Reclamation			
Belmont	3.70	5.75	267,000
Noble	5.00	4.60	332,000
Washington	5.50	3.70	6,000
Landfill	27.50	27.50	unlimited
Availability (tons)	440,000	240,000	

		Ag. Lime Substitute			
Shadyside	4,900	*	Belmont County	*	0
	400	*	Monroe County	*	0
	400	*	Noble County	*	0
	0	*	Washington County	*	2,000
		*	Reclamation	*	
	267,000	*	Belmont County	*	0
	100,000	*	Noble County	*	232,000
	0	*	Washington County	*	6,000
			Landfill		
	67,300	*	Shadyside	*	
		*	Marietta	*	0
				Marietta	

Fig. 76. Optimal distribution network for example problem. Numbers in the above example are the tons of FGD by-product that enter each route.

2.2.5.3 Model Development

In reality the FGD by-product disposal problem is made more complicated by the number of power plants that serve as sources and the number of potential destinations for the by-product. Twenty-three Ohio power plants have been identified as currently producing bottom and fly ash (Table 43). Many of these will not use the dry scrubber technology and will not be sources of dry FGD by-product. The model incorporates only those plants that might produce dry FGD by-product. In estimating the potential quantities of the by-product, it is assumed that FGD by-product is 60 percent as effective in total neutralizing power (TNP) as agricultural lime, thus 1.67 tons of FGD by-product is needed to substitute for one ton of agricultural lime. The substitutability of FGD by-product for agricultural lime will need to be altered as agronomic research results clarify the effectiveness of the FGD by-product and its handling costs.

All Ohio counties may be potential destinations for FGD by-product as it substitutes for agricultural lime. Recent agricultural lime use in each county provides an estimate of the potential market for FGD by-product in agriculture (Table 44). It is unrealistic to assume that FGD by-product would substitute completely for agricultural lime. This initial run of the model is being developed under the assumption that up to one-fourth of the agricultural lime could be replaced by FGD by-product in each county.

Ohio counties where surface mine reclamation activities occur would be potential destinations for dry FGD by-products used as alkaline amendments in reclamation. Recent reclamation activity provides an estimate of the area where the by-product might be used (Table 45), but current reclamation represents a small percent of total unreclaimed stripmine land. It is assumed that relatively high application rates, 240 tons per acre, would be used. Agronomic research results might alter this rate of application. Also, adjustments may be made in the model to reflect the fact that application rates for surface mine reclamation would vary.

Estimated costs of alternative FGD by-product use are shown in Table 46. These are distribution costs to be borne by the power plant. The minimum cost distribution system from the private financial perspective of the power plant will be estimated using a linear programming algorithm, like that used for the previous illustrative example.

In addition to these private distribution costs, there are other costs, called "externalities," that could be added to some disposal options. For example, landfill operation may cause costs to be imposed on others due to road congestion, road maintenance, loss of property, aesthetic values, etc. These externalities might be captured by a reduction in property values in nearby residences and commercial properties. Theoretically, the amount of the externality could be determined from property value loss estimates. These property value loss estimates are being approximated with hedonic pricing models discussed in the previous section and will be used to refine the costs used in this analysis of distribution costs.

The externality costs could be added to the private distribution costs to estimate the cost borne by society, or social cost, of landfilling. By the end of the project, the

intention is to estimate the optimum distribution system from two perspectives, the perspective of the power plants (termed "financial analysis") and the perspective of society as a whole (labeled "economic analysis").

Table 43. Current ash production and estimated potential FGD by-product, by source.

Power Plants	Current Bottom + Fly Ash ^a (tons/year)	Potential FGD By-Product ^b (tons/year)
Bay Shore Station	95,000	316,670
ACME Plant	13,000	43,350
Ashtabula Plant	108,000	360,000
Avon Lake Plant	131,000	436,670
Eastlake Plant	200,000	666,670
Lakeshore Plant	17,000	56,670
Toronto Plant	39,000	130,000
W. H. Sammis Plant	520,000	1,733,330
Niles Plant	14,000	46,670
Gorge Plant	10,000	33,330
Edgewater	21,000	70,000
R. E. Burger Plant	131,000	436,670
Gorsuch Station	70,000	233,330
Cardinal Plant	531,000	1,770,000
Gavin Plant	689,000	2,296,670
Muskingum River	282,000	940,000
Kyger Creek Plant	135,000	450,000
W. C. Beckjord Station	115,000	383,330
Miami Fort Station	300,000	1,000,000
Conesville	120,000	400,000
Picway Plant	20,000	66,670
J. M. Stuart Plant	780,000	2,600,000
Mead Paper Co.	47,000	156,670
Total		14,626,670

^aSource: American Coal Ash Association, 1989.

^bCurrent bottom and fly ash production = 10% of coal burned. Potential FGD by-product = 33% of coal burned.

Table 44. Potential FGD by-product use as an agricultural lime substitute, by county (tons per year)^a.

County	Tons	County	Tons
Adams	6,718	Licking	5,395
Allen	5,091	Logan	1,009
Ashland	2,799	Lorain	4,243
Ashtabula	5,599	Lucas	4,770
Athens	1,258	Madison	712
Auglaize	8,726	Mahoning	2,438
Belmont	4,921	Marion	1,903
Brown	6,523	Medina	4,879
Butler	2,021	Meigs	116
Carroll	2,041	Mercer	2,534
Champaign	4,048	Miami	2,268
Clark	3,194	Monroe	370
Clermont	4,998	Montgomery	611
Clinton	7,002	Morgan	628
Columbiana	6,853	Morrow	1,068
Coshocton	11,259	Muskingum	5,665
Crawford	6,857	Noble	398
Cuyahoga	3,989	Ottawa	6,070
Darke	6,290	Paulding	6,170
Defiance	11,016	Perry	1,241
Delaware	9,199	Pickaway	2,946
Erie	6,586	Pike	5,062
Fairfield	9,724	Portage	3,483
Fayette	5,612	Preble	2,660
Franklin	2,378	Putnam	2,501
Fulton	9,404	Richland	4,119
Gallia	3,917	Ross	1,630
Geauga	313	Sanudsky	3,019
Greene	4,418	Scioto	454
Guernsey	2,827	Seneca	5,542
Hamilton	638	Shelby	1,962
Hancock	3,577	Stark	2,381
Hardin	7,457	Summit	1,543
Harrison	456	Trumbull	3,846
Henry	5,745	Tuscarawas	2,695
Highland	14,993	Union	1,948
Hocking	499	Van Wert	1,115
Holmes	3,237	Vinton	153
Huron	16,983	Warren	1,720
Jackson	109	Washington	1,963
Jefferson	1,373	Wayne	11,462
Knox	8,513	Williams	6,405
Lake	1,539	Wood	7,023
Lawrence	148	Wyandot	5,724
		Total	364,702
		(Avg of last 6 yrs)	

^aAssumptions: 1 ton of ag-lime = 1.667 tons of FGD by-product. Maximum estimated amounts of FGD by-product potentially used is 25 percent of average ag-lime used in each county each year from 1986 to 1991.

Table 45. Potential use of FGD by-product in surface mine reclamation

Location of Surface Mines (County)	Potential FGD By-Product Use (tons/year) ^a
Athens	14,960
Belmont	267,140
Carroll	78,560
Columbiana	60,870
Guernsey	13,770
Harrison	204,560
Hocking	12,580
Holmes	44,810
Jackson	98,340
Jefferson	189,780
Lawrence	2,630
Mahoning	19,630
Muskingum	89,180
Noble	332,022
Perry	40,369
Stark	19,390
Tuscarawas	208,460
Vinton	146,270
Washington	6,480
Wayne	3,160

^aAssumes that FGD by-product is applied to all mine reclamation permit area at 240 tons per acre.

Table 46. Cost estimates used in analysis of optimum FGD by-product distribution.

Item	Cost per ton
Landfilling	\$27.50
Ag. Lime Substitute	
Application	3.50
Transportation	0.10 per mile
Reclamation Soil Amendment	
Application	3.50
Transportation	0.10 per mile

2.3 Selection of Sites for Field Studies

2.3.1 Active Mine Site

The first step taken in the site-selection process was to review the goals of the research project and prepare a list of site-selection criteria. The following criteria were considered during the site-selection process: (1) timing and extent of mining and reclamation, (2) cooperation from the land owner(s) and mining company, (3) requirement of alkaline amendments to ameliorate predicted acid-mine drainage, (4) acquisition of a representative site based on hydrogeology and soils (thereby increasing the transferability of results to similar sites in the region), (5) drainage-basin morphology and site accessibility, (6) premining land use, (7) distance to FGD by-product source, (8) availability and turn-around time for revision of permits from the Ohio Department of Natural Resources (ODNR) and the Ohio Environmental Protection Agency (OEPA), (9) local cooperation, and (10) cooperating-agency site-selection criteria.

To assess the available sites in Ohio, a list of all actively permitted coal-mining sites obtained from the ODNR, Division of Reclamation, was screened to eliminate subsurface sites and surface sites smaller than 200 acres. Because the project requires four 5- to 10-acre test plots, permit areas smaller than 200 acres would not allow as much flexibility with respect to timing of mining and reclamation. This constraint narrowed the list of potential sites to 180. More than half of these sites are in Belmont, Carroll, Columbiana, Coshocton, Guernsey, Harrison, Jefferson, Monroe, Muskingum, and Tuscarawas Counties. These counties are primarily underlain by the Monongahela and Allegheny Formations of Pennsylvanian age.

The stratigraphy of the coal-bearing strata of eastern Ohio was then investigated to evaluate the need for addition of alkaline amendments for acidic spoils and (or) soils because the stratigraphy of a mined sequence of rocks can directly influence the potential for production of acid-mine drainage. Coal is mined in eastern Ohio from Pennsylvanian rock that was deposited as sediments that were deposited in a deltaic, near-shore environment approximately 286 to 320 million years ago. Some parts of the Ohio coal section are relatively deficient in carbonate minerals, which may neutralize the production of acidic water. Data obtained from ODNR mining inspectors and mining permits indicate that marine shales associated with the number 5 and 6 coals (Lower and Middle Kittanning coals, respectively) of the Allegheny Group are most likely to produce acidic discharge after mining and reclamation. These shales are typically enriched in iron sulfide (FeS_2) that, because of mining, exposure to air, and bacterial action, oxidizes to form sulfate, which can hydrolyze to form sulfuric acid in water.

In eastern Ohio, the number 5 and 6 coals outcrop in a northeast-southwest trending line that extends from Columbiana County in the northeast, southwestward through Coshocton County and then southward to Lawrence County. Active mining sites south of Coshocton County were generally excluded from this search because

many underground mines that exist in the area could interfere with interpretations of water-quality data at the test sites. Approximately 45 sites met this criterion.

The 45 remaining sites were investigated individually. Field reconnaissance was conducted to evaluate the sites in additional detail. Each site was critically evaluated with respect to the site-selection criteria, and seven potential sites were selected as finalists (Table 47). All candidate sites were considered acceptable for use in the study, however four sites were evaluated in greatest detail (Table 48). These four sites are within 20 miles of one another, therefore the distance to the FGD by-product source (the location of which remains undecided) did not affect the site selection.

Table 47. List of potential study sites for the active mine study within Ohio.

Owner	ODNR Mining Permit Number	Location of Permit Area	Size of Permit Area (Acres)	Coal Seam(s) Mined ¹
Empire Coal Company PO Box 729 Gnaddenhutten, OH 44629 Contact: Tom McCartney	D-533	Warwick Township, Tuscarawas County	372	5, 6
Holmes Limestone Co. PO Box 295 Berlin, OH 44610 Contact: Ralph King	D-796 D-796-1	Jefferson Township, Tuscarawas County	106, 314	5, 6
Kimble Clay & Limestone Co. Rt. 1, Box 386 Dover, OH 44622 Contact: Floyd Kimble	D-852	Auburn & York Townships, Tuscarawas County	974	3A, 4, 5, 6, 7
Oxford Mining Co., Inc. PO Box 427 Coshocton, OH 43812	D-870	Franklin Township, Coshocton County	264	6
R&F Coal Company 538 North Main Street Cadiz, OH 44621 Contact: Brent Havlin	D-689 PA-1096	Oxford Township Coshocton County Rush Township, Tuscarawas County	541 489	5, 6
Valley Mining, Inc. PO Box 148 Dennison, OH 44621 Contact: Jim Klingler	D-516, PA-516-2	Salem Township, Tuscarawas County	334, 231	6
Miller Mining Co., Inc. State Route 93 N PO Box 525 Sugar Creek, OH 44681 Contact: Olen Miller	D-0967	Tuscarawas County		5, 6

¹ Coal seam names in Ohio: 7, Upper Freeport; 6, Middle Kittanning; 5, Lower Kittanning; 4, Brookville; 3A, Upper Mercer.

Table 48. Summary of site selection data and evaluation of four finalist candidate sites.

ODNR-DOR Permit Numbers D-689 and D-689-1

Owner: R & F Coal Company	Location: Oxford Township, Coshocton County,
538 North Main St.	Plainfield Quadrangle
Cadiz, Ohio 43907	Size: 1,037 acres
Contact: Brent Hevelin	Coal Seams Mined ¹ : 5, 6
(614)942-9234	

Comments:

- +² Mining plan fits project schedule.
- + Active ground-water-flow system.
- + Site morphology and accessibility is good; large site allows for project flexibility.
- + Minimal premining in area.
- + "Grey shale" beneath number 5 and 6 is noted as being up to 50 tons/1000 tons CaCO₃ deficient.
- + Abundant premining geologic and water-quality data available.
- Number 5 coal will be mined only on designated portions of permit area.
- Lower reaches of watershed may be buried under "excess spoil area".
- Although exploratory rock cores show slight CaCO₃ deficiency, no alkaline amendments for spoils intended, however, 4 tons/acre lime planned as agronomic soil amendment.

SITE VISITS: 12/21/90; 1/15/91

ODNR-DOR Permit Number D-796-1

Owner: Holmes Limestone Company	Location: Jefferson Township, Tuscarawas
Berlin, Ohio	County, Stone Creek Quadrangle
Contact: Ralph King	Size: 314 acres
(216)893-2721	Coal Seams Mined ¹ : 5, 6

Comments:

- + Site has been deforested, with mining to begin soon.
- + Liming intended for soil pending results of soil tests.
- + Active ground-water-flow system.
- + Minimal premining in area.
- + Special handling of toxic spoils noted in permit.
- Permit still in application process.
- Although cores show slight CaCO₃ deficiency, no alkaline amendments for spoils intended.

SITE VISIT: 1/31/91

¹ Coal Seam Names in Eastern Ohio: 7, Upper Freeport; 6, Middle Kittanning; 5, Lower Kittanning; 4, Brookville; 3A, Upper Mercer.

² A plus (+) indicates that this comment is a positive aspect with regards to performing the study at this site, that is it helps the site meet the site-selection criteria; a minus (-) indicates that this comment is a negative aspect.

Table 48. continued.

ODNR-DOR Permit Number D-582

Owner: Kimble Clay and Limestone	Location: Auburn and York Townships,
RD#1, P.O. Box 386	Tuscarawas County, Stone Creek Quadrangle
Contact: Keith Kimble	Size: 974 acres
(216)339-5111	Coal Seams Mined ¹ : 3A, 4, 5, 6, & 7

Comments:

- +² Mining just begun on eastern end of permit area, and progressing rapidly westward.
- + Premining land use primarily forested.
- + Liming intended for soils pending results of soil tests.
- + 320 feet local relief, but permit area large enough to allow project flexibility and site accessibility good.
- + Abundant premining geologic and water-quality data available.
- Although cores show slight CaCO₃ deficiency, no alkaline amendments for spoils intended.
- Three small "avoidance areas" may cause difficulty with subsite selection.
- Augering of coal along highwall.
- Lower reaches of watershed may be buried under "excess spoil area".

SITE VISIT: 1/31/91

ODNR-DOR Permit Number D-870

Owner: Oxford Mining Co., Inc.	Location: Franklin and Jackson Townships,
P.O. Box 427	Coshocton County, Conesville Quadrangle
Coshocton, Ohio 43812	
(614)622-6302	Size: 264 acres
	Coal Seam Mined ¹ : 6

Comments:

- + Approximately 20% of site has already been mined, but mining progressing slowly.
- + Active ground-water flow system.
- Timing may be questionable (projected mining until 1994).
- Although cores show slight CaCO₃ deficiency, no alkaline amendments for spoils or soils intended.
- Abundant premining and gob piles west of permit area may cause problems with water-quality investigation.
- Limited access through haul road (which may vary as mining continues).

SITE VISIT: 1/31/91

¹ Coal Seam Names in Eastern Ohio: 7, Upper Freeport; 6, Middle Kittanning; 5, Lower Kittanning; 4, Brookville; 3A, Upper Mercer.

² A plus (+) indicates that this comment is a positive aspect with regards to performing the study at this site, that is it helps the site meet the site-selection criteria; a minus (-) indicates that this comment is a negative aspect.

2.3.2 Abandoned Mined Site

The initial step in selecting a field site for beneficial reuse of dry FGD by-product materials for reclamation of abandoned mined lands was to develop a set of selection criteria. These criteria were:

- 1) a site that represents the major mine spoil types and that requires the addition of lime (i.e. it should have a lime test index of 66 or less),
- 2) access to the site for collection of the data after reclamation has been completed,
- 3) size of the area to be reclaimed must be sufficiently large to allow for creation of buffer space between treatments,
- 4) timing of the reclamation plans must fit with our research plans,
- 5) distance to the FGD by-product source and from Wooster,
- 6) protection of the area from vandals and/or livestock, and
- 7) cooperation of local and state agencies in preparation of reclamation plans and the implementation of those plans.

After formulating the selection criteria, a meeting was held with the Ohio Department of Natural Resources, Division of Reclamation - Abandoned Mined Lands. Seven candidate sites, in various stages of reclamation planning, were submitted by the Division of Reclamation. These sites were prioritized in order of preference for use in this project based upon the selection criteria.

After comparing the locations, conducting on-site inspections, and considering the relative merits of the different sites, the Fleming site was selected as our number one choice as a site for testing the beneficial reuse of dry FGD by-product materials for reclamation and revegetation purposes. The Fleming site is located in Sections 11 and 12, Franklin Township, Tuscarawas County, Ohio. Project coordinates are 40° 33' 19" north latitude and 81° 31' 13" west longitude.

This site consists of approximately 25 acres of exposed, highly erodible underclay bordered on two sides with about 45 acres of unreclaimed spoil and 5 acres of refuse. The site is causing sedimentation problems and flooding for landowners below the hillside and is estimated to affect 75 offsite acres. The underclay is scarred with rills and gullies up to 10 feet in depth and is completely devoid of vegetation. Based on a 2-year, 24 hour storm, the soil loss from the site averages 450 tons/acre/year. The estimated average soil loss for vegetated sites in Tuscarawas County is 2.8 tons/acre/year. Water quality has been severely impacted with pH values being measured as low as 2.9. The Fleming site has been assigned a priority 2 rating by the Division of Reclamation due to its effect on the health, safety, and general welfare of the public. This site has also been included in the National Abandoned Mined Lands Inventory (OH-994).

2.3.3 Agronomic Liming Sites

The branch farms of The Ohio State University were evaluated as possible sites to test the beneficial reuse of the FGD by-product materials as an agricultural lime

substitute. Several criteria were considered in selecting these field sites: 1) the soil must be deficient in exchangeable bases, i.e. it must have a low pH and a calcium carbonate deficiency, 2) more than one soil type must be included in the test so that the results can be applied to other areas of the state, 3) the soil types must exhibit a range in soil properties, especially in respect to soil pH and total cation exchange capacity, 4) the land must be located on Ohio State University property, and 5) we must know the history of plot use prior to the addition of the FGD by-product material.

Three field sites were chosen, after applying these criteria, and these sites are located at The Ohio Agricultural Research and Development Center (Wooster, OH), the Mahoning Experimental and Educational Farm (Canfield, OH), and the USDA-ARS North Appalachian Experimental Watershed (Coshocton, OH). The soils at the three sites are a Wooster silt loam (pH 4.6), a Canfield silt loam (pH 5.9) and a Coshocton silt loam (pH 4.8), respectively. The highest amount of lime required, as determined by the Ohio State University's soil testing laboratory in Wooster, is 9.6 tons/acre (21.5 Mg/ha) of calcium carbonate equivalency for the Wooster silt loam. This amount of lime would be sufficient to raise the pH of the Wooster soil from 4.6 to 7.

2.4 Embankment Design

The results of the laboratory tests which have been presented in Section 2.1.3.4 clearly indicate that, although the physical properties of the FGD product are highly variable, all the materials tested to date would be suitable as fill in a properly engineered embankment.

The design of an engineered embankment consists of 1) specifying a design geometry, 2) determining the appropriate engineering properties for the proposed fill material, 3) evaluating the stability of the structure designed in step 1 using the engineering properties obtained for the material in step 2, 4) revising the design as necessary until an adequate degree of safety or minimum acceptable performance is achieved, 5) monitoring the activities of the construction crews during construction, and 6) observing the long term behavior of the embankment after the construction is completed. Table 49 lists in general terms the requirements to be addressed when designing a highway embankment including the slopes, shoulders and the structural backfill placed around a buried culvert.

Table 49. Summary of properties and performance.

	Structural Component			
	Embankment (1)	Slope (2)	Shoulder (3)	Backfill (4)
Properties	static-stress-strain-strength	same as (1)	static and dynamic stress-strain-strength	same as (1)
Laboratory Tests	unconfined compression, direct shear, triaxial	same as (1)	same as (1), freeze-thaw	same as (1)
Performance Criterion	settlements	deformations	deformations, including rutting	culvert deformations
In-situ Measurements	slope indicator tubes plus magnetic collar water quality	same as (1)	dynalect and/or falling weight deflectometer	
Analytical Model	finite element models	finite element models non-finite element models	pavement equations	finite element models

2.4.1 Evaluating Embankment Performance

With the design of the embankment specifying the use of FGD materials completed and construction started, monitoring the construction to assure compliance with material placement specifications is critical. Since this can be more easily done if the FGD material can be treated by both the inspectors and the contractors as a familiar, rather than an exotic material, the results of the laboratory characterization program described in Section 2.1.3.4 were presented with the goal of describing the FGD as a natural soil. Such an approach should make it possible to have field inspectors capable of monitoring construction without special training or experience in FGD by-products. Of the several different dry FGD materials tested in the laboratory program, only the PFBC ash from the Tidd plant might require special handling since the very high early strengths observed in the laboratory indicate that placing a conditioned (water added) material could be difficult if the work cannot be completed in a timely fashion. Studies to be conducted on FGD/soil mixes during Phase 2 will increase our knowledge of the most appropriate dry FGD material and procedures to use for embankment construction.

To assess the performance of the FGD by-product in the engineered fill, two general areas will be studied. In the first, the physical behavior (i.e. stability and deformations) of the embankment will be recorded. In the second, the quality and quantity of water in the embankment and moving through it will be determined.

2.4.1.1 Embankment stability

Satisfactory performance of the embankment requires that the side slopes remain stable and that the material doesn't compress under allowable service loads. For both of these potential problems, the strengths of the FGD and the underlying natural materials are the critical parameters. The actual performance of the demonstration highway section will be most readily monitored by the installation of vertical settlement and horizontal displacement devices in the embankment, slope and shoulder.

The measurement of vertical movement will be done by installing a settlement platform. This platform consists of a square plate placed on or in the natural soil prior to the construction of the embankment. As construction proceeds vertical pipe sections are attached to the platform. After completion of the embankment the elevation of a mark on the pipe is determined by surveying the embankment thereby providing a record of the settlement with time. However, since a single settlement platform can give only a single point measurement, a number of platforms will be installed. Such a procedure allows for time dependent settlement profiles to be constructed. An effective way to obtain additional settlement information is through the use of a probe extensometer. A probe extensometer is a device that measures the distance between two or more points along a common axis. During construction of the embankment, stainless steel wire rings will be attached to a rigid vertical tube at different elevations. A readout probe with an induction coil transducer is lowered into the tube and the depth at which the coil is aligned with the ring can be noted.

Changes in the distance between marked locations over time will give estimates of the compression of each stratum of the embankment.

The measurement of horizontal motion is also an important part of the determination of the stability of the embankment slopes. The most common device for measuring horizontal movement is an inclinometer. The inclinometer measures the deformation normal to the axis of an embedded tube. In the embankment, the tube is installed vertically and any change in the orientation will be measured using an accelerometer built into a probe that fits into the tube.

Additional information regarding the suitability of the FGD as a base course can be obtained using in-situ tests such as the Dynaflect or Falling Weight Deflectometer. These tests will be performed to measure deflections of the pavement and shoulder.

2.4.1.2 Monitoring water content and quality

In both the FGD and the underlying soils, the water content and the location of the phreatic surface (from which effective intergranular stresses are calculated) are the two most important time dependent field variables, and so the measurement of these values must be included in a post-construction monitoring program. Water quality and content will be monitored in the embankment (1) so that estimates of solute mobility can be made, and (2) because the strength of the FGD material as well as the underlying soil is influenced by increasing or decreasing water content. At a minimum, the pressure in the pore water must be determined in order to calculate the effective stresses. The effective stresses must be known in order to make strength determinations.

Piezometers are typically used to measure pore water pressure at a specific depth below the embankment surface. Many types of piezometers are available and the final choice of a particular device usually depends on a variety of circumstances. However, since we have already recommended using a hollow tube for the inclinometers, it would seem reasonable to investigate ways to use the same tube as an observation well to monitor ground water. These open tube piezometers will be augmented with electronic piezometers, primarily to take advantage of the increased sensitivity this type of device offers.

The piezometers will provide the necessary field data for saturated materials. The FGD by-product, however, will be compacted at the optimum moisture content and is not saturated. Therefore, for at least some period of time after construction, the embankment, and most likely the underlying soil, will be only partially saturated. In unsaturated soil, negative (with respect to the atmosphere) pore pressure exists. Negative pressure in the pore water develops due to capillarity and adsorptive forces within the material matrix. Since water content has a significant effect on the strength of the material, the degree of saturation is an important design parameter. Tensiometers can be used to measure the value of negative pressure (or water tension) in the pore water. A tensiometer is typically comprised of a rigid plastic tube with a porous ceramic tip. The pore sizes in the tip are designed to allow movement of air across the tip while restricting water flow. The tube is filled with water and

sealed. The measurement of negative pressure can be made using either a vacuum gauge or a transducer. As with the piezometer, the tensiometer is a one location sensor, so to obtain the data at more than one location as well as at different elevations, several tensiometers will be needed.

In order to monitor the migration and concentration of potential pollutants within and around the embankment, the results of a water sampling program will be included in an evaluation of the project. Fortunately, the slope indicator tubes will be suitable for the collection of water samples from within the embankment. Water samples will be collected from outside of the area impacted by the embankment and the quality compared with that measured in samples collected from within the embankment.

2.4.1.3 Summary

Instrumentation required for monitoring embankment performance and environmental impact is summarized in Table 50. In addition to the field instrumentation, samples from the completed demonstration section will be collected and returned to the laboratory for testing. To establish the acceptability of the dry FGD material, the measured behavior of the embankment will be compared with the accepted performance of highway components constructed with conventional materials. Analytical models will be used to predict the performance of the demonstration section and these predictions will be checked against the measured performance.

Table 50. Proposed field instrumentation program.

Instrument	Property Monitored	Frequency of Measurement
1) Optical survey	overall displacements	bi-weekly (4 months) monthly
2) Settlement platform	vertical displacements	bi-weekly (4 months) monthly
3) Extensometer	vertical displacements	bi-weekly (4 months) monthly
4) Inclinator	horizontal displacements	weekly(4 months) monthly
5) Open standpipe piezometer	porewater pressure water quality	weekly(4 months) monthly
6) Tensiometer	negative pore pressure	weekly(4 months) monthly

2.5 LIMB Stockpile

The use of an FGD by-product in a highway embankment such as described in section 2.5 will require large volumes of material be delivered to the construction site over a short period of time. In order to insure a timely delivery of material to the construction site, it is likely that the FGD material will have to be stockpiled. In order to study the effects of aging on the chemical, physical and engineering properties of an FGD by-product, a 1500 ton temporary pile using the LIMB by-product, was constructed in July, 1991, on the property of the Central Fuel Company in New Philadelphia, Ohio. Details of the design and construction of the stockpile are presented in Appendix F. Measured properties of the LIMB material used to construct the pile are presented in Table 51.

Table 51. Summary of measured properties of LIMB by-product placed in storage pile.

	Water Added	Moisture Content	Slaking Temperature	Free CaO	Particle Density	Blaine Fineness	Bulk Density
	(%)	(%)	(C° 15 min ⁻¹)	(%)	(g cm ⁻³)	(cm ² g ⁻¹)	(g cm ⁻³)
Mean	43.5	17.5	8.2	21.4	2.84	10030	45.1
Number of Samples	22	8	16	24	5	5	3
Range	31.0- 53.5	7.5-35.2	6.5-13.7	11.4- 25.5	2.83-2.87	9790- 10460	44.5-45.5

3 PROBLEMS ENCOUNTERED IN COMPLETING PHASE 1 TASKS

3.1 Problems Encountered in Completing Characterization Tasks

The two major problems which slowed progress in the characterization tasks were the unavailability of representative FGD by-product samples, and the unreliable performance of the inductively coupled plasma spectrophotometer instrument. Because of the experimental nature of most dry FGD installations, units tended to go off-line frequently. Also there were frequent changes in operating parameters, making it difficult to obtain representative samples. Delays in the start-up of the Tidd PFBC unit delayed getting samples from this very important source.

The inductively coupled plasma spectrophotometer is the most important piece of analytical equipment for the overall chemical characterization of dry FGD by-product samples. Although purchased specifically for support of this project, we encountered numerous hardware problems with the instrument. This resulted in frequent down-time for the instrument, delaying data output. It also, in several instances, necessitated repeating sample preparation. Also, due to the nature of the dry FGD samples (mainly the high-salt sample matrix), analytical difficulties were encountered, particularly with respect to sample digestion and sample induction. This necessitated the testing of several different methodologies to find one which would produce high quality data.

3.2 Problems Encountered in Field Site Selection

The site-selection process revealed some interesting trends in surface mining in Ohio. New techniques for selective handling of "toxic" spoil materials can greatly reduce the threat of acid-mine drainage. Many mining companies selectively take spoils that are designated as "acid-producing" and bury them within carbonate-rock enclosures in the center of the spoil pile, thereby helping to neutralize reactions that may otherwise produce acidic water. Mining companies are also avoiding regions where potentially toxic spoils exist, which helps to minimize expenditures related to ameliorating acid-mine drainage. One question consistently raised by mine operators was how the FGD by-product would be stored, handled, and applied to the mine site. It is important that the research be conducted in a technically sound fashion but, at the same time, not disrupt the operations of the mining company. The logistics involved with material handling and application may ultimately decide the fate of using FGD by-products in active mine settings.

An unrelated, but perhaps more significant problem to site selection in regards to acid-mine drainage in Ohio appears to be abandoned-mine lands that were not reclaimed or were reclaimed using out-dated technology. These sites may require very large amounts of alkaline material to neutralize acid-mine drainage. FGD by-products may also find a use in reclamation practices that require large amounts of "fill" to return the mined land to the original contour.

With respect to acid mine drainage in Ohio, a more significant problem than active-mine sites seems to be abandoned mine lands that were not reclaimed at all or

were reclaimed using dated technology. The Fleming site is our candidate site to test the use of dry FGD by-product for reclamation of toxic spoil. This study will not only evaluate the beneficial reuse of dry FGD by-product as a reclamation amendment, but will also help eliminate acid mine drainage and sedimentation from a site in Ohio that has been documented as creating adverse environmental impacts.

4 SUMMARY AND CONCLUSIONS OF PHASE 1 TASKS

4.1 Characterization

4.1.1 Chemical Properties

The chemical composition of the FGD by-products is dominated by Ca, S, Al and Si, although the specific composition varies from sample to sample. Variation in concentration was particularly evident for the trace elements. These wide variations in concentrations seemed more likely to be due to variations in the original coal composition and sorbents used than in the specific clean coal technology employed at each coal-fired facility.

Arsenic appears to be the only regulated element present in the FGD by-products at concentrations that are in excess of proposed standards for land-applied sewage sludge. The actual consequences of these concentrations are not known at this time. However, As appears to reside primarily in the fly-ash fraction, as do most of the trace elements in the FGD by-products. Thus, it is suggested that FGD technologies "improve" the environmental impact that coal ash will have when land applied or used in mine reclamation. Trace element contents in the FGD by-products could fall under the same regulatory restrictions as trace elements in fly ash from coal burning sources.

The long-term solubility studies indicated that incubations in alkaline conditions led to production of gypsum, followed by ettringite. It is likely gypsum would still form in neutral pH regimes, but precipitation of ettringite should be inhibited.

4.1.2 Mineralogical Properties

The dry FGD by-products produced using duct injection, spray dryer, and coolside technologies were very similar in mineralogical composition. The primary constituents were portlandite, calcium sulfite-hemihydrate, calcite and fly ash. Duct injection samples produced using recycle contained more fly ash, more calcium sulfite, and less portlandite than those produced without recycle. Under field conditions, the portlandite component could be expected to dissolve and/or convert to calcite through reaction with atmospheric CO₂.

Calcium sulfite, in contrast to calcium sulfate, is relatively insoluble and mobilization probably requires oxidation to calcium sulfate. Oxygen consumption by calcium sulfite might be of interest in mine reclamation if the initial oxidation of pyritic materials could be retarded by blending with calcium sulfite. From an agronomic perspective, the effects of sulfitic materials on plant metabolism are unclear and should be studied in greater depth. The relatively low strength, low swell characteristics of the spray dryer and duct injection materials described in this report are probably also related to their sulfitic mineralogy. Ettringite, a hydrated calcium aluminum sulfate, is widely recognized as a potential agent for expansion of cementitious materials. The

presence of calcium sulfite in the spray dryer and duct injection materials would likely retard formation of ettringite.

The LIMB and pressurized-fluidized bed combustion by-products generally contained small amounts (< 10 wt%) of portlandite, 5 to 20 wt% lime, 10 to 20 wt% calcite, and 15 to 50 wt% anhydrite. When dolomite was employed as the sorbent, periclase and unreacted dolomite were also present. Coal ash contents were highly variable in the LIMB by-products and PFBC cyclone materials (30 to 80 wt%) but were consistently low in the PFBC bed materials (10 to 20 wt%). High heats of hydration associated with the conversion of lime to portlandite, periclase to brucite, and anhydrite to gypsum make handling a problem. Sufficient gypsum forms in the PFBC bed materials to cause cementation and high unconfined strengths. With time, the gypsum in all these by-products may serve as a feed material for the formation of ettringite and the onset of undesirable expansion characteristics.

4.1.3 Physical Properties

The most interesting physical feature of the FGD by-product material results from relations between particle size, water retention characteristics, saturated hydraulic conductivity and bulk density; particularly as compared with these relations for soil materials. The duct injection, spray dryer, and lime injection samples contained essentially silt sized particles. In the compressed state (25 psi), however, these materials held water tenaciously, more so than even a fine clay soil. Yet these same materials, also in a compressed state, had saturated hydraulic conductivities ranging from medium to low and corresponded to that observed for fine sand and sandy clay soils, respectively. The explanation for this inconsistent behavior may result from the relatively low bulk densities, and correspondingly high total porosities, of these materials such that they conducted water more readily than their particle sizes or water retention characteristics would suggest. Also, since these materials remain saturated at relatively high suctions, they would retain their high conductivities over a wide range of soil suction values.

The fluidized bed fly ash was somewhat coarser as compared with materials from other processes and contained a comparatively wide range of particle sizes. This wide range of particle sizes is likely the principal reason why this material had a higher compressed bulk density, a relatively low saturated hydraulic conductivity and high water retention properties. The bed ash from the fluidized bed process contained particle sizes ranging from coarse sand to fine gravel. Its bulk density, conductivity and water retention characteristics were typical for a coarse textured soil material.

4.1.4 Summary of engineering properties

The objective of the Phase 1 Engineering tests was to generate sufficient laboratory data to demonstrate that FGD by-products could, if properly compacted, be a suitable material for use in a field demonstration project (e.g. in highway construction

and repair). This objective was accomplished by conducting a comprehensive test program in the laboratory on samples obtained from a number of different dry FGD technologies. Of particular interest was a determination of compressive strength, compressibility, permeability and swell potential since, with these parameters, an engineer could properly design a highway embankment or other earth structure using the FGD by-product.

Included in the laboratory program were tests to evaluate the optimum moisture content and density of each material received in a manner consistent with widely accepted field compaction procedures. We observed that very good compaction could be achieved over a fairly broad range of moisture contents. This is an important observation since it means that a contractor who is placing an FGD by-product material probably will not have to take special care to achieve precisely the design water content in order to get specified densities. We also observed that the compacted densities of most of the FGD samples tested were well below typical compacted soil densities. Therefore an FGD embankment would be lighter than a comparable soil structure. Since a lighter FGD structure would impose a smaller load on the natural foundation soils than a conventional soil fill, the designer could expect less settlement in the underlying soils and a smaller likelihood that the loaded soils would fail.

Samples made from the compacted FGD material were found to have generally higher strengths and lower compressibilities than the natural soils that would typically be used in an embankment. High strength means that the threat of a slope failure is less for the FGD by-product material than for natural soils. Alternatively, increased stability means that designs calling for steeper slopes could be considered thereby possibly reducing significantly the amount of right-of-way that must be obtained for such projects.

Permeability tests were performed on a large number of compacted FGD samples. The coefficient of permeability was measured at 0, 7 and 28 days for most of these materials and correlations between the curing time and permeability were inferred. In spite of considerable range in the measured permeabilities, the test program clearly showed that all the FGD samples tested would be considered to be low permeability materials, with typical values in the range expected for clay.

All samples tested experienced two distinct swelling phases. In the first phase, sample hydration was accompanied by an increase in sample volume ranging between 0.1% and 12%. The second episode of swelling, which began after ten or more days had elapsed, typically ranged between 0% to 7% volume increase. The swell tests conducted on the dry FGD by-product samples indicated that the amount of volume change experienced is related to the process used to generate the FGD by-product. Care must be taken by the design engineer to correctly identify the swelling tendency of a specific FGD material since the results obtained in this laboratory program indicate the potential for volume change can be quite high.

All the tests were performed in accordance with industry accepted standards. This report should, therefore, provide much of the information state and county

highway engineers would require if they are to consider using dry FGD by-products in embankment and highway design.

4.2 Economics

Analysis of agricultural lime supply and demand relationships was considered and provides a rigorous basis for determining the potential of FGD by-products as an agronomic lime substitute. The FGD by-product is entering a very competitive market if it is to displace agricultural lime even though agricultural lime is a relatively small share of total sales of limestone.

Preliminary analysis of representative farms in northwest and northeast, Ohio was used to approximate the financial feasibility of using dry FGD by-product materials as an agricultural lime substitute. as expected, the results are very sensitive to transport distances due to the bulky nature of the product. More precise results will be possible when the agricultural land application field trials are completed.

To approximate the impacts of stripmines and landfills on adjacent property values, two types of hedonic pricing models have been developed. Primary data collection on the landfill related model is well underway. Site selection for the stripmine related model is being done to facilitate the use of results from other ongoing research at The Ohio State University which has focused on the downstream impacts of sediments on boating and property values at Ohio state park lakes.

Basic economic optimization models have been developed to summarize all of the foregoing elements from both a power plant and a societal standpoint. Initial runs of the financial model (i.e., from the power plant perspective) have been done utilizing a limited number of source points and preliminary assumptions about costs and technical parameters. These results are useful to illustrate general patterns and to further assist in model refinement prior to the final runs to be conducted at the end of this project.

4.3 Field Site Selection

Of seven abandoned mine sites submitted by the Division of Reclamation - Abandoned Mine Land Program (Ohio Department of Natural Resources) for project consideration, the Fleming site in Tuscarawas County was selected. This site consists of approximately 25 acres of exposed, highly erodible underclay bordered on two sides with about 45 acres of unreclaimed spoil and 5 acres of refuse. The site is causing sedimentation problems and flooding for landowners below the hillside and is estimated to affect 75 offsite acres. Because of the acidity levels and lack of vegetation, this site offers great potential to demonstrate the ability of dry FGD by-product materials to be used beneficially as a reclamation amendment.

Three sites at three different locations (Wooster, Canfield, and Coshocton) were selected for conducting our field studies for the evaluation of using dry FGD by-product materials as a substitute for agricultural lime. These sites are all located on property owned by The Ohio State University and have acidic soils that limit their

productivity. Treating these soils with dry FGD by-product material containing neutralization potential of approximately 50% should provide a potential benefit in terms related to improved agronomic crop growth as well as providing a controlled experimental setting for evaluating plant uptake and water quality impacts of using dry FGD by-product materials as an agricultural lime substitute.

Phase I resulted in an extensive literature review, development of criteria and a strategy for site selection, and selection of seven potential active mine sites from an initial list of 45.

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6 GLOSSARY

Abandoned mined land. An area of land that was mined for the extraction of a specific mineral resource prior to the passage of the Surface Mining Control and Reclamation Act of 1977 and not returned to an environmentally acceptable state.

Acid insoluble residue. A solid residue composed primarily of fly ash that is produced by the dissolution of dry FGD by-product with a weakly acidic buffer solution (pH 5.0) prepared by mixing sodium acetate, acetic acid, and water.

Agricultural lime. A soil amendment containing calcium carbonate, magnesium carbonate, and other material, used to neutralize soil acidity and furnish calcium and magnesium for plant growth. Classification including calcium carbonate equivalent and limits in lime particle size is usually prescribed by law or regulation.

Alkaline amendment. Any material applied to a soil or spoil to raise the pH.

Anhydrite. The mineral name for anhydrous calcium sulfate, CaSO_4 .

Approach to saturation. A measurement of the moisture content of flue gasses, in terms of the number of degrees the gas temperature is above the temperature at which the gas would be saturated (100% relative humidity) with water at its current moisture content.

ASTM leachate. The aqueous extract produced by the American Society for Testing and Materials standard test method for shake extraction of solid waste with water (ASTM D 3987-85).

Available lime index. A method for measuring the amount of calcium oxide (CaO) in a material (ASTM C 25).

Baghouse. A particulate emission control device which utilizes fabric filters in the shape of elongated bags to remove particulate matter from flue gasses.

Base saturation. The extent to which the adsorption complex of a soil is saturated with alkali or alkaline earth cations expressed as a percentage of the cation exchange capacity measured at pH 7.0, which may include acidic cations such as H^+ and Al^{3+} .

Bed (or bottom) ash. Non-combusted particulate material which accumulates on furnace beds during combustion of coal.

Beneficial reuse. Use of an industrial by-product in a manner which provides an economic and/or environmental benefit as an alternative to disposal.

Benefit-cost analysis. A procedure for evaluating decisions, or projects, in terms of their full economic consequences (i.e., social benefits and costs).

Bulk density. The ratio of the dry mass of a material to its bulk volume.

Calcine. To remove all volatile components through heating. In this report the term is used to refer more specifically to the conversion of a carbonate mineral to its corresponding oxide by the removal of CO_2 .

Calcite. The mineral name for calcium carbonate, CaCO_3

Calcium carbonate equivalency. The quantity of acid-neutralizing substances in a material expressed relative to the acid-neutralizing capacity of CaCO_3 .

Cation exchange capacity. The sum of exchangeable cations that a soil, soil constituent, or other material can adsorb at a specific pH. It is usually expressed in centimoles of charge per kilogram of exchanger ($\text{cmol}_c \text{ kg}^{-1}$)

Coefficient of determination. The ration of explained variation to total variation in multiple regression statistical analysis.

Compression index (strengths). A ratio of stress to strain used to characterize a soil subjected to one-dimensional strain.

Darcy's Law. A law describing the rate of flow of water through porous media. As formulated by Darcy the law is

$$Q = KS(H + e)/e$$

where Q is the volume of water passed in unit time, S is the area of the bed, e is the thickness of the bed, H is the depth of water on top of the bed and K is a coefficient dependent on the nature of the porous media (the hydraulic conductivity of the media).

Detection limit. The limit of an analytical technique to detect the presence of an analyte. Specifically the concentration of an analyte which produces a signal equal to twice the standard deviation of the background signal fluctuations.

Dolomite. The mineral name for calcium magnesium carbonate, $\text{CaMg}(\text{CO}_3)_2$

Dry scrubber. Any of several technologies for removing SO_2 from flue gasses in which the reaction product is collected in a dry state in the particulate emission control devices (c.f. wet scrubber).

Duct injection. A dry scrubber technology in which the sorbent is injected into the ductwork downstream from the boiler air pre-heaters in the lower flue gas temperature regions.

Economic analysis. In contrast to financial analysis, economic analysis takes into account net economic returns to the whole society which frequently involves shadow prices to adjust for market or administered price imperfections.

Elasticity (economic).

a) price elasticity of supply (demand): the ratio of the percentage change in the quantity of a commodity supplied (demanded) per unit of time to the percentage change in the price of that commodity. If the elasticity is denoted e then:

$e > 1$	elastic demand/supply,
$e < 1$	inelastic demand/supply, and
$e = 1$	unitary elastic demand/supply.

b) income elasticity (e_m): The ratio of the percentage change in the amount of a commodity purchased per unit time to the percentage change in the buyer's income. If

$e_m > 0$	the commodity is normal,
$e_m < 0$	the commodity is inferior,
$e_m = 1$	the commodity is a luxury, and
$0 < e_m < 1$	the commodity is a necessity.

Electrical conductivity. The ability of a solution to allow the passage of an electrical current, generally expressed in units of $\mu\text{mho cm}^{-1}$.

Electrostatic precipitator. A particulate emission control device in which flue gasses are passed through a charged field and particulate matter is removed due to electrostatic attraction to charged plates.

Environmental disamenity. Any environmental intrusion, such as a landfill or air pollution which is unpleasant or even dangerous.

Ettringite. A hydrated calcium-aluminum hydroxysulfate mineral,
 $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$.

Externalities. Incidental, third party or external effects from economic producers or consumption activity which is not accounted for by market prices.

Financial analysis. Refers to net returns to private equity capital based on market or administered prices.

Flue gas desulfurization (FGD). The removal of sulfur dioxide from the combustion gasses of fossil fuel- (coal-) fired boilers.

Flue gas. Gasses resulting from the combustion of fossil fuels (coal).

Fluidized bed combustion. A coal combustion process in which a bed of mixed pulverized coal and sorbent (generally limestone) is fluidized by jets of air blowing up from the furnace floor.

Fly ash. The glassy inorganic particulate residue suspended in the flue gasses resulting from combustion of fossil fuel (coal).

Geochemical speciation. The equilibrium distribution of cationic, anionic, and neutral dissolved species in a solution expressed as the activity of the species.

Gypsum. The mineral name for hydrated calcium sulfate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

Hedonic prices. The implicit prices of attributes revealed to economic agents from the observed prices of differentiated goods and the specific amounts of characteristics associated with them.

Hedonic impacts. Impacts on the implicit prices of characteristics of differentiated goods.

Hematite. The mineral name for an iron oxide with the formula Fe_2O_3 .

Hydrated lime. Portlandite, $\text{Ca}(\text{OH})_2$, formed by the reaction of lime (CaO) with water or steam.

Hydraulic conductivity. The rate of flow of pure water through a cross sectional area under a unit hydraulic gradient at the prevailing temperature. Synonymous with permeability coefficient, K .

Hydraulic gradient. The change in water level over a given distance, be it horizontal, vertical or somewhere in between. Defined as $\Delta h / \Delta l$ where Δh is the change in head or water level, and Δl is the change in distance or elevation.

ICP. Inductively Coupled Plasma atomic emission spectrophotometer.

Inclinometer. An instrument capable, when placed in an embankment, of measuring movement of a soil mass.

Instrument calibration and standardization. The optimization of an analytical instrument so as to provide specific output from analytical standards of known composition.

LIMB process. Lime Injection Multistage Burners. A dry scrubber technology in which the sorbent is injected into the furnace above the combustion zone

Lime test index. An index value generated by reaction of a soil with an alkaline buffer and used to determine the amount of agricultural lime required to raise the pH of the soil to a specified level.

Lime. The mineral name for calcium oxide, CaO .

Limestone. A rock of marine origin that is typically composed of calcite (CaCO_3).

Magnetite. The mineral name for a magnetic iron oxide with the formula Fe_3O_4 .

NIST. National Institute of Standards and Technology.

Optimum density. The maximum density achievable with a standard compaction effort.

Optimum moisture content. The moisture content at which the optimum density is achieved.

Overburden. In surface mining practices, there is usually some quantity of rock or soil that overlies the mineral resource. This material is known as overburden and must be removed during surface mining to expose the mineral.

Oxidation-reduction potential (Eh). A measurement (expressed in mV) of the tendency of a system to oxidize (accept electrons from) or reduce (donate electrons to) chemical species introduced into the system.

Particle size distribution. The fractions of the various soil separates in a soil sample, often expressed as mass percentages.

Periclase. The mineral name for magnesium oxide, MgO .

Permeability. A measure of the relative ease of fluid flow under unequal pressure.

Piezometer. A device for measuring the water pressure at a specific elevation in a soil mass.

Portlandite. The mineral name for calcium hydroxide, Ca(OH)_2 .

Potential pareto improvement. An improvement in social welfare in which those who gain from the improvement could potentially compensate the perceived losses of the losers and still be no worse off.

Pressurized fluidized bed combustion. A fluidized bed combustion technology modified such that the boiler is pressurized and the pressurized flue gas is used to turn a gas turbine for production of electricity in addition to steam generation to turn steam turbines.

Quality assurance. Refers to a program of activities organized to insure that a laboratory produces data of adequate quality for its intended end use. To meet this data quality goal, an overall quality assurance program comprises numerous quality control activities.

Quality control. Activities which address day-to-day analyses, as well as laboratory management, and are designed to insure that the data produced by a specific analytical procedure is of adequate quality for its intended end use.

Residuals. The amount of a resource which is left over after a material has been transformed from one state to another in a economic production or consumption process, e.g., fly ash is a residual of the process of transforming coal to electric energy.

Saturation index (SI). A measurement of the degree to which a chemical system is under- or oversaturated with respect to a particular solid phase mineral. When SI is greater than 0, the system is oversaturated and the mineral will tend to precipitate; when SI is less than 0, the system is undersaturated and the mineral will tend to dissolve.

Shift variable. In a supply and demand system, a shift variable is one which is exogenous, or outside, of the system. It effectively causes exogenous changes in supply and/or demand.

Soil stabilization. The application of physical or chemical additives to a soil mass for the purpose of improving soil strength.

Specific surface area. The surface area per unit weight of a material, generally expressed in units of $\text{m}^2 \text{g}^{-1}$.

Spoil. Typically a mixture of overburden and uneconomic mineral deposits that are the result of mining operations.

Spray dryer. A dry scrubber technology in which the sorbent is injected into a dry scrubber vessel located downstream from the boiler air preheater in the lower flue gas temperature region. The scrubber vessel allows for increased flue gas residence time and therefore increased time for the sorbent to react with SO_2

Stiffness (soil). The ratio of applied stress to induced strain i.e. σ/ϵ .

Strength (soil). The maximum imposed stress a soil can withstand without failing.

TCLP leachate. The extract produced by the US EPA Method 1311 Toxicity Characteristic Leaching Procedure which is designed to determine the mobility of both organic and inorganic analytes present in liquid, solid, and multiphasic wastes.

Tensiometer. A device for measuring soil water tension.

Thermal reactivity. The amount of heat generated by a material upon addition of water. Generally expressed as the increase in temperature in a specified time period from the addition of a specified amount of water to specified amount of the material.

Thermal gravimetric analysis. An analytical method for the quantification of mineral components in a sample by measuring the weight loss induced by heating over a specified temperature range.

Tipping fee. The amount charged by a facility accepting waste materials for the disposal of a given weight or volume of a specified waste.

Total neutralizing potential. The total amount of alkalinity in a material, determined by causing a complete reaction of a specified amount of the material with a specified amount of a standard acid.

Wet scrubber. A process for removing SO_2 from flue gasses in which the sorbent is injected downstream from the particulate emission control system, and the reaction product is collected in the form of a slurry consisting primarily of gypsum (c.f. dry scrubber).

Willingness to accept. This is the supply curve of an economic agent; it is the price at which the agent is willing to engage in trade with a demander of a good.

Willingness to pay. The demand curve of an economic agent. The price at which the agent is willing to purchase a good from a supplier.

X-ray diffraction. An analytical technique for the qualitative identification of crystalline mineral components by measuring the scattering of X-rays by the atoms of a crystal in definite directions away from the crystal (diffraction pattern).

7 APPENDICES

APPENDIX A
Steering Committee

Baker, Bob
Ohio Dept. of Natural Resources
1855 Fountain Square Court
Columbus, OH 43224
614-265-6633

Bedick, Robert C.
U.S. Department of Energy
Morgantown Energy Technology Center
P.O. Box 880
Collins Ferry Rd.
Morgantown, WV 26505
304-291-4505

Beeghly, Joel
Dravo Lime Co.
Research Center
3600 Neville Rd.
Pittsburgh, PA 15225
412-777-0711

Bigham, Jerry
The Ohio State University
420A Kottman Hall
2021 Coffey Rd.
Columbus, OH 43210
614-292-9066

Bird, Jacqueline
Ohio Coal Development Office
77 S. High Street
P.O. Box 1001
Columbus, OH 43266-0101
614-466-3465

Brdicka, Ed
Ohio Env. Prot. Agency
Division of Solid Waste Management
P.O. Box 1049
1800 Water Mark Drive
Columbus, OH 43266-1049
614-644-3181

Cook, Adrian
Ohio Edison Co.
76 South Main St.
Akron, OH 44308
216-384-4550

Dick, Warren
The Ohio State University
109A Williams Hall
OARDC/OSU
Wooster, OH 44691-4096
216-263-3877

Forsythe, Russ
Dravo Lime Company
3600 One Oliver Plaza
Pittsburgh, PA 15222-2682
412-566-5553

Haefner, Ralph
USGS Water Resources Division
975 West Third Ave.
Columbus, OH 43212-3192
614-469-5553 (FTS 943 5553)

Harness, Jerry
U.S. Department of Energy
Morgantown Energy Technology
Center
P.O. Box 880
Collins Ferry Road
Morgantown, WV 26505
304-291-4835

Hopkins, Ed
Ohio Citizens Action
17 Brickel Street
Columbus, OH 43215
614-224-4111

Hyman, David
U.S. Bureau of Mines
Cochran Mill Road
P.O. Box 18070
Pittsburgh, PA 15236
412-892-6572

Johnson, Howard
Ohio Coal Development Office
77 S. High Street
P.O. Box 1001
Columbus, OH 43266-0101
614-466-3465

Keenan, Gregory
AEP Service Corporation
1 Riverside Plaza
Columbus, OH 43215
614-223-1388

MacDonald, R. Jeffrey
ODNR Div of Reclamation AML
1855 Fountain Square Ct.
Columbus, OH 43224
614-265-1016

Militaru, Calin
AEP Service Corporation
1 Riverside Plaza
Columbus, OH 43215
614-223-1384

Murarka, Ishwar P.
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303
415-855-2150

Rotering, Ernest
Ohio EPA, Div. Solid Waste
Management
P.O. Box 1049
1800 Water Mark Drive
Columbus, OH 43266-1049
614-644-3020

Seibel, Rick
Office of Surface Mining
U.S. Department of Interior
Ohio Section
2242 S. Hamilton
Columbus, OH 43232
614-866-0578

Showman, Ray
AEP Service Corporation
1 Riverside Plaza
Columbus, OH 43215
614-223-1000

Shupert, John
Ohio Mining & Reclamation Association
129 N Tenth Street
Cambridge, OH 43725
614-432-5645

Skiles, Mervin S.
USDA- Soil Conservation Service
200 N. High Street
Columbus, OH 43215
614-469-6980

Stehouwer, Rick
The Ohio State University
110A Williams Hall
OARDC/OSU
Wooster, OH 44691-4096
216-263-3655

Theodore, Frank W.
Consolidation Coal Co.
4000 Brownsville Road
Liberty, PA 15129
412-854-6663

Tostenson, Neal
Ohio Mining & Reclamation Association
50 S. Young
Columbus, OH 43215
614-228-6336

APPENDIX B

Following are two bibliographies of literature related to FGD production, characterization, and environmental impacts of land application and disposal. The first was compiled by the USGS, Water Resources Division, and the second was compiled by the Ohio State University, Department of Agronomy. There are several entries which appear in both bibliographies.

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Appendix C

Dry FGD by-Product Samples and Plant Operating Conditions

Sample code	BAB-LID-01
Date	7-03-90
Sampling Point	baghouse hoppper
Sampler	Gerald T. Amrhein (LIDS project Manager)
Comments	Sample from Babcock & Wilcox Alliance Research Center
Cond. of Op.	Sorbent: Calcitic lime
	Ca/S: 1.22
 Sample code	 BAB-LID-02
Date	7-20-90
Sampling Point	Baghouse hopper
Sampler	Gerald T. Amrhein (LIDS project Manager)
Comments	Sample from Babcock & Wilcox Alliance Research Center
Cond. of Op.	Sorbent: Dolomitic lime
	Ca/S: 2.74
 Sample code	 BAB-LID-03
Date	1-04-91
Sampling Point	Dry scrubber hopper
Sampler	Gerald T. Amrhein (LIDS project Manager)
Comments	Sample from Babcock & Wilcox Alliance Research Center
Cond. of Op.	Sorbent: Calcitic lime
	Ca/S: 2.42
 Sample code	 BEV-DUC-02
Date	12/17/90
Sampling Point	Electrostatic precipitator
Sampler	Atef Demian
Comments	This sample is from tests of slaked lime slurry injection.
Cond. of Op.	SO2 inlet concentration: 1300 ppm
	Ca/S: 1.8
	Gas flow: 50,000 acfm
	Gas temperature (inlet): 300 F
	Gas temperature (ESP): 170 F
	S removal efficiency: 60%
	Pebble lime analysis: 92% CaO, 1.9% MgO

Sample code	BEV-DUC-03	
Date	1-04-91	
Time	1400	
Sampling Point	ESP Hopper	
Sampler	Atef Demian	
Cond. of Op.	SO2 inlet concentration:	1300 ppm
	Ca/S:	2.8
	Gas flow:	50,000 acfm
	Gas temperature (inlet):	300 F
	Gas temperature (ESP)	160 F
	Approach to sat.	30 degrees
	S removal efficiency	75%
	Pebble lime analysis:	92% CaO, 1.9% MgO
Sample code	BEV-DUC-05	
Date	7-23-91	
Time	1345	
Sampling Point	ESP hopper	
Sampler	Atef Demian	
Comments	Slurry/Recycle system, ash recycled through injection system.	
Cond. of Op.	SO2 inlet concentration:	2000 ppm
	Ca/S:	1.5
	Gas flow:	50,000 acfm
	Gas temperature (inlet):	300 F
	Gas temperature (ESP):	155 F
	Approach to sat.	25 degrees
	Recycle ratio	3.3:1 (ash to pebble lime)
Sample code	BEV-DUC-06	
Date	1-3-92	
Time	1410	
Sampling Point	ESP Hopper	
Sampler	Atef Demian	
Comments	Sample with Cl added to slurry at 3%	
Cond. of Op.	SO2 inlet concentration:	2000 ppm
	Ca/S:	2.0
	Gas flow:	50,000 acfm
	Gas temperature (inlet):	300 F
	Gas temperature (ESP):	165 F
	Approach to sat.	35 degrees
	S removal efficiency	64%
	Recycle ratio	no recycle

Sample code	BEV-DUC-07
Date	2-10-92
Time	1200
Sampling Point	ESP hopper
Sampler	Atef Demian
Comments	Ash recycle system
Cond. of Op.	SO2 inlet concentration: 2000 ppm
	Ca/S: 1.4
	Gas flow: 50,000 acfm
	Gas temperature (inlet): 300 F
	Gas temperature (ESP): 170 F
	Approach to sat. 40 degrees
	S removal efficiency 55%
	Recycle ratio 2:1 (ash:lime)

Sample code	BEV-DUC-08
Date	2-25-92
Time	1600
Sampling Point	ESP Hopper
Sampler	Atef Demian
Comments	Sample with 3% Cl additive
Cond. of Op.	SO2 inlet concentration: 1000 ppm
	Ca/S: 2.0
	Gas flow: 50,000 acfm
	Gas temperature (inlet): 300 F
	Gas temperature (ESP): 165 F
	Approach to sat. 35 degrees
	S removal efficiency 84%
	Recycle ratio 2:1 (ash:lime)

Sample code	EDG-CLS-01
Date	02-14-90
Sampling Point	ESP-second field
Sampler	B&W
Cond. of Op.	Coal: 1.5% S, 1.4% N, 66.4% C, 9.88% ash
	Unburned C in ash: 6.2%
	Sorbent: 96.3% Ca(OH)2, 7.3% inert/SiO2
	Coal flow: 40 Klb/hr
	Sorbent flow: 1109 lb/hr
	NaOH flow (dissolved in water): 112.3 lb/hr
	Na/Ca: 0.19
	Ca/S: 0.8
	SO2 removal: 20-25%
	Inlet temp: 245 F
	Ash production: app. 3100 lb/hr

Sample code	EDG-LIM-03
Date	06-14-90
Time	0000 - 0830
Sampling Point	ESP-second field
Sampler	B & W
Cond. of Op.	Coal: 2.66% S, 1.42% N, 66.64% C, 10.2% ash Unburned C in ash: 6.2% Sorbent: 97.5% CaCO ₃ , 0.68% MgCO ₃ , 1.82 inert/SiO ₂ Coal flow: 40 Klb/hr Sorbent flow: app. 7700 lb/hr Ca/S: app 2.2 SO ₂ removal: app. 70%
Sample code	EDG-LIM-04
Date	10-23-90
Time	0000 - 0830
Sampling Point	ESP second field
Sampler	Adrian Cook
Comments	LIMB using dolomitic lime as sorbent.
Cond. of Op.	Coal: 2.26% S, 1.37% N, 65.23% C, 10.6% ash Unburned C in ash: 4.6% Sorbent: 33.73% Ca, 19.06% Mg Coal flow: app 37 Klb/hr Sorbent flow: app 4000 lb/hr Ca/S: 1.25 SO ₂ removal: n.a.
Sample code	EDG-LIM-05
Date	10-29-90
Time	1100
Sampling Point	Ash silo
Sampler	Joe Hoffman
Comments	This sample was pulled from ash silo after mixing with sufficient water to achieve 15-20% moisture by weight. Representative of what is loaded on trucks for hauling to landfill. The sample is likely a composite of operating conditions on 10/28/90.
Cond. of Op.	Coal: 2.61% S, 1.37% N, 65.23% C, 10.25% ash Unburned C in ash: 4.6% Sorbent: 33.73% Ca, 19.06% Mg Coal flow: app. 37 Klb/hr Sorbent flow: app. 5000 lb/hr Ca/S: 1.4 SO ₂ removal: app 30%

Sample code	EDG-LIM-06
Date	11/16/90
Time	1000
Sampling Point	2nd field ESP
Sampler	A. Cook
Cond. of Op.	Sorbent: 33.85% Ca, 19.42% Mg
	Sorbent flow: app. 4000 lb/hr
	Ca/S: 1.2
	SO2 removal: app. 25%

Sample code	EDG-LIM-07
Date	11/20/90
Time	1030
Sampling Point	2nd field ESP
Sampler	A. Cook
Cond. of Op.	Sorbent: 33.85% Ca, 19.42% Mg
	Sorbent flow: app. 3000 lb/hr
	Ca/S: 1.3
	SO2 removal: 35-40%

Sample code	EDG-LIM-08
Date	1-25-91
Time	1300
Sampling Point	ESP 2nd field
Sampler	A. Cook
Comments	calcitic limestone sorbent
Cond. of Op.	Coal: 1.58% S, 1.37% N, 65.23% C, 11.23 ash
	Unburned C in ash: 4.6%
	Sorbent: 33.73% CaCO3, 0.68% MgCO3
	Coal flow: app. Klb/hr
	Sorbent flow: app. lb/hr
	Ca/S: 2.00
	SO2 removal: 35

Sample code	EDG-LIM-09
Date	2-13-91
Time	1130
Sampling Point	ESP 2nd field
Sampler	A. Cook
Comments	lime sorbent
Cond. of Op.	Coal: 3.27% S, 1.37% N, 65.23% C, 9.59% ash
	Unburned C in ash: 4.6%
	Sorbent: 62.3% Ca(OH)2, 00% Mg
	Coal flow: app Klb/hr
	Sorbent flow: app 5000 lb/hr
	Ca/S: 1.25
	SO2 removal: 30-35%

Sample code	EDG-LIM-10
Date	3-8-91
Time	1200
Sampling Point	ESP 2nd field
Sampler	J. Hoffman
Cond. of Op.	Coal: 1.61% S, 1.37% N, 65.23% C, 11.25% ash
	Unburned C in ash: 4.6%
	Sorbent: 96.3% Ca(OH) ₂ , 00% Mg
	Coal flow: app 37 Klb/hr
	Sorbent flow: app 15000 lb/hr
	Ca/S: 0.7
	SO ₂ removal: 5-10%

Sample code	EDG-LIM-11
Date	4-16-91
Time	1400
Sampling Point	ESP 2nd field
Sampler	J. Hoffman
Cond. of Op.	Coal: 2.60% S, 1.27% N, 65.09% C, 11.96% ash
	Unburned C in ash: 4.6%
	Sorbent: 87.8% Ca(OH) ₂ , 12.2% Inert
	Coal flow: app Klb/hr
	Sorbent flow: app 4000 lb/hr
	Ca/S: 1.75
	SO ₂ removal: 35-45%

Sample code	EDG-LIM-12
Date	5-24-91
Sampling Point	ESP 2nd field
Sampler	A. Cook
Cond. of Op.	Coal: 1.75% S, 1.27% N, 65.09% C, 12.81% ash
	Unburned C in ash: 4.6%
	Sorbent: 87.8% Ca(OH) ₂ , 12.2% Inert
	Coal flow: app 50 Klb/hr
	Sorbent flow: app 4000 lb/hr
	Ca/S: 1.7
	SO ₂ removal: 55%

Sample code	EDG-LIM-13
Date	7-10-91
Sampling Point	ESP 2nd field
Sampler	A. Cook
Cond. of Op.	Coal: 3.53% S, 1.27% N, 65.09% C, 11.03% ash
	Unburned C in ash: 4.6%
	Sorbent: 87.8% Ca(OH) ₂ , 12.2% Inert
	Coal flow: app 35 Klb/hr
	Sorbent flow: app 4500 lb/hr
	Ca/S: 1.40
	SO ₂ removal: 35-40%

Sample code	EDG-LIM-14
Date	7-15-91
Sampling Point	ESP 2nd field
Sampler	J. Hoffman
Cond. of Op.	Coal: 4.20% S, 1.27% N, 65.09% C, 10.36% ash
	Unburned C in ash: 4.6%
	Sorbent: 87.8% Ca(OH) ₂ , 12.2% Inert
	Coal flow: app 50 Klb/hr
	Sorbent flow: app 10000 lb/hr
	Ca/S: 2.2
	SO ₂ removal: 55%
Sample code	GMC-FLB-01
Date	Jan 13, 1992
Sampling Point	Bottom ash
Sampler	Joel Beeghly
Comments	Sample from GMC Pontiac, Pontiac MI, for use in N-Viro soil mixture for Fleming AML site
Cond. of Op.	Coal: 2.77% S, 8.13% ash
	Sorbent: limestone, 90% CaCO ₃ , 9% MgCO ₃ +inerts
	Coal flow: app 36.25 Klb/hr
	Sorbent flow: app 6.46 Klb/hr
Sample code	GMC-FLB-02
Date	1/13/92
Sampling Point	Fly ash
Sampler	Joel Beeghly
Comments	Sample from GMC Pontiac, Pontiac MI for use in N-Viro soil mixture
Cond. of Op.	Coal: 2.77% S, 8.13% ash
	Sorbent: limestone, 90% CaCO ₃ , 9% MgCO ₃ +inerts
	Coal flow: app 36.25 Klb/hr
	Sorbent flow: app 6.46 Klb/hr
Sample code	GMC-FLB-03
Date	February
Sampling Point	Silo - mixture of fly and bed ash
Sampler	Kyle Grathwol
Comments	Subsample of truckload of GMC plant bed and fly-ash mix sent to N-Viro Tech. and used in production of N-Viro Soil (#3).
Cond. of Op.	Coal: 2.77% S, 8.13% ash
	Sorbent: limestone, 90% CaCO ₃ , 9% MgCO ₃ + inerts
	Coal flow: app 36.25 Klb/hr
	Sorbent flow: app 6.46 Klb/hr

Sample code	HST-SPD-01
Date	3-20-91
Sampling Point	baghouse fabric filter
Sampler	Joe Peterson
Cond. of Op.	Sorbent: Mississippi lime
	Ca/S: 1.3
	Spray dryer inlet SO2 conc: 1500 ppm
Sample code	HST-SPD-02
Date	3-20-91
Sampling Point	Spray dryer drop out solids
Sampler	Joe Peterson
Cond. of Op.	Sorbent: Mississippi lime
	Ca/S: 1.3
	Spray dryer inlet SO2 conc: 1500 ppm
Sample code	HST-SPD-03
Date	4-15-91
Sampling Point	Baghouse fabric filter
Sampler	Joe Peterson
Cond. of Op.	Sorbent: Mississippi lime
	Ca/S: 1.6
	Spray dryer inlet SO2 conc: 2500 ppm
Sample code	HST-SPD-04
Date	4-15-91
Sampling Point	spray dryer drop out solids
Sampler	Joe Peterson
Cond. of Op.	Sorbent: Mississippi lime
	Ca/S: 1.6
	Spray dryer inlet SO2 conc: 2500 ppm
Sample code	HST-SPD-05
Date	10-03-91
Sampling Point	Mix of SPD dropout solids and baghouse ash
Sampler	Joe Peterson, Joel Beeghly
Comments	This sample is a mix of two ash streams; spray dryer drop-out solids and pulse jet fabric filter ash. The previous samples are separate samples of these ash streams.
Sample code	NSP-SPD-01
Date	3-7-91
Sampling Point	baghouse
Sampler	John Hietala
Cond. of Op.	Sorbent: 90% CaO (slaked then fed as slurry)
	Coal flow: 370-400 tons/hr
	Sorbent flow: app 39.5 Klb/hr
	Ca/S: 1.2
	Spray dryer inlet SO2 conc: 532 ppm
	SO2 removal: 75.5%

Sample code	NSP-SPD-02
Date	February, 1992
Sampling Point	baghouse
Sampler	John Hietala
Sample code	OSU-SPD-01
Date	1-11-91
Time	1115
Sampling Point	Baghouse
Sampler	Don Smith
Sample code	OSU-SPD-02
Date	2-22-91
Time	1030
Sampling Point	Baghouse compartment A
Sampler	Don Smith
Sample code	OSU-SPD-03
Date	4-1-91
Time	1305
Sampling Point	Baghouse compartment B
Sample code	OSU-SPD-04
Date	4-1-91
Time	1236
Sampling Point	Bottom Ash
Sampler	John Harris
Sample code	OSU-SPD-05
Date	5-23-91
Time	1300
Sampling Point	Baghouse compartment C
Sampler	Frank Paskievitch
Sample code	OSU-SPD-07
Date	5-23-91
Time	0930
Sampling Point	North Economizer hopper
Sampler	Frank Paskievitch
Comments	economizer ash
Sample code	OSU-SPD-08
Date	5-23-91
Time	1040
Sampling Point	Boiler bottom ash
Sampler	Frank Paskievitch
Comments	Bottom Ash

Sample code	OSU-SPD-09
Date	5-23-91
Time	1030
Sampling Point	Bottom siftings
Sampler	Frank Paskievitch
Comments	Siftings
Sample code	OSU-SPD-10
Date	January 29, 1992
Sampling Point	Baghouse
Sample code	OSU-SPD-11
Date	February 13, 1992
Sampling Point	Ash silo
Sampler	Bill Wolfe
Comments	Mixture of baghouse and bed ash
Sample code	PED-RCB-01
Date	9-24-91
Sampling Point	Baghouse
Comments	Rotary Cascading Bed Boiler located at North American Rayon, Elizabethton, Tenn. Formerly at Hudepohl Brewery, Cincinnati Ohio and supported by OCDO.
Cond. of Op.	Coal: 4.45% S (Waterloo Coal from Ohio)
	Sorbent: Calcite Limestone 85% CaCO ₃
	Total run time: 46.0 hr.
	Coal usage: 524 lbs/hr
	Sorbent usage: 113 lbs/hr
	Steam Flow: 4,789 lbs/hr
	Ave Steam Temp: 558 F
	Ave Comb. Zone Temp: 1623 F
	SO ₂ Emission: 0.29 lbs/million BTU
	NO _x Emission: 0.12 lbs/million BTU
	Ca/S ratio: 1.3
Sample code	QST-FLB-01
Date	10-10-90
Sampling Point	economizer ash
Sampler	Joel Beehly
Comments	high coal content ash
Cond. of Op.	Sorbent: limestone
	Coal flow: 146 Ton/day, 6.1 Ton/hr
	Sorbent flow: app. 1.6 Ton/hr
	Ca/S: 2.9

Sample code	QST-FLB-02
Date	10-10-90
Sampling Point	baghouse
Sampler	Joel Beeghly
Comments	high coal content ash
Cond. of Op.	Sorbent: limestone
	Coal flow: 146 Ton/day, 6.1 Ton/hr
	Sorbent flow: app. 1.6 Ton/hr
	Ca/S: 2.9

Sample code	QST-FLB-03
Date	10-24-90
Sampling Point	boiler bottom ash
Sampler	Joel Beeghly
Cond. of Op.	Sorbent: limestone
	Coal flow: 146 Ton/day, 6.1 Ton/hr
	Sorbent flow: app. 1.6 Ton/hr
	Ca/S: 2.9

Sample code	STA-FLB-01
Date	
Sampling Point	fly ash
Sampler	J. Beeghly
Cond. of Op.	Coal: 2.8-3.0% S
	Sorbent: high Ca limestone
	Coal flow: app 380,000 tons/yr
	Ash production app 150,000 tons/yr
	Ca/S: 3.0

Sample code	TID-FLB-01 (primary cyclone ash)
Date	8/28/91 (sampling date)
Time	sample from 12 hr burn on 8/25/91 (60% load)
Sampling Point	Cyclone ash silo
Sampler	Jim Holland
Cond. of Op.	Sorbent: Dolomite (National Lime)
	28.0% CaO (20.0% Ca)
	15.9% MgO (9.6% Mg)
	Coal: 3.5% S (dry basis)
	Sorbent feed rate: 19.0 K lb/hr
	Coal feed rate: 40.0 K lb/hr (of 25.5% moisture coal paste)
	Ca:S molar ratio: 2.91
	Emissions: 0.4 lb SO ₂ /million BTU

Sample code	TID-FLB-02 (bed ash)
Date	8/28/91 (sampling date)
Time	sample from 12 hr burn on 8/25/91 (60% load)
Sampling Point	bed ash silo
Sampler	Jim Holland
Cond. of Op.	Sorbent: Dolomite (National Lime)
	28.0% CaO (20.0% Ca)
	15.9% MgO (9.6% Mg)
	Coal: 3.5% S (dry basis)
	Sorbent feed rate: 19.0 K lb/hr
	Coal feed rate: 40.0 K lb/hr (of 25.5% moisture coal paste)
	Ca:S molar ratio: 2.91
	Emissions: 0.4 lb SO2/million BTU

Sample code	TID-FLB-03 (primary cyclone ash)
Date	9/16/91 (sampling date)
Time	sampled ash from 58 hr burn 9/5 -9/8 (60% load)
Sampling Point	Primary Cyclone Ash Silo
Sampler	R. Stehouwer
Cond. of Op.	Sorbent: Dolomite (Plum Run 57)
	27.0% CaO (19.3% Ca)
	16.8% MgO (10.1% Mg)
	Coal: 3.44% S (dry basis)
	Sorbent feed rate: 14.9 K lb/hr
	Coal feed rate: 48.2 K lb/hr (of 25.5% moisture coal paste)
	Ca:S molar ratio: 1.86
	Ash ratio from burn: 40.5% bed ash, 59.5% primary cyclone ash
	Emissions: 0.4 lb SO2/million BTU

Sample code	TID-FLB-04 (bed ash)
Date	9/16/91 (sampling date)
Time	sampled ash from 58 hr burn 9/5 - 9/8 (60% load)
Sampling Point	Bed Ash silo
Sampler	Rick Stehouwer
Cond. of Op.	Sorbent: Dolomite (Plum Run 57)
	27.0% CaO (19.3% Ca)
	16.8% MgO (10.1% Mg)
	Coal: 3.44% S (dry basis)
	Sorbent feed rate: 14.9 K lb/hr
	Coal feed rate: 48.2 K lb/hr (of 25.5% moisture coal paste)
	Ca:S molar ratio: 1.86
	Ash ratio from burn: 40.5% bed ash, 59.5% primary cyclone ash
	Emissions: 0.4 lb SO2/million BTU

Sample code	TID-FLB-05 (electrostatic precipitator ash)
Date	9-17-91
Time	am
Sampling Point	landfill site
Sampler	Joel Beeghly
Comments	These ESP samples were collected from the landfill disposal site. They were exposed to environment for up to two weeks. A surface crust formed from rainfall was removed before sampling. The ESP ash stream is in the range of 3-5% of the total PFBC ash production (ESP+primary+secondary cyclone+bed)

Sample code	TID-FLB-06
Date	3-06-92 (sampled)
Sampling Point	Cyclone ash silo
Sampler	Jim Holland
Comments	Primary cyclone ash (combined with ESP ash)
Cond. of Op.	Sorbent: Dolomite (Plum Run 57) 27.9% CaO (19.3% Ca) 19.1% MgO (11.5% Mg) 3.26% S (dry basis) Coal: 20.0 K lb/hr Sorbent feed rate: 20.0 K lb/hr Coal feed rate: 55.0 K lb/hr (of 27.35% moisture coal paste) Ca:S molar ratio: 2.5 Emissions: 0.47 lb SO2/million BTU

Sample code	TID-FLB-07
Date	3-06-92 (sampled)
Sampling Point	Bed ash silo
Sampler	Jim Holland
Comments	Bed ash sample
Cond. of Op.	Sorbent: Dolomite (Plum Run 57) 27.9% CaO (19.3% Ca) 19.1% MgO (11.5% Mg) 3.26% S (dry basis) Coal: 20.0 K lb/hr Sorbent feed rate: 20.0 K lb/hr Coal feed rate: 55.0 K lb/hr (of 27.35% moisture coal paste) Ca:S molar ratio: 2.5 Emissions: 0.47 lb SO2/million BTU

Sample code	TVA-FLB-01
Date	3-4-91
Time	am
Sampling Point	Char "o" flow (char overflow)
Sampler	Arnold M. Manaker
Cond. of Op.	Coal: 3.5% S, 1.6% N, 65.0% C, 9.6% ash
	Unburned C in ash: 6.5%
	Sorbent: limestone, 35.4% Ca
	Coal flow: app 90.3 Klb/hr
	Sorbent flow: app 39.5 Klb/hr
	Ca/S: 3.6
	SO2 removal: 95.8%
Sample code	TVA-FLB-02
Date	composite sample of late Jan-early Feb '91
Sampling Point	Fly ash (baghouse)
Sampler	Arnold M. Manaker
Cond. of Op.	Coal: 3.6% S, 1.3% N, 65.0% C, 9.6% ash
	Unburned C in ash: 7.8%
	Sorbent: limestone, 32.3% Ca
	Coal flow: app 81.6 Klb/hr
	Sorbent flow: app 33.4 Klb/hr
	Ca/S: 3.0
	SO2 removal: 98.0%
Sample code	TVA-FLB-03
Date	3-4-91
Time	am
Sampling Point	Spent bed ash (bed drain)
Sampler	Arnold M. Manaker
Cond. of Op.	Coal: 3.5% S, 1.6% N, 65.0% C, 9.6% ash
	Unburned C in ash: 0.0%
	Sorbent: limestone, 35.4% Ca
	Coal flow: app 90.3 Klb/hr
	Sorbent flow: app 39.5 Klb/hr
	Ca/S: 3.6
	SO2 removal: 95.8%

APPENDIX D

Table D1. ASTM leachate analysis.

SAMPLE	Al mg/L	As* mg/L	B mg/L	Ba mg/L	Be mg/L	Ca mg/L	Cd* mg/L	Co mg/L	Cr mg/L	Cu mg/L	Fe mg/L
BEV-DUC-02	<0.05	<0.005	2.33	0.14	<0.002	1073.6	<0.001	0.01	0.026	<0.009	<0.01
BEV-DUC-05	<0.11	<0.08	4.06	0.39	0.004	1015.5	0.004	<0.01	0.027	0.012	<0.01
BRG-SNR-01	<0.05	<0.08	0.35	0.19	-	1125.9	0.003	-	<0.004	<0.007	0.016
EDG-CLS-01	<0.11	<0.08	7.50	0.49	<0.002	1190.2	0.001	<0.01	0.014	<0.009	<0.01
EDG-LIM-06	<0.11	<0.08	12.80	0.28	<0.002	1932.5	0.001	0.01	0.017	0.013	0.03
EDG-LIM-07	<0.11	<0.08	10.79	0.31	<0.002	1826.2	<0.003	0.02	0.015	<0.009	0.01
EDG-LIM-14	<0.05	<0.005	3.93	0.23	<0.002	1841.6	<0.003	0.01	<0.011	<0.009	<0.01
GMC-FLB-01	0.13	<0.08	0.94	0.43	<0.002	1644.6	<0.003	<0.01	<0.011	<0.009	<0.01
GMC-FLB-02	<0.11	<0.08	1.65	0.32	<0.002	1774.2	<0.003	<0.01	<0.011	<0.009	<0.01
GMC-FLB-03	<0.05	<0.005	1.01	0.31	<0.002	1539.9	<0.001	<0.01	<0.011	<0.009	<0.01
HST-SPD-01	0.68	<0.08	3.99	0.24	0.002	428.4	<0.003	<0.01	0.066	<0.009	<0.01
HST-SPD-02	0.13	<0.08	3.60	0.36	<0.002	647.3	<0.003	<0.01	0.059	<0.009	<0.01
HST-SPD-03	<0.11	<0.08	3.89	0.37	<0.002	994.5	<0.003	<0.01	0.083	<0.009	<0.01
HST-SPD-04	<0.11	<0.08	2.58	0.32	<0.002	925.4	<0.003	<0.01	0.070	<0.009	<0.01
HST-SPD-05	0.11	<0.08	4.19	0.42	<0.002	823.1	<0.003	<0.01	0.077	<0.009	<0.01
OSU-SPD-03	<0.05	<0.005	5.15	0.29	<0.002	1193.4	<0.001	0.01	<0.011	<0.009	<0.01
OSU-SPD-05	<0.11	<0.08	5.95	0.25	<0.002	1200.9	<0.003	0.02	0.026	<0.009	0.02
PED-RCB-01	<0.11	<0.08	0.08	0.42	0.007	1754.4	0.007	<0.01	<0.011	<0.009	0.02
QST-FLB-02	<0.11	<0.08	0.16	0.25	<0.002	1314.0	<0.003	<0.01	<0.011	<0.009	0.01
QST-FLB-03	<0.11	<0.08	0.11	0.23	<0.002	1643.2	<0.003	<0.01	<0.011	<0.009	0.01
TID-FLB-03	<0.05	<0.005	0.83	0.17	<0.002	844.4	<0.001	0.02	<0.011	<0.009	<0.01
TID-FLB-04	<0.05	<0.005	0.21	0.20	<0.002	1139.6	<0.001	<0.01	<0.011	<0.009	<0.01
TID-FLB-05	<0.11	0.080	1.15	0.11	<0.002	558.7	<0.003	0.02	0.020	<0.009	0.02
TVA-FLB-03	<0.11	<0.08	0.19	0.16	<0.002	1620.2	<0.003	<0.01	0.024	<0.009	0.01

Table D1. continued.

SAMPLE	Hg*	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
BEV-DUC-02	<0.0002	3.94	0.15	<0.04	<0.053	0.073	4.77	<0.01	<0.11	<0.001	127.2
BEV-DUC-05	<0.04	10.08	0.31	<0.04	<0.053	0.206	9.31	<0.01	<0.11	<0.093	112.9
BRG-SNR-01	<0.04	19.92	-	4.11	<0.001	-	4.05	<0.01	<0.11	<0.040	737.9
EDG-CLS-01	<0.04	18.99	0.19	<0.04	<0.053	0.980	612.78	<0.01	<0.11	<0.093	306.1
EDG-LIM-06	<0.04	2.64	0.12	0.07	<0.053	0.559	2.27	<0.01	<0.11	<0.093	639.9
EDG-LIM-07	<0.04	2.22	0.09	<0.04	<0.053	0.314	1.67	<0.01	<0.11	<0.093	676.9
EDG-LIM-14	<0.0002	1.60	0.05	0.07	<0.053	0.101	1.13	<0.01	<0.11	<0.001	740.7
GMC-FLB-01	<0.04	<0.23	0.02	0.15	<0.053	0.129	0.31	<0.01	<0.11	<0.093	666.9
GMC-FLB-02	<0.04	2.40	0.05	<0.04	<0.053	0.175	1.17	<0.01	<0.11	<0.093	675.4
GMC-FLB-03	<0.0002	1.78	0.04	0.06	<0.053	0.183	2.46	<0.01	<0.11	<0.001	638.4
HST-SPD-01	<0.04	4.59	0.08	0.05	<0.053	0.091	6.21	<0.01	<0.11	<0.093	89.1
HST-SPD-02	<0.04	3.49	0.06	<0.04	<0.053	0.062	5.18	<0.01	<0.11	<0.093	65.2
HST-SPD-03	<0.04	3.98	0.08	<0.04	<0.053	0.046	6.34	<0.01	<0.11	<0.093	78.3
HST-SPD-04	<0.04	3.55	0.05	<0.04	<0.053	0.031	4.75	<0.01	<0.11	<0.093	43.7
HST-SPD-05	<0.04	3.16	0.07	<0.04	<0.053	0.064	4.29	<0.01	<0.11	<0.093	84.3
OSU-SPD-03	<0.0002	21.72	0.08	<0.04	<0.053	0.091	3.51	<0.01	<0.11	0.012	201.2
OSU-SPD-05	<0.04	18.84	0.09	0.71	<0.053	0.140	3.65	<0.01	<0.11	<0.093	187.6
PED-RCB-01	<0.04	9.14	0.09	<0.04	<0.053	<0.018	0.45	<0.01	<0.11	<0.093	538.8
QST-FLB-02	<0.04	<0.23	0.01	<0.04	<0.053	0.049	<0.08	<0.01	<0.11	<0.093	395.7
QST-FLB-03	<0.04	1.72	0.02	1.31	<0.053	0.016	<0.08	<0.01	<0.11	<0.093	549.5
TID-FLB-03	<0.0002	21.68	0.13	0.19	<0.053	0.033	8.26	<0.01	<0.11	<0.001	654.3
TID-FLB-04	<0.0002	3.43	<0.030	0.09	<0.053	0.035	1.26	<0.01	<0.11	<0.001	641.7
TID-FLB-05	<0.04	231.64	1.20	1349.70	<0.053	0.190	107.29	<0.01	<0.11	<0.093	1972.8
TVA-FLB-03	<0.04	1.38	0.02	0.05	<0.053	0.051	<0.08	<0.01	<0.11	<0.093	539.4

Table D1. continued.

SAMPLE	Sb mg/L	Se* mg/L	Si mg/L	Sr mg/L	V mg/L	Zn mg/L	Cl mg/L	F mg/L	SO3 mg/L	SO4 mg/L	pH	TDS mg/L
BEV-DUC-02	<0.06	0.021	<0.072	2.56	<0.006	<0.006	42.2	4.0	23.2	233.3	12.22	2916
BEV-DUC-05	<0.06	<0.27	1.359	1.94	<0.029	<0.006	68.9	3.5	31.2	243.1	10.66	2676
BRG-SNR-01	-	<0.27	<0.024	1.52	-	<0.005	65.2	1.8	63.8	1214.3	12.20	-
EDG-CLS-01	<0.06	<0.27	0.540	1.05	<0.029	0.008	543.2	5.6	47.9	806.0	10.84	4838
EDG-LIM-06	<0.06	<0.27	0.119	2.80	0.034	0.017	102.5	3.6	<1.0	1924.2	10.44	-
EDG-LIM-07	<0.06	<0.27	0.130	3.00	0.034	0.016	84.6	3.6	<1.0	1924.2	10.48	-
EDG-LIM-14	<0.06	<0.005	0.122	2.58	<0.006	<0.006	54.4	3.4	31.3	1871.7	12.14	4830
GMC-FLB-01	<0.06	<0.27	0.094	0.68	<0.029	0.006	1.7	1.0	<1.0	1801.0	11.83	4870
GMC-FLB-02	<0.06	<0.27	0.167	1.29	0.031	0.006	17.4	3.0	<1.0	1822.8	11.10	5065
GMC-FLB-03	<0.06	<0.005	0.197	1.04	<0.006	<0.006	19.9	2.9	<1.0	1479.9	12.01	4825
HST-SPD-01	<0.06	<0.27	3.984	1.09	<0.029	<0.006	299.0	12.0	41.7	157.1	11.68	1642
HST-SPD-02	<0.06	<0.27	1.035	1.57	<0.029	<0.006	141.2	4.1	35.4	128.8	12.23	1908
HST-SPD-03	<0.06	<0.27	0.992	2.14	<0.029	<0.006	180.3	3.5	33.3	152.3	12.53	2508
HST-SPD-04	<0.06	<0.27	0.341	1.66	<0.029	<0.006	102.1	2.2	29.2	68.4	12.56	2190
HST-SPD-05	<0.06	<0.27	0.713	1.88	<0.029	<0.006	84.6	3.0	20.8	202.4	12.44	2198
OSU-SPD-03	<0.06	<0.005	0.125	2.35	<0.006	0.007	40.5	2.5	35.7	443.5	12.26	3516
OSU-SPD-05	<0.06	<0.27	0.152	2.62	<0.029	0.025	38.1	2.2	25.0	485.5	10.53	3194
PED-RCB-01	<0.06	<0.27	0.307	5.22	0.037	<0.006	10.8	3.2	<1.0	1255.0	12.64	5039
QST-FLB-02	<0.06	<0.27	0.615	3.94	<0.029	0.008	10.2	2.5	<1.0	860.5	10.45	3626
QST-FLB-03	<0.06	<0.27	0.107	7.42	<0.029	0.006	5.7	2.2	<1.0	1122.0	10.55	4581
TID-FLB-03	<0.06	<0.005	1.261	0.66	<0.006	<0.006	7.9	2.8	<1.0	1698.7	11.42	3136
TID-FLB-04	<0.06	<0.005	0.337	0.61	<0.006	<0.006	3.2	2.3	<1.0	1569.0	11.77	5154
TID-FLB-05	<0.06	0.30	3.076	2.03	0.043	0.017	3.9	5.4	<1.0	5887.2	8.44	9044
TVA-FLB-03	<0.06	<0.27	0.220	3.76	<0.029	0.009	1.5	2.8	<1.0	1246.0	10.48	4603

Table D2. Means and relative standard deviations of ASTM and TCLP leachates

ASTM Leachates

Sample	Al	As*	B	Ba	Ca	Cd*	Co	Cr	Cu	Fe	Hg*	K	Li
BEV-DUC-02	<0.110	<0.08	2.35	0.130	1067.2	<0.003	<0.01	0.020	<0.009	<0.010	<0.04	3.96	0.146
BEV-DUC-02	<0.110	<0.08	2.36	0.150	1083.9	<0.003	<0.01	0.027	<0.009	<0.010	<0.04	4.85	0.151
BEV-DUC-02	<0.110	<0.005	2.33	0.136	1073.6	<0.001	0.011	0.026	<0.009	<0.010	<0.0002	3.94	0.145
mean			2.35	0.139	1074.9			0.024				4.25	0.147
rsd (%)**			0.48	5.88	0.64			12.14				10.02	1.57
OSU-SPD-03	<0.110	<0.08	5.25	0.303	1251.3	<0.003	<0.01	<0.011	<0.009	<0.010	<0.04	23.15	0.085
OSU-SPD-03	<0.110	<0.08	5.46	0.330	1177.0	<0.003	<0.01	<0.011	<0.009	<0.010	<0.04	23.39	0.090
OSU-SPD-03	<0.110	<0.005	5.15	0.292	1193.4	<0.001	0.013	<0.011	<0.009	<0.010	<0.0002	21.72	0.085
mean			5.29	0.308	1207.2							22.75	0.086
rsd (%)			2.46	5.25	2.64							3.25	2.65
EDG-LIM-14	0.141	<0.08	4.38	0.233	1795.2	<0.003	<0.01	<0.011	<0.009	<0.010	<0.04	1.69	0.044
EDG-LIM-14	<0.110	<0.08	3.75	0.242	1825.9	<0.003	<0.01	<0.011	<0.009	<0.010	<0.04	1.46	0.045
EDG-LIM-14	<0.110	<0.005	3.93	0.231	1841.6	<0.001	0.010	<0.011	<0.009	<0.010	<0.0002	1.60	0.045
mean			4.02	0.236	1820.9							1.59	0.045
rsd (%)			6.61	2.06	1.06							5.95	0.97
TID-FLB-03	<0.110	<0.08	1.11	0.248	907.0	<0.003	<0.01	0.012	<0.009	<0.010	<0.04	28.95	0.186
TID-FLB-03	<0.110	<0.08	1.14	0.252	926.9	<0.003	<0.01	0.013	<0.009	<0.010	<0.04	29.84	0.177
TID-FLB-03	<0.110	<0.005	0.83	0.166	844.4	<0.001	0.017	<0.011	<0.009	<0.010	<0.0002	21.68	0.133
mean			1.03	0.222	892.8			0.013				26.82	0.165
rsd (%)			13.43	17.79	3.93			0.32				13.62	13.86
TID-FLB-04	<0.110	<0.08	0.18	0.185	1245.0	<0.003	<0.01	<0.011	<0.009	0.013	<0.04	3.02	0.023
TID-FLB-04	<0.110	<0.08	0.17	0.197	1287.2	<0.003	<0.01	<0.011	<0.009	<0.010	<0.04	3.30	0.012
TID-FLB-04	<0.110	<0.005	0.21	0.202	1139.6	<0.001	<0.01	<0.011	<0.009	<0.010	<0.0002	3.43	<0.030
mean			0.18	0.195	1223.9							3.25	0.018
rsd (%)			9.83	3.79	5.07							5.21	32.14
TID-FLB-05	<0.110	<0.08	1.16	0.083	567.1	<0.003	<0.01	<0.011	<0.009	0.029	<0.04	223.55	1.170
TID-FLB-05	<0.110	0.080	1.15	0.108	558.7	<0.003	0.016	0.020	<0.009	0.019	<0.04	231.64	1.200
mean			1.15	0.095	562.9							227.60	1.185
rsd (%)			0.41	13.42	0.75							1.78	1.26
HST-SPD-05	0.113	<0.08	4.19	0.424	823.1	<0.003	<0.01	<0.011	<0.009	<0.010	<0.04	3.16	0.069
HST-SPD-05	0.134	<0.08	4.98	0.464	820.9	<0.003	0.014	<0.011	0.012	0.013	<0.04	3.21	0.071
mean	0.123		4.58	0.444	822.0							3.18	0.070
rsd (%)	8.47		8.56	4.56	0.13							0.72	1.69

Table D2. continued.

ASTM Leachates

Sample	Mg	Mn	Mo	Na	Ni	P	S	Sb	Se*	Si	Sr	V	Zn
BEV-DUC-02	<0.053	<0.053	0.063	4.62	<0.010	<0.108	104.5	<0.060	<0.266	0.103	2.503	<0.029	<0.006
BEV-DUC-02	0.079	<0.053	0.060	5.03	0.013	<0.108	119.7	<0.060	<0.266	0.175	2.564	<0.029	0.010
BEV-DUC-02	<0.053	<0.053	0.073	4.77	<0.010	<0.108	127.2	<0.060	<0.005	<0.072	2.555	<0.029	<0.006
mean			0.066	4.81			117.2			0.139	2.541		
rsd (%)**			8.61	3.48			8.07			25.66	1.06		
OSU-SPD-03	<0.053	<0.053	0.110	3.93	<0.010	<0.108	215.1	<0.060	<0.266	0.250	2.795	<0.029	<0.006
OSU-SPD-03	<0.053	<0.053	0.097	3.82	<0.010	<0.108	195.5	<0.060	<0.266	0.202	2.501	<0.029	0.008
OSU-SPD-03	<0.053	<0.053	0.091	3.51	<0.010	<0.108	201.2	<0.060	<0.005	0.125	2.350	<0.029	0.007
mean			0.099	3.75			203.9			0.193	2.549		0.007
rsd (%)			7.96	4.74			4.03			26.77	7.25		4.26
EDG-LIM-14	0.030	<0.053	0.107	1.30	<0.010	<0.108	664.2	<0.060	<0.266	0.256	2.597	0.043	<0.006
EDG-LIM-14	0.019	<0.053	0.104	1.73	<0.010	<0.108	675.0	<0.060	<0.266	0.207	2.630	0.034	<0.006
EDG-LIM-14	0.073	<0.053	0.101	1.13	<0.010	<0.108	740.7	<0.060	<0.005	0.122	2.579	<0.029	<0.006
mean	0.041		0.104	1.38			693.3			0.195	2.602	0.039	
rsd (%)	57.21		2.52	18.13			4.88			28.44	0.81	11.08	
TID-FLB-03	0.171	<0.053	0.046	11.37	<0.010	<0.108	587.6	<0.060	<0.266	2.144	0.855	<0.029	<0.006
TID-FLB-03	0.173	<0.053	0.035	11.59	<0.010	<0.108	660.7	<0.060	<0.266	2.544	0.880	<0.029	<0.006
TID-FLB-03	0.190	<0.053	0.033	8.26	<0.010	<0.108	654.3	<0.060	<0.005	1.261	0.657	<0.029	<0.006
mean	0.178		0.038	10.41			634.2			1.983	0.797		
rsd (%)	4.65		15.31	14.65			5.21			27.02	12.47		
TID-FLB-04	0.174	<0.053	0.048	1.10	<0.010	<0.108	596.5	<0.060	<0.266	0.552	0.590	<0.029	<0.006
TID-FLB-04	0.127	<0.053	0.041	0.70	<0.010	<0.108	621.8	<0.060	<0.266	0.596	0.617	<0.029	<0.006
TID-FLB-04	0.092	<0.053	0.035	1.26	<0.010	<0.108	641.7	<0.060	<0.005	0.337	0.615	<0.029	<0.006
mean	0.131		0.041	1.02			620.0			0.495	0.607		
rsd (%)	25.63		12.93	22.93			2.99			22.84	1.99		
TID-FLB-05	1338.1	<0.053	0.191	101.44	<0.010	<0.108	1800.8	<0.060	<0.266	4.318	2.286	<0.029	<0.006
TID-FLB-05	1349.7	<0.053	0.190	107.29	<0.010	<0.108	1972.8	<0.060	0.301	3.076	2.027	0.043	0.017
mean	1343.9		0.190	104.36			1886.8			3.697	2.156		
rsd (%)	0.43		0.15	2.80			4.56			16.79	6.01		
HST-SPD-05	<0.053	<0.053	0.064	4.29	<0.010	<0.108	84.3	<0.060	<0.266	0.713	1.880	<0.029	<0.006
HST-SPD-05	<0.053	<0.053	0.094	4.82	<0.010	<0.108	96.8	<0.060	<0.266	0.519	2.106	<0.029	0.016
mean			0.079	4.55			90.6			0.616	1.993		
rsd (%)			19.19	5.81			6.92			15.70	5.65		

Table D2. continued.

TCLP Leachates

Sample	Al	As*	B	Ba	Ca	Cd*	Co	Cr	Cu	Fe	Hg*	K	Li
EDG-LIM-14	0.196	<0.005	3.46	0.250	3858.0	<0.003	0.017	0.007	<0.013	<0.029	<0.0002	1.32	0.044
EDG-LIM-14	0.187	<0.084	4.19	0.250	3957.5	<0.003	0.009	<0.005	<0.013	<0.029	<0.07	1.52	0.030
mean	0.191		3.83	0.250	3907.8		0.013					1.42	0.037
rsd (%)**	2.25		9.67	0.05	1.27		30.70					6.91	18.82
TID-FLB-03	0.118	<0.005	0.77	0.141	1382.8	<0.003	0.026	0.011	<0.013	<0.029	<0.0002	21.13	0.178
TID-FLB-03	0.057	<0.084	0.73	0.110	1408.2	<0.003	0.004	<0.005	<0.013	<0.029	<0.07	23.42	0.170
mean	0.087		0.75	0.125	1395.5		0.015					22.28	0.174
rsd (%)	35.29		2.78	12.38	0.91		71.90					5.13	2.23
TID-FLB-04	0.145	<0.005	0.54	0.141	1741.1	<0.003	0.017	<0.005	<0.013	<0.029	<0.0002	3.01	0.073
TID-FLB-04	0.042	<0.084	0.67	0.145	1897.1	<0.003	0.002	<0.005	<0.013	<0.029	<0.07	3.76	0.049
mean	0.093		0.60	0.143	1819.1		0.010					3.38	0.061
rsd (%)	55.14		10.14	1.50	4.29		75.72					11.13	19.83

SAMPLE	Mg	Mn	Mo	Na	Ni	P	S	Sb	Se*	Si	Sr	V	Zn
EDG-LIM-14	0.07	<0.001	0.103	1.32	<0.011	<0.12	581.5	<0.241	0.005	0.095	2.55	0.021	<0.006
EDG-LIM-14	0.05	<0.001	0.097	1.39	<0.011	<0.12	660.8	<0.241	<0.294	0.140	2.62	0.043	<0.006
mean	0.06		0.100	1.35			621.1			0.118	2.59	0.032	
rsd (%)	17.58		2.82	2.60			6.38			19.07	1.38	33.39	
TID-FLB-03	1351.8	<0.001	0.025	9.82	<0.011	<0.12	979.0	<0.241	<0.001	0.331	1.21	0.022	<0.006
TID-FLB-03	1347.2	<0.001	0.018	10.09	<0.011	<0.12	1014.7	<0.241	<0.294	0.267	1.27	0.016	<0.006
mean	1349.5		0.021	9.95			996.8			0.299	1.24	0.019	
rsd (%)	0.17		16.83	1.34			1.79			10.69	2.70	16.96	
TID-FLB-04	881.5	<0.001	0.031	1.67	<0.011	<0.12	736.6	<0.241	0.001	0.313	0.83	0.024	<0.006
TID-FLB-04	737.2	<0.001	0.031	1.98	<0.011	<0.12	723.7	<0.241	<0.294	0.289	0.88	0.027	<0.006
mean	809.36		0.031	1.82			730.2			0.301	0.86	0.026	
rsd (%)	8.92		0.50	8.60			0.89			3.88	2.60	5.49	

*Analysis by graphite furnace AA

**Relative standard deviation

Table D3. Eh, pH, specific conductance, inorganic carbon and solution chemistry of long-term equilibration samples.

SAMPLE	Time (days)	Eh (mV)	pH	SC*	IC** (mg/L)	Cl (mg/L)	SO4 (mg/L)	S03 (mg/L)	Al (mg/L)	B (mg/L)	Ba (mg/L)	Ca (mg/L)	Cr (mg/L)	Co (mg/L)
OSU-SPD-03														
A	1	106	11.2	9.1	3.2	109	1170	18	0.17	5.18	0.19	1737	0.04	<0.014
A	7	182	11.9	9.8	1.5	132	1163	12	0.19	9.47	0.12	1760	0.02	0.04
A	21	94	12.6	8.4	3.3	141	1246	12	0.09	8.78	0.15	1599	0.02	0.03
A	36	119	12.6	8.2	2.1	131	1131	12	0.11	6.62	0.18	1395	0.02	<0.014
A	56	147	13.0	8.4	3.1	149	987	16	0.08	4.81	0.56	1387	0.01	0.02
A	70	152	11.5	7.6	4.0	125	847	17	0.09	2.15	0.58	1331	<0.004	<0.014
A	84	156	12.0	7.9	2.2	126	763	14	0.06	1.06	0.31	1140	0.02	0.02
A	112	189	12.0	8.5	3.1	137	616	9	<0.050	0.38	0.35	1042	0.01	0.02
B	1	158	11.6	9.4	9.4	112	1159	30	0.18	4.80	0.20	1793	0.04	<0.014
B	7	181	11.1	9.4	1.4	135	1206	12	0.12	9.50	0.33	1716	0.02	<0.014
B	21	131	12.6	8.4	1.8	140	1234	12	<0.050	8.83	0.16	1586	0.02	0.02
B	36	130	12.6	8.6	2.1	123	1106	13	0.06	6.54	0.27	1384	0.02	<0.014
B	56	143	13.0	8.7	4.1	177	983	16	0.11	5.43	0.58	1400	0.01	<0.014
B	70	156	11.4	8.3	2.7	123	836	17	0.13	2.11	0.55	1275	0.01	<0.014
B	84	160	11.6	8.9	2.2	124	732	14	0.02	1.05	0.23	1152	0.02	0.02
B	112	208	12.1	8.1	4.2	133	581	9	0.06	0.40	0.37	1065	0.00	<0.014
BEV-DUC-02														
A	1	169	11.8	8.8	3.0	126	448	12	0.07	2.53	0.15	1320	0.04	<0.014
A	7	185	11.1	8.9	1.4	150	468	8	0.07	3.70	0.30	1443	0.07	<0.014
A	21	177	12.6	7.5	2.0	154	272	10	<0.050	1.31	0.61	1246	0.08	0.03
A	36	146	12.6	7.9	2.2	153	73	10	0.07	0.19	1.21	1005	0.05	<0.014
A	56	146	12.9	7.6	6.2	148	NA	9	0.21	0.57	1.82	962	0.02	<0.014
A	70	156	11.7	7.6	2.4	144	5	16	0.23	0.03	2.14	935	0.01	<0.014
A	84	136	12.3	8.1	1.0	NA	4	11	0.14	0.04	2.01	772	0.03	0.02
A	112	202	12.0	8.2	3.2	121	7	9	0.22	0.02	2.13	634	0.00	<0.014

Table D3. continued

SAMPLE	Time (days)	Eh (mV)	pH	SC*	IC** (mg/L)	Cl (mg/L)	SO4 (mg/L)	S03 (mg/L)	Al (mg/L)	B (mg/L)	Ba (mg/L)	Ca (mg/L)	Cr (mg/L)	Co (mg/L)
BEV-DUC-02														
B	1	177	12.0	8.8	2.6	123	451	10	0.13	2.70	0.18	1344	0.04	<0.014
B	7	188	11.2	8.6	1.5	141	464	8	<0.050	3.58	0.31	1381	0.05	0.03
B	21	178	12.6	7.6	1.4	154	258	10	0.06	1.16	0.68	1234	0.08	0.02
B	36	180	12.6	7.9	1.5	147	70	11	0.05	0.18	1.16	1002	0.05	<0.014
B	56	149	12.7	7.6	4.1	158	8	12	0.50	0.62	1.81	972	0.02	0.02
B	70	157	11.5	7.5	3.2	140	5	16	0.23	0.00	2.20	960	0.01	<0.014
B	84	156	12.2	8.1	3.2	137	5	16	0.12	0.03	2.01	755	0.02	<0.014
B	112	206	12.1	8.3	1.8	130	7	7	0.21	0.01	2.12	633	0.00	<0.014
EDG-LIM-14														
A	1	174	12.0	10.2	1.5	225	2017	15	0.11	7.44	0.23	2117	0.03	0.02
A	7	193	11.2	9.3	2.2	256	1481	6	<0.050	4.37	0.36	1833	<0.004	0.04
A	21	176	12.6	8.0	1.5	249	1273	<0.1	0.11	0.04	0.16	1547	<0.004	0.04
A	36	195	12.6	8.6	1.8	221	1257	<0.1	0.10	0.07	0.18	1370	0.01	<0.014
A	56	149	12.7	9.1	3.9	261	1307	<0.1	0.14	0.15	0.17	1340	<0.004	0.02
A	70	159	11.7	8.7	2.7	168	1395	<0.1	0.06	0.13	0.19	1363	<0.004	<0.014
A	84	152	12.1	9.6	2.6	186	1356	<0.1	<0.050	0.04	0.16	1175	0.02	0.02
A	112	206	12.0	10.0	2.6	229	1580	<0.1	<0.050	0.00	0.15	1069	<0.004	<0.014
B	1	183	12.0	9.3	1.8	225	1991	15	0.13	7.36	0.08	1972	0.03	<0.014
B	7	195	11.3	9.5	1.3	237	1461	6	<0.050	4.47	0.08	1751	<0.004	<0.014
B	21	179	12.6	8.3	2.5	257	1285	<0.1	0.08	0.03	0.16	1592	<0.004	<0.014
B	36	192	12.5	8.6	1.7	227	1349	<0.1	0.08	0.03	0.18	1383	0.01	<0.014
B	56	90	12.9	9.1	1.9	234	1249	<0.1	0.17	0.11	0.18	1350	<0.004	0.02
B	70	162	11.7	8.6	1.8	206	1374	<0.1	0.12	0.00	0.17	1317	0.00	0.00
B	84	154	11.8	9.8	2.0	214	1366	<0.1	<0.050	0.02	0.16	1198	0.02	0.02
B	112	211	12.0	9.3	2.7	220	1542	<0.1	<0.050	0.01	0.14	1090	<0.004	<0.014

Table D3. continued

SAMPLE	Time (days)	Eh (mV)	pH	SC*	IC** (mg/L)	Cl (mg/L)	SO4 (mg/L)	S03 (mg/L)	Al (mg/L)	B (mg/L)	Ba (mg/L)	Ca (mg/L)	Cr (mg/L)	Co (mg/L)
TID-FLB-03														
A	1	183	11.0	3.7	2.2	29	1945	<0.1	0.08	1.07	0.08	1059	0.05	<0.014
A	7	147	11.4	4.9	1.3	30	1761	<0.1	<0.050	1.68	0.15	1037	0.00	0.02
A	21	167	11.8	3.5	1.2	31	1859	<0.1	0.19	1.65	0.17	729	0.01	0.02
A	36	225	11.4	3.5	1.5	32	1848	<0.1	0.36	1.22	0.14	629	0.01	<0.014
A	56	210	11.5	3.3	1.3	26	1903	<0.1	0.38	0.89	0.13	613	<0.004	<0.014
A	70	228	10.6	3.2	1.8	26	1998	<0.1	0.28	0.63	0.14	607	<0.004	<0.014
A	84	237	10.6	3.6	1.2	29	1983	<0.1	0.11	0.61	0.11	544	0.01	<0.014
A	112	303	9.9	3.6	2.1	32	2171	<0.1	0.18	0.71	0.10	528	<0.004	<0.014
B	1	165	11.1	3.8	1.8	33	1967	<0.1	<0.050	0.98	0.07	1103	0.04	<0.014
B	7	164	11.6	5.0	1.4	28	1795	<0.1	<0.050	1.83	0.18	1017	<0.004	<0.014
B	21	165	11.8	3.5	1.7	32	1823	<0.1	0.10	1.64	0.16	713	0.01	<0.014
B	36	261	11.4	3.4	1.4	33	1875	<0.1	0.30	1.17	0.13	617	0.01	<0.014
B	56	203	11.5	3.2	1.5	28	1863	<0.1	0.46	1.10	0.14	622	<0.004	<0.014
B	70	241	10.5	3.2	1.3	41	2004	<0.1	0.30	0.59	0.14	631	<0.004	<0.014
B	84	239	10.5	3.6	1.5	31	2166	<0.1	0.30	0.76	0.12	543	<0.004	<0.014
B	112	304	10.1	3.6	1.5	38	2131	<0.1	0.12	0.57	0.08	505	<0.004	<0.014
TID-FLB-04														
A	1	100	11.1	2.8	1.2	15	479	<0.1	0.10	0.15	0.11	450	0.04	<0.014
A	7	5	11.8	6.3	1.7	4	1160	<0.1	<0.050	0.31	0.16	1137	<0.004	0.03
A	21	123	12.6	7.1	1.3	24	1527	<0.1	0.06	0.45	0.18	1499	<0.004	<0.014
A	36	109	12.5	7.7	1.2	30	1393	<0.1	0.08	0.54	0.14	1425	<0.004	<0.014
A	56	88	12.8	8.1	2.4	28	1283	<0.1	0.16	0.38	0.09	1393	<0.004	<0.014
A	70	116	12.8	7.3	2.1	25	1302	<0.1	<0.050	0.11	0.07	1420	<0.004	<0.014
A	84	148	12.2	7.6	2.4	27	1270	<0.1	0.05	0.10	0.05	1272	<0.004	<0.014
A	112	213	12.0	7.2	2.0	30	1291	<0.1	<0.050	0.06	0.05	1134	<0.004	<0.014

Table D3. continued

SAMPLE	Time (days)	Eh (mV)	pH	SC*	IC** (mg/L)	Cl (mg/L)	SO4 (mg/L)	S03 (mg/L)	Al (mg/L)	B (mg/L)	Ba (mg/L)	Ca (mg/L)	Cr (mg/L)	Co (mg/L)
TID-FLB-04														
B	1	101	11.2	2.7	0.9	13	440	<0.1	0.09	0.14	0.12	465	0.03	<0.014
B	7	13	11.7	6.5	1.3	4	1202	<0.1	0.08	0.32	0.13	1177	<0.004	0.02
B	21	119	12.5	8.0	1.4	28	1684	<0.1	0.07	0.47	0.17	1470	<0.004	<0.014
B	36	183	12.5	7.5	1.5	24	1948	<0.1	0.06	0.48	0.11	1328	<0.004	<0.014
B	56	129	12.6	7.8	2.1	12	3183	<0.1	0.14	0.22	0.09	1391	<0.004	<0.014
B	70	122	12.5	7.4	2.2	27	1211	<0.1	0.06	0.08	0.08	1400	<0.004	<0.014
B	84	156	11.7	7.2	3.6	26	1254	<0.1	0.10	0.17	0.08	1216	<0.004	<0.014
B	112	210	11.7	7.0	3.1	31	1302	<0.1	0.09	0.13	0.06	1110	<0.004	<0.014
TID-FLB-MIX														
A	1	161	10.9	3.4	2.5	23	1649	<0.1	0.15	0.73	0.08	905	0.05	<0.014
A	7	115	11.4	5.3	3.2	5	1614	<0.1	<0.050	1.40	0.14	1071	<0.004	0.02
A	21	210	12.0	3.8	1.4	29	1739	<0.1	0.09	1.26	0.16	811	<0.004	<0.014
A	36	215	11.6	3.4	1.4	36	1735	<0.1	0.17	1.05	0.12	675	<0.004	<0.014
A	56	187	11.5	3.6	2.3	43	1799	<0.1	0.26	0.82	1.21	638	<0.004	<0.014
A	70	205	11.3	3.3	2.4	53	1818	<0.1	0.09	0.18	0.11	625	<0.004	<0.014
A	84	233	10.1	3.4	2.4	33	1969	<0.1	0.07	0.07	0.12	571	<0.004	<0.014
A	112	289	10.4	3.6	2.4	36	2070	<0.1	0.11	0.12	0.09	511	0.01	<0.014
B	1	163	10.9	3.5	2.2	24	1661	<0.1	0.05	0.72	0.08	914	0.04	<0.014
B	7	167	11.3	4.7	1.7	5	1636	<0.1	0.05	1.09	0.10	998	<0.004	<0.014
B	21	216	12.0	3.8	1.1	29	1756	<0.1	0.12	1.31	0.18	860	0.02	<0.014
B	36	218	11.6	3.4	1.1	31	1825	<0.1	0.14	0.80	0.14	658	<0.004	<0.014
B	56	200	11.4	3.2	2.4	36	1780	<0.1	0.23	0.45	0.15	629	<0.004	<0.014
B	70	206	11.2	3.2	2.4	48	1882	<0.1	0.08	0.11	0.11	645	<0.004	<0.014
B	84	233	10.2	3.3	3.5	36	1962	<0.1	<0.050	0.07	0.11	583	0.01	<0.014
B	112	301	10.3	3.3	1.2	41	2003	<0.1	0.07	0.13	0.09	509	0.01	<0.014

Table D3. continued

SAMPLE	Fe (mg/L)	K (mg/L)	Li (mg/L)	Mg (mg/L)	Mn (mg/L)	Mo (mg/L)	Na (mg/L)	Ni (mg/L)	P (mg/L)	S (mg/L)	Si (mg/L)	Sr (mg/L)	Zn (mg/L)
OSU-SPD-03													
A	<0.029	69	0.13	<0.043	<0.001	0.21	9	<0.011	<0.109	431	0.17	3.6	0.16
A	<0.029	103	0.28	<0.043	<0.001	0.29	17	<0.011	<0.109	454	0.21	6.5	0.02
A	0.09	138	0.46	0.08	0.032	0.33	23	<0.011	<0.109	469	0.22	9.8	2.92
A	<0.029	156	0.64	<0.043	<0.001	0.27	26	<0.011	<0.109	411	0.23	10.9	0.01
A	0.03	189	0.91	<0.043	<0.001	0.21	31	<0.011	<0.109	385	0.20	12.9	0.06
A	<0.029	227	1.11	<0.043	<0.001	0.19	35	<0.011	<0.109	332	0.15	13.9	<0.006
A	<0.029	237	1.19	<0.043	0.006	0.20	36	<0.011	<0.109	296	0.17	12.5	0.06
A	<0.029	278	1.41	<0.043	0.003	0.17	42	<0.011	<0.109	240	0.21	11.8	0.01
B	<0.029	61	0.12	<0.043	<0.001	0.19	8	<0.011	<0.109	421	0.20	3.2	0.03
B	<0.029	101	0.28	<0.043	<0.001	0.30	17	<0.011	<0.109	444	0.19	6.6	0.02
B	<0.029	139	0.48	<0.043	<0.001	0.30	23	<0.011	0.12	462	0.21	10.0	0.04
B	<0.029	151	0.62	<0.043	<0.001	0.29	25	<0.011	0.25	404	0.20	10.8	<0.006
B	<0.029	188	0.91	<0.043	<0.001	0.23	30	<0.011	<0.109	389	0.25	13.0	0.04
B	<0.029	218	1.06	<0.043	<0.001	0.20	34	<0.011	<0.109	327	0.17	13.2	<0.006
B	<0.029	237	1.18	<0.043	0.005	0.20	36	<0.011	<0.109	302	0.14	12.5	0.09
B	<0.029	306	1.58	<0.043	0.001	0.18	46	<0.011	<0.109	235	0.18	12.8	0.01
BEV-DUC-02													
A	<0.029	12	0.29	<0.043	<0.001	0.10	14	<0.011	<0.109	185	0.12	2.6	0.01
A	<0.029	20	0.47	<0.043	<0.001	0.17	20	<0.011	0.25	226	0.20	5.2	0.01
A	<0.029	43	0.78	<0.043	<0.001	0.19	27	<0.011	0.20	145	0.23	9.1	0.02
A	<0.029	75	1.13	<0.043	<0.001	0.13	35	<0.011	0.31	54	0.28	11.0	<0.006
A	<0.029	134	1.80	<0.043	<0.001	0.11	56	<0.011	<0.109	42	0.57	13.9	0.03
A	<0.029	190	2.39	<0.043	<0.001	0.10	63	<0.011	<0.109	38	0.25	15.4	<0.006
A	<0.029	206	2.51	<0.043	0.005	0.08	64	<0.011	<0.109	36	0.17	13.5	0.07
A	<0.029	304	3.52	<0.043	<0.001	0.06	86	<0.011	<0.109	30	0.16	13.1	<0.006

Table D3. continued

SAMPLE	Fe (mg/L)	K (mg/L)	Li (mg/L)	Mg (mg/L)	Mn (mg/L)	Mo (mg/L)	Na (mg/L)	Ni (mg/L)	P (mg/L)	S (mg/L)	Si (mg/L)	Sr (mg/L)	Zn (mg/L)
BEV-DUC-02													
B	<0.029	11	0.29	<0.043	<0.001	0.11	14	<0.011	<0.109	189	0.13	2.6	0.01
B	0.16	20	0.48	0.05	<0.001	0.13	20	<0.011	0.22	227	0.18	5.1	0.02
B	<0.029	44	0.79	<0.043	<0.001	0.21	28	<0.011	<0.109	141	0.23	9.3	0.01
B	<0.029	73	1.12	<0.043	<0.001	0.14	34	<0.011	<0.109	53	0.29	10.9	<0.006
B	0.06	130	1.77	<0.043	<0.001	0.12	48	<0.011	<0.109	41	0.34	13.8	0.08
B	<0.029	181	2.32	<0.043	<0.001	0.08	61	<0.011	<0.109	37	0.26	15.4	<0.006
B	<0.029	198	2.41	<0.043	0.004	0.07	62	<0.011	<0.109	36	0.16	13.3	0.20
B	<0.029	309	3.54	<0.043	<0.001	0.06	87	<0.011	<0.109	31	0.16	13.0	0.01
EDG-LIM-14													
A	<0.029	3	0.11	<0.043	<0.001	0.18	3	<0.011	<0.109	793	0.19	3.5	0.05
A	<0.029	24	0.25	<0.043	<0.001	0.28	8	0.02	<0.109	618	0.18	8.8	0.02
A	<0.029	116	0.82	<0.043	<0.001	0.29	28	<0.011	<0.109	447	0.22	14.9	<0.006
A	<0.029	213	1.42	<0.043	<0.001	0.31	48	<0.011	0.12	429	0.24	16.7	0.01
A	<0.029	355	2.19	<0.043	<0.001	0.26	72	<0.011	<0.109	476	0.21	18.8	0.05
A	<0.029	449	2.67	<0.043	<0.001	0.25	89	<0.011	<0.109	466	0.19	20.1	0.01
A	<0.029	500	2.86	<0.043	0.005	0.26	96	<0.011	<0.109	488	0.16	17.7	0.05
A	<0.029	634	3.46	<0.043	<0.001	0.23	120	<0.011	<0.109	492	0.15	17.5	<0.006
B	<0.029	3	0.11	<0.043	<0.001	0.18	3	<0.011	<0.109	660	0.21	3.2	0.76
B	<0.029	23	0.23	0.07	<0.001	0.24	8	<0.011	<0.109	536	0.19	8.5	0.03
B	<0.029	119	0.85	<0.043	<0.001	0.32	29	<0.011	<0.109	461	0.24	15.3	<0.006
B	<0.029	214	1.43	<0.043	<0.001	0.29	47	<0.011	0.24	435	0.25	16.9	<0.006
B	<0.029	360	2.20	0.05	<0.001	0.25	72	<0.011	<0.109	468	0.17	19.0	0.05
B	<0.029	423	2.50	0.07	<0.001	0.26	84	<0.011	<0.109	471	0.23	18.8	0.01
B	<0.029	509	2.83	0.11	0.005	0.13	97	<0.011	<0.109	243	<0.070	18.3	0.14
B	<0.029	610	3.29	0.08	<0.001	0.24	115	<0.011	<0.109	498	0.13	17.1	0.00

Table D3. continued

SAMPLE	Fe (mg/L)	K (mg/L)	Li (mg/L)	Mg (mg/L)	Mn (mg/L)	Mo (mg/L)	Na (mg/L)	Ni (mg/L)	P (mg/L)	S (mg/L)	Si (mg/L)	Sr (mg/L)	Zn (mg/L)
TID-FLB-03													
A	<0.029	46	0.34	1.23	<0.001	0.08	21	<0.011	0.12	725	1.26	1.2	0.02
A	<0.029	119	0.49	0.11	<0.001	0.06	37	<0.011	<0.109	632	1.02	1.8	0.01
A	<0.029	319	1.03	0.07	0.006	<0.018	73	<0.011	<0.109	667	2.87	2.4	0.02
A	<0.029	397	1.21	0.16	<0.001	<0.018	86	<0.011	0.18	655	6.98	2.6	<0.006
A	<0.029	454	1.22	0.31	<0.001	0.02	97	<0.011	<0.109	719	11.31	3.1	0.02
A	<0.029	489	1.14	0.55	<0.001	<0.018	101	<0.011	<0.109	696	11.07	3.2	<0.006
A	<0.029	503	1.03	0.26	0.004	<0.018	100	<0.011	<0.109	707	7.53	2.8	0.03
A	<0.029	511	0.89	0.37	<0.001	<0.018	103	<0.011	<0.109	670	6.92	2.7	0.02
B	<0.029	40	0.28	1.19	<0.001	0.04	18	<0.011	<0.109	758	1.19	1.0	0.02
B	<0.029	121	0.50	<0.043	<0.001	0.05	37	<0.011	<0.109	617	1.11	1.8	0.01
B	<0.029	307	0.98	<0.043	<0.001	<0.018	70	<0.011	<0.109	647	2.53	2.3	0.01
B	<0.029	383	1.18	0.16	<0.001	<0.018	83	<0.011	<0.109	645	6.91	2.5	0.01
B	0.04	470	1.26	0.53	<0.001	<0.018	104	<0.011	<0.109	727	11.76	3.2	0.09
B	<0.029	511	1.18	0.38	<0.001	<0.018	105	<0.011	<0.109	697	11.06	3.4	0.05
B	0.08	547	1.12	0.48	0.005	<0.018	114	<0.011	<0.109	665	7.66	2.8	0.39
B	<0.029	493	0.84	0.32	<0.001	<0.018	98	<0.011	<0.109	690	7.05	2.6	0.04
TID-FLB-04													
A	<0.029	11	0.04	0.17	<0.001	0.03	3	<0.011	0.27	155	0.70	0.3	0.01
A	<0.029	16	0.21	0.05	<0.001	0.04	5	<0.011	<0.109	426	0.41	0.8	0.02
A	<0.029	27	0.64	0.09	<0.001	0.09	8	<0.011	<0.109	608	0.28	2.2	0.01
A	<0.029	34	1.04	<0.043	<0.001	0.12	11	<0.011	<0.109	530	0.32	2.8	0.01
A	<0.029	42	1.36	0.29	<0.001	0.08	13	<0.011	<0.109	559	0.24	3.4	0.05
A	<0.029	44	1.47	<0.043	<0.001	0.09	13	<0.011	<0.109	533	0.25	3.3	<0.006
A	<0.029	42	1.26	0.14	0.001	0.07	12	<0.011	<0.109	423	0.17	2.6	0.19
A	<0.029	46	1.34	0.06	<0.001	0.06	12	<0.011	<0.109	445	0.14	2.6	<0.006

Table D3. continued

SAMPLE	Fe (mg/L)	K (mg/L)	Li (mg/L)	Mg (mg/L)	Mn (mg/L)	Mo (mg/L)	Na (mg/L)	Ni (mg/L)	P (mg/L)	S (mg/L)	Si (mg/L)	Sr (mg/L)	Zn (mg/L)
TID-FLB-04													
B	<0.029	10	0.04	0.09	<0.001	0.04	3	<0.011	<0.109	152	0.71	0.3	0.02
B	0.03	16	0.20	0.27	0.007	0.06	5	<0.011	<0.109	439	0.51	0.9	0.01
B	<0.029	28	0.65	0.05	<0.001	0.08	8	<0.011	0.14	538	0.24	2.2	0.02
B	<0.029	33	1.07	0.07	0.006	0.15	10	<0.011	0.27	481	0.30	2.6	0.04
B	<0.029	41	1.39	0.08	<0.001	0.09	12	<0.011	<0.109	548	0.19	4.0	0.03
B	<0.029	48	1.41	0.07	<0.001	0.08	13	<0.011	<0.109	540	0.23	4.9	<0.006
B	<0.029	48	1.71	0.05	<0.001	0.07	14	<0.011	<0.109	443	0.22	3.2	0.10
B	<0.029	50	1.50	<0.043	<0.001	0.06	14	<0.011	<0.109	460	0.18	3.3	0.02
TID-FLB-MIX													
A	<0.029	30	0.20	0.93	<0.001	0.07	13	<0.011	<0.109	571	1.06	0.9	0.02
A	<0.029	86	0.44	<0.043	<0.001	0.03	27	<0.011	<0.109	574	0.83	1.7	0.01
A	<0.029	209	0.85	<0.043	<0.001	<0.018	48	<0.011	<0.109	605	1.44	2.2	<0.006
A	<0.029	284	1.17	0.07	<0.001	<0.018	60	<0.011	0.19	609	3.38	2.4	0.30
A	0.03	393	1.59	0.19	<0.001	<0.018	79	<0.011	<0.109	657	5.82	3.2	0.06
A	<0.029	439	1.71	0.29	<0.001	<0.018	86	<0.011	<0.109	665	5.43	3.1	<0.006
A	<0.029	471	1.85	0.20	<0.001	<0.018	94	<0.011	<0.109	657	6.13	3.4	0.01
A	<0.029	467	1.61	0.15	0.001	<0.018	89	<0.011	<0.109	681	6.14	2.9	0.01
B	0.04	29	0.19	1.34	<0.001	0.02	13	<0.011	0.11	571	1.06	0.9	0.02
B	<0.029	73	0.35	<0.043	<0.001	0.03	23	<0.011	0.15	549	0.93	1.5	0.03
B	0.06	221	0.92	<0.043	<0.001	0.02	51	<0.011	0.21	632	1.65	2.4	0.01
B	<0.029	274	1.14	0.08	<0.001	<0.018	58	<0.011	0.11	593	3.59	2.4	<0.006
B	<0.029	393	1.64	0.19	<0.001	<0.018	79	<0.011	<0.109	668	8.02	3.3	0.04
B	<0.029	442	1.76	0.32	<0.001	<0.018	86	<0.011	<0.109	670	5.50	3.3	<0.006
B	<0.029	430	1.60	0.17	<0.001	<0.018	85	<0.011	<0.109	645	7.16	3.1	0.03
B	<0.029	457	1.63	0.12	<0.001	<0.018	88	<0.011	<0.109	641	5.70	3.1	<0.006

Table D3. continued

* Specific conductance(mmhos/cm)

** Inorganic carbon

NA Not available

Fig. D1. Concentration of Ba versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D2. Concentration of Be versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D3.

Concentration of Co versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D4. Concentration of Cr versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D5. Concentration of Cu versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D6. Concentration of Fe versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D7. Concentration of K versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D8. Concentration of Li versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D9. Concentration of Mn versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D10. Concentration of Ni versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D11. Concentration of P versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D12. Concentration of Pb versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D13. Concentration of Si versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D14. Concentration of V versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D15. Concentration of Mg versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D16. Concentration of Mo versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D17. Concentration of Se versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D18. Concentration of Sr versus the weight fraction of fly ash (acid insoluble residue) in FGD by-products.

Fig. D19. Concentration of Al in the fly ash fraction (acid insoluble residue) versus the concentration of Al in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D20. Concentration of Ba in the fly ash fraction (acid insoluble residue) versus the concentration of Ba in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D21. Concentration of Be in the fly ash fraction (acid insoluble residue) versus the concentration of Be in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D22. Concentration of Co in the fly ash fraction (acid insoluble residue) versus the concentration of Co in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D23. Concentration of Fe in the fly ash fraction (acid insoluble residue) versus the concentration of Fe in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D24. Concentration of K in the fly ash fraction (acid insoluble residue) versus the concentration of K in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D25. Concentration of Li in the fly ash fraction (acid insoluble residue) versus the concentration of Li in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D26. Concentration of Mn in the fly ash fraction (acid insoluble residue) versus the concentration of Mn in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D27. Concentration of P in the fly ash fraction (acid insoluble residue) versus the concentration of P in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D28. Concentration of V in the fly ash fraction (acid insoluble residue) versus the concentration of V in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

Fig. D29. Concentration of Sr in the fly ash fraction (acid insoluble residue) versus the concentration of Sr in whole FGD by-product. Data for samples: OSU-SPD-03, BEV-DUC-02, EDG-LIM-14, TID-FLB-03 and TID-FLB-04.

APPENDIX E

Social Costs and Benefits of Recycling Coal Fired Electric Power Plant FGD By-Products

Fredrick Hitzhusen*

Summary

Flue gas desulfurization (FGD) by-products from coal-fired electric power generation are increasing due to Clean Air Act legislation in the U.S. requiring removal of sulfur from coal. The FGD by-products are one of many waste products or residuals of economic production and consumption activities that may impose social costs when entering a natural environment with limits to its assimilative or "sink" capacity. The options for dealing with this problem include reducing levels of throughput, converting the residuals to new products or recycling them as inputs, changing the wastes to a more benign form, altering the time and place of residuals discharge and changing the assimilative capacity of the environment. This paper is part of a larger multidisciplinary research effort on FGD Recycling at The Ohio State University (see Dick et al., 1991) and focuses on developing a correct method for assessing the social or complete costs and benefits. It is oriented primarily to non-economists. The three options for converting FGD by-products to new products or recycling them as inputs include FGD by-products as an agronomic lime substitute, as an amendment on active and abandoned stripmine spoil, and as an embankment stabilizer for highway construction.

Social cost benefit analysis is concerned with estimating full willingness to pay and willingness to accept measures of economic value regardless of whether or not those values are currently reflected in market prices. It

* Professor of Resource Economics, The Ohio State University, 2120 Fyffe Road, Columbus, Ohio 43210 USA. This paper was presented at ENVIROTECH Conference, Vienna, Austria, April 23, 1992. Helpful comments were received from OSU colleagues, Leroy Hushak, Joe Havlicek and Diane Hite.

recognizes that technological externalities or unpriced environmental services can result in large gaps between private and social costs and benefits. A rapidly growing methodological literature in environmental economics is drawn upon to demonstrate how several of these gaps can be given economic expression in the coal-fired electricity production case. Examples in the landfill disposal vs. recycling of FGD by-products include: (1) monitoring, testing and remediation costs of groundwater contamination, (2) reduced rerouting, highway repair and maintenance costs related to embankment stabilization from FGD by-products, and (3) property value impacts (hedonic pricing) and contingent evaluation of willingness to pay for changes in amenities from landfill and stripmine reclamation activities. Finally, a hedonic pricing model is developed to illustrate how one might estimate the benefits of using FGD by-products for stripmine reclamation.

A Materials Balance

Flue gas desulfurization (FGD) by-products are one of the many residuals of production and consumption activities prevalent in a contemporary society. Specifically, FGD by-products result from the post-combustion "scrubbing" of flue gases in coal burning electric power plants by wet or dry lime processes. As the gross national product (GNP) or value of goods and services of a society grows so does the variety and volume of FGD and other residuals. In fact, it has been suggested that GNP might more appropriately refer to "gross national pollution." According to Boulding (1968), Georgesen-Roegen (1977) and others, the controversy over the foregoing residuals and the environment stems from the tendency to treat the environment as a free good or God given right rather than a source of raw materials and a waste disposal "sink" with limits. In the simplest materials balance model, Freeman et al. (1974) view

the environment as a large shell surrounding the economic system. It has the same relationship to the economy as does a mother to an unborn child--it provides sustenance and carries away wastes.

Raw materials flow from the environment, are processed in the production sector (that is, converted into consumer goods), and then--at least in part--pass on to the household sector. The materials returning to the environment from the household sector are wastes or residuals. They are the unwanted by-products of the consumption activities of households. Similarly, not all of the material inputs that enter the production sector are embodied in the consumption goods flowing on to the household sector. These are the wastes or residuals from production. Thus, there is a flow of residuals from both the production and consumption sectors back to the environment.

If the environment's capacity to absorb or assimilate wastes or residuals were unlimited, there would be no pollution problem and waste management would be a non-issue. However, the assimilative capacity of the environment is limited and in the case of some residuals like mercury it has no assimilative capacity. One of the limits of the environment's capacity to assimilate is the conflict or competition with other environmental services such as human habitat, amenities and materials inputs to the economic system. Many of these environmental services provide significant economic benefits even though they may not be currently or directly priced in markets.

The materials balance model and the notion of a service producing environment provide critical insights for the proper management of wastes or residuals. Examples suggested by Freeman et al. (1973) include (1) identification of the full range of technical options, (2) recognition of the interdependency among the various kinds of residual flows, (3) illumination of the relationships among population growth, economic growth and pollution, and (4)

emphasis in public environmental institutions on broad jurisdiction over air, water and land pollution and over major physical systems such as river basins.

With increasing evidence of wastes or residuals exceeding the assimilative capacity of various environmental "sinks", it is important to first identify the major technical alternatives for either reducing wastes or altering assimilative capacity. Examples include the following:

1. Reducing the rate of throughput of materials and energy by reducing production, increasing the efficiency of production, converting residuals to new products or recycling them as inputs, or by changing the composition of GNP to lower residual products. The three alternatives¹ uses proposed for FGD by-products all involve recycling or conversion to new products.
2. Biologically, chemically or mechanically treating or changing the residual to a more benign form for discharge to the environment.
3. Altering the time and place of residuals discharge.
4. Man-made investments to increase the residual assimilative capacity of the environment such as dams to store water for dispensing heavy waste loads and paddle wheels to augment the natural supplies of dissolved oxygen.

Social Costs and Benefits

Social costs and benefits or gains and losses from an economic perspective refer to the aggregation of individual producer and consumer measures of full willingness to accept or pay compensation. Individual preferences count in the determination of social benefits and costs and are weighted by income or more narrowly market by power. Since most policy changes involve economic gainers and losers, economists have developed the concept of potential Pareto

improvement (PPI) to add up gains and losses to get net benefits. Simply stated, the concept holds that any policy change is a PPI or an increase in economic efficiency if at least one individual is better off after all losers are compensated to their original or before the policy change income positions. The compensation need not actually occur but must be possible (Dasgupta and Pearce, 1978).

These measures of social costs and benefits are not fully reflected in current market prices (thus the "social" terminology) such as the price of electricity resulting from the coal-fired power generation for several reasons. First, because there are consumers willing to pay more and producers willing to sell for less than prevailing market or regulated prices, they receive what economists call consumer and producer surpluses. Secondly, technological externalities in coal-fired electric power generation exist to the extent that external to the production and consumption of the resulting electricity, individuals experience uncompensated real economic losses or gains. Examples include water pollution or adjacent property value losses from strip mining of coal or air pollution and lake acidification from the combustion of coal to produce electricity. Finally, there may be willingness to pay to keep future economic options such as sport and commercial fishing open or for existence value of plant or animal species threatened by water or air pollution which are not reflected in the market price of electricity.

Figure 1 illustrates both the concepts of economic surplus and technological externalities. For example, at market price P consumer surplus is equal to area PEC and producer surplus is equal to area PEA . One might think of P as the market price for a kilowatt of electricity based on the intersec-

FIGURE 1 ACID RAIN AS AN EXTERNALITY

Technological Externality Defined (Dasgupta & Pearce 1978)

1. Necessary Condition

Physical interdependence of production
and/or utility functions

2. Sufficient Condition

Not fully priced or compensated

S = marginal private (power plant) cost function

S' = marginal social (air shed) cost function

tion of marginal private cost (from the power plants perspective or accounting stance) of coal-fired production with demand.

The fact that some aquatic and forestry economic losses appear to be related to the sulfur emissions from coal burning electric power plants, the fact that strip mining of coal can lead to water contamination and lower surrounding property values and the possible global warming implications of CO₂ emissions from coal combustion for electric power all suggest the presence of uncompensated technological externalities. Stated another way, output Q exceeds the assimilative capacity of the environment. These external or social costs are internalized into the cost of producing coal-fired electricity in S' or the marginal social cost function and P' represents the price per kilowatt that would prevail if these external costs were included. The shaded area BE'EA represents the net loss in producer and consumer surpluses from the presence of these uncompensated externalities.

The foregoing is a static analysis and does not show the adjustments that might occur over time due to, for example, a tax on or a subsidy for electricity equal to the distance between P and P*. The willingness to pay to keep future options open or for existence value of species is also not shown in Figure 1. However, if a proposed stripmine site impacts an endangered species for which considerable WTP exists, it could result in the development of a higher cost alternative site which in turn would further increase the MSC function in Figure 1.

A rapidly growing empirical economic literature (see, for example, Hufschmidt et al., 1983 and Pearce and Turner, 1990) has evolved from the foregoing conceptual concerns which has the following major subsets relevant to the coal fired electricity production case:

1. Market values in related external markets such as agricultural or forest crops damaged from air pollution or reduced maintenance and private re-routing costs from highway embankment stabilization, replacement costs such as electricity generation from biomass or natural gas, and restoration or clean-up costs such as the liming of acidified lakes to return pH to normal levels or monitoring and treatment costs of contaminated groundwater. For example, analysis by Hitzhusen and Nyamaah (1984) of private re-routing costs from the closure or weight limit posting of bridges in rural Ohio found very large private savings relative to public repair costs. This would suggest the possibility of relatively large economic benefits from the stabilization of highway embankments from FGD by-products. As a second example, Sweden is spending several million dollars per year on a very modest program to apply lime to a few of many acidified lakes. This is an attempt to reintroduce fish and other aquatic life lost from coal burning induced acid rain which the Swedes claim comes primarily from their European neighbors to the south, an example of a transnational externality.
2. Surrogate market measures such as willingness to incur travel costs to use or avoid a particular natural resource or environmental service, impacts (hedonic) on property values from the decrease or increase in the quality of a particular environmental service such as a stripmine reduction of a landscapes utility, and wage differentials reflecting desirable or undesirable environmental attributes of a particular location impacted by water, air or sight pollution. For example, a travel cost analysis was done by Mullen

and Menz (1985) on the economic effect of acidification damage in the Adirondack fishery to fisherman from New York State. The lost willingness to pay as expressed by the willingness of New York fishermen to travel to Adirondack lakes and make expenditures to fish exceeded \$1 million per year in 1976 values.

3. Direct surveys of WTP and WTA for gain or loss of goods and services such as loss of visibility from air pollution or loss of sport fishing from an acid rain impacted lake. Originally called hypothetical evaluation, this methodology now goes under the rubric of contingent valuation and includes much concern for various forms of strategic behavior of respondents. Bidding and trade-off games are used to elicit the responses on WTA and WTP. For example, Brookshire et al. (1976) used pictures of three alternative levels of visibility related to smokestacks and emissions from a proposed coal fired power plant in Lake Powell, Arizona. To elicit WTP measures from respondents for these aesthetic damages or losses, an entrance fee to Lake Powell was used as the instrument to collect bids. The estimated aggregate bids ranged from \$400,000 to \$700,000 per year, not a trivial sum.

Hedonic Pricing Illustration

One beneficial reuse or recycling option for FGD by-products is as a reclamation material for abandoned coal stripmines. While federal regulations in the U.S. require current mining activity to restore the mining area to its original environmental state, the legislation does not require abandoned stripmines to be reclaimed. If there are no substitute reclamation materials for the FGD by-products or no plan to reclaim the area, FGD-based reclamation

will increase the income stream of the reclaimed land. In addition, it may increase surrounding property and land values and increase the life of existing landfills by diverting the FGD waste from landfills to reclamation of abandoned stripmines.

Hedonic pricing attempts to infer or derive a value for the pleasure lost or gained from environmental changes. The approach involves an attempt econometrically to capture differential prices for property (e.g., land and housing) which can be attributed to variations in one or more environmental characteristics. The hedonic pricing model for land and housing values assumes a well-functioning housing/land market in equilibrium with the major environmental costs and benefits accruing to owners of land and housing. It also assumes that buyers can perceive environmental impacts (e.g., stripmine reclamation) on land and housing values. The basic model can be stated as follows:

$$S_i = f(P_i, N_i, Q_i)$$

where

S_i = Sale price of property unit i

P_i = Characteristics of property unit i

N_i = Characteristics of neighborhood for property unit i

Q_i = Environmental quality characteristic for property unit i .

The foregoing hedonic implicit price function model is sufficient for estimating the land and/or housing price impacts of marginal changes in Q_i . However, for non-marginal changes in Q_i more complex procedures are required to "net out" an entire demand function from supply side factors. Figure 2 presents a schematic of the foregoing simple hedonic model showing housing, land use, community and environmental variables and data sources for applying

FIGURE 2

A Schematic of the Hedonic Model

the model to the estimation of property value benefits from FGD based stripmine reclamation. Remaining conceptual and empirical issues include identifying correct time lags in realization of benefits, estimating the increased landfill capacity from diversion of FGD, and any potential impacts of FGD chemical properties.

Earlier hedonic analysis by Havlicek et al. (1985) of adjacent residential property value impacts of a sanitary landfill in Fort Wayne, Indiana found significant statistical coefficients on both distance of the property from the landfill and the location (in absolute degrees) of the property away from being downwind (prevailing) from the landfill. Specifically, residential property values increased an average of \$1.92 per foot of additional distance from the landfill and an average of \$32.96 for each additional degree away from being directly in line and downwind from prevailing winds and the landfill.

Research by Ibrahim et al. (1982) using 1976 cross-sectional data studied the relationship between surface coal mining and reclamation activity, and property values in seven Ohio counties. Mining activity was found to have a positive relationship with residential property values and a negative relationship with agricultural and commercial property values. The opposite relationship is observed with surface mine reclamation. One explanation for the unexpected results on residential property is that surface mining reduces and reclamation increases supply of residential property sufficiently to impact price. Surface mine reclamation enforcement has also gotten more strict since 1976 which suggests the need to update this earlier analysis.

To the extent that stripmine reclamation reduces soil erosion from the mine site, related downstream sediment impacts may also decrease. Hedonic

pricing was used by Hitzhusen et al. (1992) to estimate the downstream sediment impacts on residential property owners at four Ohio state park lakes. The statistical results are presented in Appendix A and show that the set of variables measuring housing, community and environmental characteristics explain from 67 to 75 percent of the variation in prices of lakeside residential properties. For each foot of lake depth lost to sedimentation, the average lakeside property price decrease was \$1,875.

The statistical estimation of the model in Figure 2 is underway but not complete. However, the earlier empirical results, preliminary hedonic results, and increasing public concern for environmental impacts of surface mining and coal combustion suggest that these externality values (as well as the earlier discussed existence values) will not be trivial and may be increasing over time. Economically efficient public policy requires that these "social" values be estimated and incorporated into the decision-making process. One need not necessarily appeal to non-economic motives or values to be more sustainable or environmentally correct in the analysis of FGD by-products or other issues.

APPENDIX A

Table 1: Coefficient and Associated Standard Errors for Alternative Property Price Models.

Variable	Model I		Model II		Model III	
	Coef.	Std.Err	Coef	Std.Err	Coef.	Std.Err
CONST.	3.006	0.3069***	0.718	0.5273	2.679	0.8788***
SIZE	0.113	0.0319***	0.176	0.0331***	0.235	0.0365***
DWELL	0.654	0.1054***	0.664	0.1041***	0.554	0.1012***
ROOM	0.419	0.1252***	0.235	0.1264*	0.203	0.1211*
AC	0.012	0.0379	0.021	0.0366	0.072	0.0382*
GR	0.058	0.0284**	0.065	0.0265**	0.049	0.0253*
DSTL	0.237	0.0286***	-0.229	0.0275***	-0.250	0.0273***
AGE	0.099	0.0341**	-0.085	0.0319***	-0.086	0.0302***
PCOM			0.648	0.1146***	0.405	0.1546***
DCTY			-0.042	0.1208	-0.329	0.1383**
ADEP					0.196	0.0447***
STPS					-0.221	0.0852**
R ²	0.685		0.729		0.762	
ADJ R ²	0.674		0.718		0.749	
Fvalue	64.885		62.009		59.529	

*** indicates the significant level at 0.01 percent for t-test.

** indicates the significant level at 0.05 percent for t-test.

* indicates the significant level at 0.10 percent for t-test.

All * imply rejection of the null hypothesis which $H_0 : a_i = 0$.

Table 2: The Marginal Effects of Independent Variables on Property Value.

Variable	Marginal Price	
SIZE	21437.45	\$/ac.
DWELL	26.88	\$/sq.ft
ROOM	1589.58	\$/room
AC	35.57	\$/AC
GR	24.34	\$/GR
DSTL	49.43	\$/ft.
AGE	147.00	\$/yr.
PCOM	2.96	\$/person
DCTY	282.71	\$/mi.
ADEP	1875.06	\$/ft.
STPS	879.74	\$/ton/ac.

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APPENDIX F

An Interim Report:

5-14-92

LIMB Ash Stockpile Environmental Impact Study

J. Beeghly, Dravo Lime Company
R. Stehouwer, Dept. of Agronomy, The Ohio State University
April, 1992

A 1,500 ton "temporary" storage pile of LIMB ash by-product from the Ohio Edison Edgewater plant was constructed in July 1991 at the Central Fuel Company, New Philadelphia, Ohio. Four environmental operating permits required for construction of the storage pile were obtained; three from Ohio EPA (air, water and solid waste), and one from the ODNR Division of Reclamation (revised permit). Costs of building the clay liner, berm, and drainage system required by these permits were donated by the Central Fuel Co. (This LIMB ash is a type of dry FGD scrubber residual solid waste from the LIMB clean coal combustion technology as opposed to a wet FGD scrubber sludge solid waste.)

The purpose of this interim report is to review technical information on the stockpile material as it was placed and during 8 months of storage.

Stockpile Construction and Moisture

The storage pile was constructed as proposed in our permit application except that a single pile was constructed with a residual moisture content of approximately 17%. The normal amount of water to control fugative dust was added in the ash conditioner at the power plant while being loaded into the

dump trucks. More water would have plugged the mixer conditioner. Our objective was to add enough water to be close to the optimum moisture content (OMC) for optimum compacted density i.e., to construct a compacted fill or road base. It turned out that the amount of water they add normally in the conditioning process is close to the OMC, which is about 40 - 50 % on a dry weight basis.

It is important to note that during construction of the pile, efforts were made to minimize compaction of the LIMB ash by avoiding driving over it with the dump trucks or front end loader. The pile was constructed by placement with a large front end loader. Some compaction around the edges with the tires was unavoidable to stockpile the ash as high as possible.

Because of the chemical characteristics of the LIMB ash (i.e., contains free lime (CaO) and anhydrite (CaSO_4)) it has a high demand for waters of hydration, also called combined water. An attempt was made to estimate the moisture content of LIMB by-product leaving the Lorain, Ohio Power Plant by measuring the total amount of water added and the wet ash weight of each truck load leaving the plant (Table 1). This amounted to an average of 43.5% water added (dry weight basis) and is based on 22 separate truckloads. This number is a good estimate but the measurements are not precise and an unknown fraction of added water was lost as steam vapor. In any case, about 43% of the 1,500 ton pile was water added at the power plant.

Free moisture was also determined on samples collected on delivery of the conditioned LIMB by-product to the storage pile to determine the initial pile

moisture content (Table 1). This average value of 17.5% residual moisture is lower than the water added values of 43.5% due in part to the reasons given above as well as chemical reaction of added water with the by-product, and drying during transport and handling of the by-product.

A rain gauge has been installed at the storage pile site and a precipitation record is being kept (Table 2). Rainfall during the summer and fall of 1991 was below average. The pile has been monitored during all significant rainfall events since construction; however, there have been no runoff events or leachate from the storage pile.

Moisture After 3 and 6 Months

The effects of weathering on chemical, physical and engineering properties of the storage pile material will be determined by analyses of samples collected after 3, 6, 9 and 12 months of storage. Results of the 3 and 6 month sampling period are given in Table 3. After 3 months the exposed pile had only a weak crust from cementation. After six months, the ash moisture content at the surface of the pile was about 70% (dry weight basis) and under 6 inches was 43-49%. The pile is very firm and easy to walk on because of the conditioning process. Water infiltration has apparently not been significantly decreased by the crust formation since the rainfall events (>1 inch) of 4 and 13 December resulted in no surface runoff from the pile. The increase in moisture content from 17 to 70% during 6 months of exposure demonstrates the high capacity of the LIMB ash to absorb water and prevent storm runoff and leaching.

Physical & Lime Neutralization Properties

Data on physical properties of the LIMB ash by-product in a dry condition are presented in Table 1: These include particle density, surface area, Blaine fineness, and bulk unit weight (lbs/cubic feet).

Available free lime content averaged about 21% CaO as per ASTM method C-25. In terms of calcium carbonate equivalency (CCE as% CaCO_3), the total neutralizing power was about 50% as per ASTM method C-602, based on 10 samples. Data on percent free lime and CCE after 6 months is seen in Table 3.

Total Chemical & Leachate Analysis

Leachate tests by both the ASTM 3987-85 water method (20:1, water:FGD) and the TCLP acetic acid extraction method #1311 are shown in Table 4 as conducted on the original dry LIMB ash (Sample EDG-LIM-14) which represents the material shipped to the stockpile. The ASTM results and TCLP results (As, Hg, & Se were not yet tested on TCLP leachate) were less than primary drinking water standards, which are far lower than levels required for classification as non-toxic fly ash by the Ohio EPA Policy 4.07.

The major ions in the leachate were calcium, sulfate and hydroxide. Long term equilibrium solubility leaching tests on this sample are not yet complete.

The total chemical analysis is also given in Table 4.

All the above data in Table 4 are very similar to that shown in the two articles on characterization of LIMB FGD by-products included in the LIMB Stockpile application: Field Study of Wastes From a Lime Injection Technology by L. Holcombe, R. Butler, and J. Harness; and Properties of Solid Waste From the Edgewater Coolside and LIMB Process Demonstration by M. Wu, R. Winschel, G. Wasson and T. Jageman.

The data are also representative of reported values in the literature of stabilized/fixated forced oxidized FGD waste as shown in Table 5.

Mineralogy

The major mineral phases in LIMB ash are Lime (CaO), Portlandite (Ca(OH)_2), and Anhydrite (CaSO_4). Minor phases are Quartz (SiO_2), Hematite (Fe_2O_3), Magnetite (Fe_3O_4), and Mullite (Al_2SiO_5). Upon aging other mineralogical forms will appear i.e., ettringite. Ettringite is a calcium sulfo-aluminate ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$). Note the high degree of hydration which helps explain the water absorbing properties of LIMB ash in addition to that of free lime and anhydrite.

LIMB Ash Test Cells

To review, approximately 140 truckloads of LIMB ash were placed in two test cells in 1989 at the Ohio Edison Sheffield Township ash landfill under a

related US Dept. of Energy-sponsored study. Data from their report when complete should be compared to these results. The background information on this test cell study was also presented in the proposal for this stockpile study.

Conclusion & Summary

- 1) A description of the 1500T (wet weight) LIMB ash stockpile (storage pile) is presented herein in terms of water added, moisture contents, physical, chemical, and leachate properties.
- 2) About 43% of the 1500 tons is water added in the conditioning process. Moisture gains (surface only) after six months of exposure to rain are also reported herein. On average the initial residual moisture was 17% but the surface moisture level increased to 70% (dry weight basis or about 40% on wet weight basis). Below 6 inches the residual moisture increased to about 43-49% (dry weight basis or about 29-34% on wet weight basis).
- 3) The ASTM water and acid TCLP leachate laboratory procedure yielded metals concentrations less than drinking water standards for important water quality parameters. This is due to very low levels of these metals in the LIMB ash.
- 4) Some physical properties are listed in Table 1. Engineering properties of this aged material for use in fill or embankment construction will be shown in a future report.

- 5) Rainfall events during 8 months of observation have caused no surface runoff or leaching from the stockpile. The enclosed photographs show there is no sign of any discharge from the pipes which drain surface and leachate water. Thus, there is no data for the impact of the stockpile on water quality.

TABLE 1

SUMMARY OF MEASURED PROPERTIES OF LIMB BY-PRODUCT PLACED IN STORAGE PILE

	Water Added	Moisture Content	Slaking Temperature	Free CaO	OCE	Particle Density	Blaine Fineness	Bulk Density
	(%)	(%)	($^{\circ}\text{C}$ 15 min $^{-1}$)	% CaO	% CaCO_3	(g cm $^{-3}$)	(cm 2 g $^{-1}$)	(g cm $^{-3}$)
Mean	43.5	17.5	8.2	21.4	46x	2.84	10,030	45.1
# of Samples	22	8	16	24	9	5	5	3
Range	31.0 53.5	7.5-35.2	6.5-13.7	11.4- 25.5	27.3-48.2	2.83-2.87	9,790- 10,460	44.5-45.5

TABLE 2

Rainfall Events (inches) From September '91 Through March '92 At The LIMB
Ash Storage Pile Site

	1991				1992		
Date	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March
4	0.70	—	—	2.25	—	—	1.25
9	—	0.24	—	0.07	—	—	—
10	1.95	—	0.62	—	—	—	0.50
13	—	—	—	1.25	0.3	0.5	—
17	0.50	—	—	—	—	0.6	0.75
19	—	0.30	0.20	—	0.7	—	—
22	—	—	0.32	—	—	—	0.75
23	0.36	—	—	—	—	—	0.50
25	0.50	—	—	—	1.25	0.3	1.00
27	—	0.20	—	—	—	—	—
30	—	—	—	0.82	—	—	0.75
Monthly Total	4.01	0.74	1.14	4.39	2.25	1.4	4.50

TABLE 3

CHARACTERIZATION OF LIMB BY-PRODUCT AFTER 3 & 6 MONTHS OF EXPOSED STORAGE

Sample	Depth (cm)	Moisture Content (%)	Optimum Moisture Content (% water added)	DryBulk Density (g/cm ³)	0-Day Unconfined Compress. Strength (psi)
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After 3 months:

STO-01	0-5	25	25	1.24	38.4
STO-01	50	33			
STO-02	0-70	10.0			
STO-02	70	12.0			

After 6 months:

Sample	Depth (cm)	Moisture Content (%)	Free CaO %	OCE % CaCO ₃
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STO-03	0-15	43	—	—
STO-04	0-15	73	—	—
STO-05	0-5	70	12.4	51
STO-06	15	49	1.2	49

TABLE 4

LIMB FGD ASH LEACHATE AND TOTAL CHEMICAL ANALYSIS

SAMPLE I.D. SAMPLE DATE	LEACHATE ASTM 20:1 LIM-14 7-17-91	LEACHATE TCLP N-VIRO 7-16&17-91	TOTAL CHEMICAL ANALYSIS LIM-14 7-17-91
	<u>mg/L</u>	<u>mg/L</u>	<u>% or ug/g</u>
Major Cations:			
Al	<0.11	0.15	3.60 %
Ca	1,842	3,670	33.68 %
Fe	<0.01	<0.01	5.32 %
Mg	0.07	0.12	0.60 %
Na	1.1	1.8	0.08 %
K	1.6	2.1	0.38 %
Si	0.12	0.15	5.74 %
Sr	2.58	2.21	0.03 %
Major Anions:			
F	3.4	—	—
Cl	54.4	64.8	—
SO ₃	31.3	—	—
SO ₄	1,872	1,590	—
S	740.7	605	5.77 %
			(17.3 % as SO ₄)
			<u>ug/g</u>
Trace Metals:			
Sb	<0.06	<0.060	
As	<0.005	*	
Ba	0.231	0.26	100 ug/g
Be	<0.002	<.002	4 ug/g
B	3.93	5.78	
Cd	<0.001	<0.005	
Cr	<0.011	<0.011	33 ug/g
Co	0.01	<0.01	20 ug/g
Cu	<0.009	0.01	10 ug/g
Pb	<0.093	<0.093	

TABLE 4
CON'D

	LEACHATE ASTM 20:1 mg/L	LEACHATE TCLP (ave. of 2) mg/L	Total Chemical Data % or ug/g
<hr/>			
Major Cations:			
	<u>mg/L</u>	<u>mg/L</u>	<u>ug/g</u>
Li	0.05	0.08	36
Mn	<0.053	<0.01	182
Hg	<.0002	*	
Mo	0.101	0.15	10
Ni	<0.01	<0.012	28
P	<0.108	0.054	300
Se	<0.005	*	
Ag	—	—	
Sn	—	—	
V	<0.029	0.049	9
Zn	<0.006	<0.006	54
pH	10.63		
TDS	4,815		
(Total Dissolved Solids)			

* data reported later

Table 5
Literature Reported Values of Leachate From
Stabilized/Fixated Forced Oxidized FGD Waste (a)

<i>Constituent/ Parameter</i>	<i>Range (mg/L)</i>	<i>Mean (mg/L)</i>	<i>Drinking Water Standards</i>
<u>Major Cations</u>			
Calcium	67 - 647	520	
Magnesium			
Sodium			
Potassium			
<u>Major Anions</u>			
Chloride	40 - 80	60	250
Sulfate	85 - 1356	886	250
Fluoride			2 - 4
<u>Trace Constituents</u>			
Aluminum			
Antimony			
Arsenic	0.005 - 0.032	0.014	0.05
Barium	<0.5 - <1	<1	1
Beryllium			
Boron	0.25 - 1.6	0.925	
Cadmium	<0.01 - 0.10	0.04	0.01
Chromium	<0.05 - 0.20	0.09	0.05
Cobalt			
Copper	<0.1	<0.1	1
Iron	<0.1	<0.1	0.3
Lead	<0.05 - 0.56	0.15	0.05
Manganese			0.05
Mercury	0.0008 - 0.0052	0.0014	0.002
Molybdenum			
Nickel	0.05	0.05	
Selenium	0.002 - 0.043	0.018	0.01
Silicon	<0.05	<0.05	
Silver	<0.01 - 0.05	0.03	0.05
Tin			
Vanadium			
Zinc	<0.1	<0.1	
<u>Parameters</u>			
TDS	177 - 2372	1865	500
pH	6.6 - 10.5	7.6	6.5 - 8.5

(a) Source: Conversion Systems, Inc.

Source: Golden, D.M. 1981. EPRI FGD Sludge Disposal Demonstration and Site Monitoring Projects; In Proceedings: Symposium on Flue Gas Desulfurization Houston, October 1980; Volume 2. EPA- 0600/9-81-09b.