Abstract. The PHOBOS experiment at RHIC has measured the charged-particle density \( dN/d\eta \) at mid-rapidity for central Au+Au collisions at center-of-mass energies of \( \sqrt{s} = 56, \) and 130 GeV. We deduce that \( dN/d\eta = 408 \pm 12 \) (stat) \( \pm 30 \) (syst) and 555 \( \pm 12 \) (stat) \( \pm 35 \) (syst) for collision energies of 56, and 130, GeV, respectively. These numbers suggest energy densities that are some 70-90\% higher than have been achieved in any heavy-ion collisions previously studied, and also 25-40\% higher than nucleon-nucleon collisions at comparable center-of-mass energies.
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1.0 INTRODUCTION

For the past 70 years, much of the electricity consumed in the United States has been generated from coal. Until about 20 years ago, the future of the coal utilization industry was very promising because the U.S. has abundant coal reserves, and constant improvements in combustion technology have made power production processes more efficient. In recent years however, environmental concerns about acid rain, global warming, and other problems associated with coal combustion have challenged the growth of the industry.

The enactment of environmental regulations such as the Clean Air Act of 1970 and its subsequent amendments has progressively increased the cost of generating electricity by mandating the use of flue gas desulfurization (FGD) systems to control SO₂ emissions. More recently, the Clean Air Amendments of 1990 have set a goal to reduce SO₂ emissions to 8.9 million tons per year. This will be accomplished in two phases. The first phase requires large power plants (i.e., those producing 100 megawatts or more) to reduce their SO₂ emissions to 2.5 pounds per million Btu, and the second phase requires most power plants to reduce SO₂ emissions to 1.2 pounds per million Btu. Installing the necessary equipment to meet these goals will be expensive, and the cost of generating electricity from coal will increase proportionately.

If the United States is to continue to use its substantial coal reserves effectively, we will need to develop new "clean coal" technologies to improve power production efficiency and reduce emissions from power plants. The U.S. Department of Energy (DOE) through its Clean Coal Technology Program, is helping in the development of innovative new technologies by the power industry. Because of the combined efforts of the federal government and private companies, much new technology has been demonstrated over the past ten years.

Solid wastes produced by clean coal technologies may have significantly different properties than solid wastes produced by conventional coal combustion processes. This is because a common goal of all of the clean coal technologies is to reduce air pollution emissions and most utilize some type of sorbent material to enhance pollutant capture from the combustion gas. Spent sorbents from these processes usually have high calcium and sulfur contents and they are often mixed with other wastes such as fly ash or bottom ash.

Successful disposal practices for solid wastes produced from advanced coal combustion and coal conversion processes must provide for efficient management of large volumes of wastes in a cost-effective and environmentally safe manner. At present, most coal utilization solid wastes are disposed of using various land-based systems, and this mode of disposal will probably continue to be widely used in the future for advanced process wastes.

Proper design and operation of land-based disposal systems for coal combustion wastes normally require appropriate waste transfer, storage, and conditioning subsystems at the plant to prepare the waste for transport to an ultimate disposal site. Further, the overall waste management plan should include a by-product marketing program to reduce the amount of waste requiring ultimate disposal. To properly design and operate a waste management system for an advanced coal utilization process, a fundamental understanding of the physical properties, chemical/mineral composition, and leaching behavior of the waste is required.
To gain information about wastes produced by advanced coal utilization processes, a research project was conducted to characterize the geotechnical and geochemical properties of advanced coal process wastes. In task one of this project, 55 wastes from 16 different coal gasification, fluidized-bed combustion (FBC), and advanced flue gas-scrubbing processes were collected by the Department of Energy (DOE) and sent to Universal Fuel Development Associates, Inc. (UFDA). Thirty-four of these wastes were characterized at the University of North Dakota Energy & Environmental Research Center (EERC) for their bulk chemical and mineral compositions and tested for a detailed set of disposal-related physical properties. The results of these waste characterizations are contained in a report entitled "Geotechnical/Geochemical Characterization of Advanced Coal Process Waste Streams: Task one Report".

This report contains the results of waste characterizations done for task three of this project and a discussion of potentially useful waste management practices for advanced coal utilization processes. Since the properties of advanced process wastes are in some respects different from conventional coal combustion wastes, an analysis was done to identify any potential problems that could occur when conventional, off-the-shelf waste management technologies are used for handling and disposal of advanced process wastes. When potential problems were identified, alternative technologies were examined.

2.0 ACCOMPLISHMENTS

The following activities were done for task three of this research project:

- Thirteen solid wastes, six coals, and one unreacted sorbent were characterized. These materials were collected from seven different advanced coal combustion processes demonstrated at full-scale or pilot-scale facilities in the U.S. The characterization protocol used for the wastes included an extensive set of waste management-related physical property tests, bulk chemical analyses, and mineral analyses. The coals were analyzed for major and trace element contents, proximate and ultimate data, and higher heating value.

- Two conversion processes were conducted with the wastes, and the conversion products were evaluated with appropriate tests and analyses to determine the suitability of advanced process wastes for useful applications involving these conversions.

- A task three report was prepared which summarized and evaluated the results of the waste characterizations. The report focused on 1) the suitability of current coal combustion waste management practices for advanced process wastes, 2) the possible use of alternative waste management practices for the advanced process wastes, and 3) an evaluation of any deficiencies in our understanding of how to safely and economically dispose of the advanced process wastes.

3.0 MATERIALS AND METHODS

3.1 Advanced Process Wastes

The advanced coal utilization processes that produced samples for the task three work included a gas reburning sorbent injection process, a pressurized fluidized-bed combustion process, a coal reburning process, a $\text{SO}_x$, $\text{NO}_x$, $\text{RO}_x$, $\text{BOX}$ process, a low $\text{NO}_x$ burner process with advanced over-fire
air, an advanced flue gas desulfurization process, and an advanced coal-cleaning process. The waste samples ranged from coarse materials such as bottom ashes and spent bed materials to very fine materials such as fly ashes and cyclone ashes. Table 1 gives a brief description of each waste. All advanced process wastes were examined upon receipt at UFDB to make sure that they were properly preserved.

3.1.1 Gas-Reburning Sorbent Injection Process

The gas-reburning sorbent injection (GRSI) process is sponsored by the Energy & Environmental Research Corporation. Partial funding for the demonstration was obtained in round one of DOE’s Clean Coal Technology Program. The waste samples characterized for this project were obtained from a test run of a full-scale GRSI process. Table 2 contains some operating data and mass flow data from the test run.

### TABLE 1

Descriptions of the Advanced Process Wastes Characterized for Task 3

| Advanced Process                                      | Sample Descriptions*       |
|-------------------------------------------------------|----------------------------|
| Gas-Reburning with Sorbent Injection (two samples)     | GRSI-FA: Grey fly ash collected in an electrostatic precipitator       |
|                                                       | GRSI-BA: Dark grey bottom ash discharged from a tangentially fired, pulverized-coal boiler |
| Pressurized Fluidized-Bed Combustion (three samples)   | PFBC-FA: Reddish-brown fly ash collected in an electrostatic precipitator |
|                                                       | PFBC-CA: Grey-brown fine ash collected in a mechanical cyclone          |
|                                                       | PFBC-BA: Tan granular ash discharged from the bed of the combustor     |
| Coal-Reburning (two samples)                           | CR-FA: Brown fly ash collected in an electrostatic precipitator        |
|                                                       | CR-BA: Black glassy bottom ash (sometimes referred to as slag) produced from a cyclone-fired boiler |
| SO\textsubscript{x}, NO\textsubscript{x}, RO\textsubscript{x}, BOX (two samples) | SNRB-FA: Grey fly ash collected in a baghouse                          |
|                                                       | SNRB-S: Off-white sorbent powder, actually a fresh Ca(OH)\textsubscript{2} sorbent, not a waste |
| Low NO\textsubscript{x} Burner with Advanced Over-Fire Air (three samples)  | LNB-FA: Grey fly ash collected in an electrostatic precipitator        |
|                                                       | LNB-EA: Granular ash collected from boiler economizer                   |
|                                                       | LNB-BA: Tan-grey-black granular bottom ash                            |
| CT-121 Flue Gas Desulfurization (one sample)           | FGD-SS: Yellow-tan spent scrubber material                            |
| Advanced Coal-Cleaning (one sample)                    | ACC-FA: Grey fly ash collected in an electrostatic precipitator       |

* These sample designations will be used throughout this report to identify the samples.
One bottom ash and one ESP fly ash obtained from the GRSI process were characterized at EERC. The bottom ash sample was obtained from the ash storage container, and the fly ash sample was obtained from an ash hopper located below the ESP.

The objective of the GRSI project is to demonstrate that the process can reduce 60% of the NO\textsubscript{x} by gas reburning and capture 50% of the SO\textsubscript{2} by sorbent injection. It is expected that the GRSI process can be used for either tangentially fired or cyclone-fired boilers. The GRSI process operates by supplying 80 to 85% of the total fuel to the main burner of a coal-fired boiler. The remaining 15 to 20% of the fuel is supplied as natural gas to a reburn zone located above the main burner. The air-to-fuel ratio in the reburn zone is controlled so that reducing conditions are created. This promotes the conversion of NO\textsubscript{x} created in the main burner to nitrogen and water. Additionally, a calcium hydroxide sorbent is injected into the boiler above the reburn zone for SO\textsubscript{2} capture. Before the combustion gas leaves the boiler, enough air is added to complete combustion of the natural gas. After the flue gas leaves the boiler, humidification water is added to promote further SO\textsubscript{2} capture in the flue gas (2).

When combustion is completed, molten bottom ash produced in the combustor falls into a water-filled quench tank. The quenched ash is crushed and sent to a storage container. Fly ash is formed when very fine ash particles are carried out of the combustor with the flue gas. The fly ash is removed from the flue gas in an ESP. Some of the spent sorbent is collected with the bottom ash and the rest is collected with the fly ash. Figure 1 shows a diagram of the GRSI process.

**TABLE 2**

| Parameter                          | Value  |
|------------------------------------|--------|
| Coal Flow Rate, lb/min             | 956    |
| Sorbent Flow Rate, lb/hr           | 6731   |
| Boiler Load, MW                    | 70     |
| Excess Air in Boiler Exit Gas, %    | 18.7   |
| Bottom Ash Production, lb/hr       | 1440   |
| ESP Fly Ash Production, lb/hr      | 10985  |
| Ash in Coal, %                     | 9.56   |
| Sulfur in Coal, %                  | 2.82   |
Figure 1. Diagram of the gas-reburning sorbent injection process (2).

3.1.2 Pressurized Fluidized-Bed Coal Combustion Process

The pressurized fluidized-bed combustion (PFBC) process is sponsored by the Ohio Power Company. Partial funding for the demonstration was obtained in round one of DOE's Clean Coal Technology Program. The waste samples characterized for this project were obtained from a test run of a 70-MW (design load) PFBC process. Table 3 contains some operating data and mass flow data from the test run.

TABLE 3
Average Operating and Mass Flow Data for the Period When Samples Were Collected From the PFBC Process

| Parameter                          | Value  |
|------------------------------------|--------|
| Coal Flow Rate, lb/min             | 829    |
| Sorbent Flow Rate, lb/hr           | 15465  |
| Boiler Load, MW                    | 50.3   |
| Excess Air in Boiler Exit Gas, %   | 4.4    |
| Vessel Pressure, psig              | 137.5  |
| Bed Temperature, °F                | 1557   |
In a typical FBC, a mixture of crushed coal and limestone or sand is fluidized by a powerful air flow. Under these conditions, the burning coal is brought into contact with the boiler tubes, producing highly efficient heat transfer. This increased heat transfer allows the FBC to operate at a lower temperature than conventional pulverized-coal (pc) boilers (i.e., about 1500°F for FBC compared with 3000°F for pc). The advantages of FBC are reduced production of nitrogen oxides (NOx) because of lower combustion temperature, capture of 90% or more of the sulfur dioxide produced if limestone is used in the FBC bed, and reduced ash-fouling of the boiler tubes because the temperature in the FBC is below the melting point of the ash. FBC technology also lends itself well to use in small boilers that can be installed as required to meet increased power demands. This is considered a distinct advantage for designing future power plants.

The objective of the PFBC demonstration project is to verify the performance of the technology in a combined-cycle application. The process is expected to remove more than 90% of the SO2 from the combustion gas, achieve a NOx emission level of 0.2 lb/MM BTU, and achieve a power production efficiency of 38%. The PFBC process uses a bubbling bed configuration in which crushed coal and dolomite are injected into the combustor. The dolomite is a sorbent for SO2 capture.

During operation, bottom ash is removed from the combustor and fly ash is carried out with the flue gas. The flue gas first passes through a set of cyclones that collect about 98% of the fly ash. When the flue gas leaves the cyclones, it passes through a turbine to generate additional electric power and then is directed to the ESP where the remainder of the fly ash is removed. The bottom ash falls into a pressurized lock hopper. When the hopper is full, the bottom ash is conveyed to an ash storage silo. Since the temperature in the PFBC combustor is usually not high enough to melt the ash, there is much less agglomeration of the PFBC bottom ash compared to bottom ash obtained from a conventional combustion process. Therefore, the PFBC bottom ash does not have to be crushed before it is transported to a disposal site. Figure 2 shows a diagram of the PFBC process.

Figure 2. Diagram of the pressurized fluidized-bed combustion process (2).
A bottom ash, a cyclone fly ash, and an ESP fly ash obtained from the PFBC process were characterized at EERC. The bottom ash was collected from the conveyor leading to the ash silo. The cyclone fly ash was collected from a sampling port at the entrance to the cyclone ash hopper, and the ESP fly ash sample was collected from the ash hopper located below the ESP. All three samples were collected dry.

### 3.1.3 Coal Reburning Process

The coal-reburning (CR) process is sponsored by the Babcock & Wilcox Company. Partial funding for the demonstration was obtained in round two of DOE's Clean Coal Technology Program. The waste samples characterized for this project were obtained from a test run of a 100-MW cyclone-fired boiler. Operating data and mass flow data were not available for the CR test run.

The objective of the CR process is to reduce NO\textsubscript{x} emissions from a coal-fired cyclone boiler by more than 50% with no serious impact on cyclone boiler operation. The process involves injecting 20 to 30\% of the coal into a reburn zone above the main cyclone burner. Pulverized-coal is injected into the reburn zone with just enough air to achieve partial combustion of the coal. This arrangement creates reducing conditions in the reburn zone and promotes conversion of the NO\textsubscript{x} produced by the main burner to nitrogen and water. Coal combustion is completed in a burnout zone above the reburn zone by adding more air to the boiler. Figure 3 shows a diagram of the CR process (2).

![Figure 3. Diagram of the coal-reburning process (2).](image-url)
A bottom ash and an ESP fly ash obtained from the CR process were characterized at EERC. The bottom ash sample was collected after it had been quenched and crushed. The fly ash sample was collected dry from an ESP storage hopper.

3.1.4 SO\textsubscript{x}, NO\textsubscript{x}, RO\textsubscript{x}, BOX Process

The SO\textsubscript{x}, NO\textsubscript{x}, RO\textsubscript{x}, BOX (SNRB) flue gas cleanup process is sponsored by Babcock & Wilcox Company. Partial funding for a pilot-scale demonstration of the process was obtained in round two of DOE's Clean Coal Technology Program. The samples characterized for this project were obtained from a test run done with a 5-MW flue gas slipstream from a commercial coal combustion plant. Table 4 contains some operating data and mass flow data from the test run.

The objective of the SNRB project is to demonstrate a high level of reduction of SO\textsubscript{x}, NO\textsubscript{x}, and particulate emissions with a single postcombustion, high-temperature baghouse. The SNRB process is intended to be used in retrofitting power plants burning high-sulfur coal. The SNRB process uses hydrated-lime sorbent injection into the flue gas to capture SO\textsubscript{2} and ammonia injection to capture NO\textsubscript{x}. After sorbent and ammonia are injected, the flue gas passes through a high-temperature baghouse containing ceramic fiber filter bags. The ammonia in the flue gas reacts with NO\textsubscript{x} in a selective catalytic reduction bed located in the filters. The reaction products are nitrogen and water. Spent sorbent and fly ash are trapped on the filters and collected as a dry mixture in an ash hopper located below the baghouse. The ash hopper is periodically emptied and the combined fly ash and spent sorbent are conveyed to a dry ash storage silo. Figure 4 shows a diagram of the SNRB process (2).

A sorbent and a baghouse fly ash obtained from the SNRB process were characterized at EERC. The sorbent sample was hydrated lime collected from a sampling port on the sorbent rotary feeder. The fly ash sample (containing spent sorbent) was obtained from a sampling port on one of the baghouse ash hoppers.

![Figure 4](image-url)  
**Figure 4.** Diagram of the SO\textsubscript{x}, NO\textsubscript{x}, RO\textsubscript{x}, BOX process (2).
TABLE 4
Average Operating and Mass Flow Data for the Period When Samples Were Collected from the SNRB Process

| Parameter                        | Value |
|----------------------------------|-------|
| Sorbent Flow Rate, lb/hr         | 494   |
| Baghouse Outlet Temperature, °F  | 781   |
| Excess Air in Boiler Exit Gas, % | 3.2   |
| Sorbent:SO₂ Ratio, mole:mole     | 2.0   |
| Ammonia:NOₓ Ratio, mole:mole     | 0.79  |

3.1.5 Low-NOₓ/Advanced Over-Fire Air Process

The low-NOₓ burner with advanced over-fire air process (LNB) is sponsored by Southern Company Services Inc. Partial funding for the project was provided in round two of DOE’s Clean Coal Technology Program. The samples characterized for this project were provided from a demonstration run with a 500-MWe pulverized coal, wall-fired boiler. Figure 5. shows a diagram of the LNB process. Operational data from the demonstration run was not available.

Figure 5. Diagram of low NOₓ/advanced over-fire air process (2).
The low-NO\textsubscript{x} burner uses a controlled fuel/air mixture to reduce NO\textsubscript{x} formation. This is done by controlling furnace operation to create a fuel-rich flame. The advanced over-fire air modification mixes over-fire air with furnace gases from the low NO\textsubscript{x} burner to achieve complete combustion and supplies air to the wall tube surfaces to prevent slagging and furnace corrosion. The objective of the process is to achieve a 50% reduction in NO\textsubscript{x} formation (2).

An ESP fly ash, an economizer ash and a bottom ash collected from the LNB process were characterized at EERC.

3.1.6 CT-121 Advanced Flue Gas Desulfurization Process

The CT-121 advanced flue gas desulfurization (FGD) process is sponsored by Southern Company Services Inc. Partial funding was provided in round two of DOE's Clean Coal Technology Program. The process combines limestone FGD reaction, forced oxidation, and gypsum crystallization in one reaction vessel. Since the CT-121 process is mechanically and chemically less complicated than conventional FGD processes, it is expected to be less expensive to use. Figure 6 shows a diagram of the CT-121 process. Operating data and mass flow data from the demonstration run were not available.

The CT-121 process is designed to remove 90% of the SO\textsubscript{2} from the flue gas with high reliability when a 2.5% sulfur coal is being used. The process should operate successfully with and without simultaneous particulate removal. The objective of the clean coal project is to demonstrate the CT-121 process along with several design innovations at a 100-MWe scale (2).

A sample of spent scrubber material collected from the CT-121 process was characterized at EERC. This sample was produced from a run that used particulate removal prior to the FGD process.

![Diagram of the CT-121 advanced flue gas desulfurization process](image)

Figure 6. Diagram of the CT-121 advanced flue gas desulfurization process (2).
3.1.7 Advanced Coal-Cleaning Process

The advanced coal-cleaning process (ACC) is sponsored by Custom Coals International. The process involves coal preparation using advanced physical coal cleaning and fine magnetite separation coupled with sorbent addition. The objective of the clean coal project is to demonstrate that advanced coal cleaning can produce low-cost compliance coals that meet full regulatory requirements for commercial-scale utility power plants.

A fly ash sample collected from a test burn of a Carefree Coal™ was characterized at EERC. The test burn was done at a commercial power plant. The Carefree Coal™ was produced by breaking and screening run-of-mine coal and using dense-media cyclones and finely sized magnetite to remove up to 90% of the pyritic sulfur and most of the ash. Figure 7 shows a diagram of the advanced coal-cleaning process. Operational data from the test burn was not available (2).

![Diagram of the advanced coal-cleaning process](image)

Figure 7. Diagram of the advanced coal-cleaning process (2).

3.2 Test Methods

The various tests and analyses done to characterize the advanced process wastes are listed in Table 5. Since some of these tests were not applicable to all of the wastes, a preliminary examination of the wastes followed by a review of selected test results was used to decide which additional tests would be appropriate for a specific waste.

The amount of waste material supplied for the characterization ranged from approximately twenty pounds up to a few hundred pounds. For all but one sample, enough material was supplied to do all of the desired tests and analyses. Most of the waste samples were received in a dry form, but a few had significant moisture contents. A high moisture content was not necessarily considered a problem as long it was determined that the waste had been originally collected wet.
TABLE 5

Tests and Analyses Included in the Waste Characterization Protocol

| Physical Tests                                      |
|-----------------------------------------------------|
| **Bulk Density**                                   |
| **Compacted Density**                              |

3.2.1 Physical Tests

3.2.1.1 Bulk Density

Bulk densities are used to estimate volume requirements for storage facilities and transportation equipment. Both poured and packed bulk densities were determined for each of the advanced process wastes. The poured bulk density estimates the volume occupied by the waste during temporary storage, before the material has time to compact under its own weight. The packed bulk density estimates the volume occupied by the waste during long-term storage.

To do the poured bulk density test, dry waste was weighed in a tared 100-mL graduated cylinder. The density was calculated by dividing the weight of the dry solids by their volume. To do the packed bulk density test, the poured waste sample was compacted by dropping the graduated cylinder 100 times, using a 1/2-in. drop. After compaction, the decrease in volume of the waste was noted, and the density was recalculated. These density tests were developed specifically to characterize coal combustion wastes and have been used for that purpose in previous studies (3,4).

3.2.1.2 Compacted Density

The compacted density of a waste can be used to estimate the fill space required for its ultimate disposal in a landfill. Compacted density also indicates the expected stability of the material after it has been permanently placed at a disposal site.
ASTM method D698-78, "Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using a 5.5-lb Rammer and 12-in. Drop," was used to determine the maximum compacted densities for the waste materials. This method involves preparation of a series of waste cylinders with different moisture contents using standard Proctor compaction.

The characteristic moisture–density relationship for a fine-grained, cohesive material is one where the density initially increases as the moisture content is increased until a maximum compacted density is reached. The moisture content at which maximum compacted density occurs is called the optimum moisture content. When the moisture content is increased above the optimum, the density will begin to decrease. A plot of compacted density versus moisture content has a characteristic inverted U shape and is referred to as a moisture–density curve.

In a few cases, the waste materials did not produce a normal moisture–density curve. These particular wastes were typically granular, noncohesive materials that did not display a distinct maximum compacted density.

3.2.1.3 Specific Gravity

Specific gravity is the ratio of the specific weight of the waste particles to the specific weight of distilled water at 4°C. Specific gravity indicates the average mass per unit volume of the solid particles contained in the waste.

ASTM method C188, "Standard Test Method for Density of Hydraulic Cement," was used to determine the specific gravities of the coal utilization wastes. The test is conducted by adding a known weight of the waste to kerosene contained in a special graduated flask. The kerosene volume displaced is recorded and used to calculate the specific gravity. ASTM method C188 is routinely used to measure specific gravities of fly ashes. This method is particularly useful for testing samples that contain a significant amount of water-soluble material.

3.2.1.4 Particle-Size Analysis

Particle-size analysis was used to determine the weight distribution of the various particle-size fractions contained in the coal utilization wastes. Particle-size data are useful for evaluating many handling- and disposal-related properties of the wastes, such as dusting potential, fluidization behavior, compaction, self-cementing behavior, and potential pozzolanic activity.

ASTM method D422-63, "Method of Particle-Size Analysis of Soils," was used to determine the particle-size distribution of the wastes. The method involves passing a dried sample through a set of sieves and recording the weight of the material retained on each sieve. The sieve series used for the waste analyses included 3/4-inch, 3/8-inch, No. 4, No. 10, No. 40, No. 100, and No. 200 sieves. If more than a small percentage of the waste sample passed the No. 200 sieve, a hydrometer analysis was done to measure the weight distribution of the minus-200 fraction.

Hydrometer analysis involves measuring the settling rates of the minus-200 waste particles in water. The settling rates can be related to particle sizes because smaller particles have a lower ratio of weight-to-drag resistance than larger particles; therefore, the smaller particles settle more slowly than the larger particles. The analysis is done by inserting a hydrometer into a well-mixed particle slurry, recording the reduction in the specific gravity of the slurry over time, and then calculating a particle-size distribution based on the specific gravity data.
3.2.1.5 Specific Surface Area

The specific surface area of a waste is important because it may affect leaching behavior. Usually, the larger the surface area of the waste, the more contact there will be between the water-soluble material contained in the waste and the aqueous leaching phase. Specific surface area is also a key indicator of how easily a waste can be fluidized in an airstream. Material fluidization is necessary for proper operation of certain types of pneumatic transfer equipment.

Specific surface areas of coal utilization wastes were measured with a Quantachrome single-point monosorb instrument, using the BET liquid nitrogen adsorption principle.

3.2.1.6 Blaine Fineness

Blaine fineness is calculated by relating the number and size of pores in the sample to the particle size and rate of airflow through the sample. It is useful for indicating the potential pozzolanic activity of a material. ASTM method C204-84, "Test Method for Fineness of Portland Cement by Air Permeability Apparatus," was used to determine the Blaine fineness of the coal utilization waste samples. The test is commonly used to estimate the specific surface area of fine materials such as fly ash.

Since Blaine fineness relates specifically to pozzolanic activity, only those samples expected to be reactive were tested. The characteristics that indicate potential pozzolanic activity are a high percentage of material passing the No. 200 sieve, a high specific surface area, and high silica and alumina contents.

3.2.1.7 Moisture Content

The moisture content of each advanced process waste was measured when the sample container was first opened at the EERC. The analysis was performed using ASTM method D2216-80, "Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures." The procedure involves weighing a sample of as-received fly ash, drying the sample at 110°C, and then reweighing the sample to determine the moisture loss.

Most of the wastes were dry when received, some had a significant moisture content, and a few had standing water in the container. No attempt was made to measure the moisture content of the samples that had standing water.

3.2.1.8 Heat of Hydration

Some coal utilization wastes release significant amounts of heat when conditioning water is added. The heat is generated because of hydration reactions that occur when water reacts with compounds such as calcium oxide contained in the waste.

The heats of hydration of the advanced process wastes were measured with a modified version of ASTM method C110-87, "Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone." The standard procedure is designed to test quicklime, and it calls for the addition of 400 mL of water to 100 g of quicklime in an insulated flask. The mixture is stirred, and the temperature increase recorded. For the modified procedure, the temperature increase was measured when the optimum amount of moisture (for maximum compacted density) was added to 500 g of waste material.
The objective of the modified test was to evaluate the heating behavior of the waste under typical handling and disposal conditions.

3.2.1.9 Pozzolanic Reactivity Test

Pozzolanic materials are usually composed of finely divided particles that contain a high total percentage of silica, alumina, and iron oxide. These materials react with lime in the presence of moisture to form cementitious interparticle bonds. Pozzolanic reactions, in contrast to hydraulic cementitious reactions, often occur slowly and continue for an extended time.

The method for testing coal utilization wastes for pozzolanic reactivity is contained in ASTM C311-87, "Method for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete." To do the pozzolanic reactivity test, the waste material is combined with Portland cement in a sand-mortar mix and then cast into 2-inch cubes. After curing, the cubes are tested for unconfined compressive strength. The pozzolanic reactivity of the waste is evaluated by comparing the strength of the cubes containing waste to a set of control cubes made with only Portland cement.

Since pozzolanic materials must be composed of very fine particles, coarse wastes such as bottom ash and FBC spent bed material were not tested for pozzolanic reactivity.

3.2.1.10 Unconfined Compressive Strength

The unconfined compressive strength of a compacted and cured waste indicates the expected load-bearing capacity and general stability of the material after disposal. Typically, the greater the unconfined compressive strength of the material, the higher it can be safely stacked at a disposal site and the steeper can be the side slopes on the pile.

Development of unconfined compressive strength is caused by hydraulic (i.e., cementitious) and pozzolanic chemical reactions in the waste. If the reactions are hydraulic, they may take place in a relatively short time (a matter of hours to days). However, if the reactions are pozzolanic, they may take longer to occur (a matter of weeks to months, or longer).

ASTM method D2166-66(79), "Test Methods for Unconfined Compressive Strength of Cohesive Soil," was used to prepare the advanced process waste specimens for unconfined compressive strength tests. The specimens were compacted in a 1.25-inch-diameter by 3-inch-long cylindrical mold, and they were cured in sealed plastic bags for 7, 14, and 28 days at 70°F before testing. All of the specimens were prepared at their optimum moisture contents as determined with the compacted density tests described above. The different curing times were used to determine how the unconfined compressive strength increased during an initial curing period.

The strengths of the cured waste cylinders were measured by applying a gradual compressive load until failure occurred. The load was applied with a hydraulic table, and it was measured with a proving ring and an indicating dial.

Only those wastes that displayed significant self-cementing behavior after curing were fully evaluated for unconfined compressive strength.
3.2.1.11 Permeability

The permeability (also referred to as hydraulic conductivity) of a waste is an important property because it indicates how rapidly water can move through a waste deposit and possibly generate a waste leachate.

The permeability of a waste is usually related to several factors such as particle-size distribution, self-cementing behavior, and degree of compaction. Poorly graded materials containing mostly sand- and gravel-sized particles will typically have a high permeability from $10^3$ to $10^4$ cm/sec. Well-graded materials containing a large fraction of very fine particles will typically have a moderately low permeability from $10^5$ to $10^6$ cm/sec. If the waste is actively self-cementing, the permeability of the material will tend to decrease further after it has been conditioned and allowed to cure, due to the occurrence of cementitious chemical reactions in the voids between the particles. Permeabilities of self-cementing wastes may decrease to below $10^7$ cm/sec after conditioning, compaction, and curing (5).

In the laboratory, permeabilities can be measured by several different methods. For this project, a constant-head permeability test was done while the sample was confined with a rubber membrane inside a triaxial cell. The advantage of this type of sample confinement is that it eliminates the possibility of sidewall leakage. The pressure head used for the permeability tests was approximately 5 psi, and the confining pressure was approximately 10 psi.

The waste specimens for the permeability tests were compacted at optimum moisture in a 1.25-inch-diameter by 3-inch-long mold. If the waste was actively self-cementing, it was cured for 28 days at 70°F before it was tested.

The permeability measurements obtained in the laboratory for the advanced process wastes may not be exactly representative of the permeabilities exhibited in the field. The in-field permeabilities of these wastes will depend on a number of factors, the most important of which are usually the degree of compaction used to place the waste at the disposal site, the moisture content of the compacted waste, and possibly the age of the waste deposit.

Generally, if the compacted density obtained in the field for a specific waste is lower than the compacted density used to prepare the waste specimens tested in the laboratory, then the in-field permeability will tend to be higher than the value measured in the laboratory. Further, if the moisture content of the waste in the field is significantly lower than the moisture content used for the specimens tested in the laboratory, then the in-field permeability will tend to be higher.

For those advanced process wastes that are either self-cementing or pozzolanic, in field permeabilities may decrease over time once they have been placed at a disposal site because continuing cementitious chemical reactions tend to clog the internal pores in the waste deposit. Thus for both self-cementing wastes and pozzolanic wastes, their in-field permeabilities may eventually be lower than the values reported from the laboratory tests.

3.2.1.12 Compressibility/Consolidation

When a noncementitious waste is stacked at a disposal site, it will gradually settle under its own weight. The rate of consolidation depends on both the load applied and the rate of migration of water out of the particle voids.
The test method used to measure waste compressibility/consolidation is described in ASTM D2435-80, "Test Method for One-Dimensional Consolidation Properties of Soil." No attempt was made to measure the rebound characteristics of the waste samples.

The consolidation test is done by placing a waste specimen in a special apparatus called a consolidometer. The specimen is loaded under compression, and the vertical deflection is measured as a function of time with an indicator dial gage. The test data can be used to determine a coefficient of consolidation (Cv) for the waste. Only three of the wastes met the criteria for testing.

3.2.1.13 Angle of Internal Friction

A waste having a low unconfined compressive strength can still develop a high load-bearing capacity if it is securely held in place by well-consolidated surrounding material. Thus, when a compacted waste material did not display significant unconfined compressive strength, its load-bearing capacity was tested while the specimen was confined in a triaxial chamber.

The function of the triaxial chamber is to confine the waste cylinder with an evenly applied pressure while a separate axial load is applied. Inside the chamber, the waste cylinder is enclosed in a rubber membrane, and water is used to transmit the confining pressure to the specimen.

ASTM method D2850-87, "Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression," was used as a general guide for the tests. The procedure was altered so that the specimens were allowed to drain while they were being loaded. The waste specimens for the triaxial strength tests were compacted at their optimum moisture content in a 1.25-inch-diameter by 3-inch-long mold.

The data generated from the triaxial strength test were used to determine an angle of internal friction for the compacted waste. This parameter indicates the degree to which the waste particles consolidate and interlock to resist shearing under a load. Usually, the higher the angle of internal friction, the higher will be the load-bearing capacity of the waste.

3.2.1.14 Angle of Repose

Angle of repose is the angle formed between the side slope and bottom of the pile when a dry waste is slowly poured onto a flat horizontal surface. The magnitude of the angle of repose, which is measured with a protractor, indicates how easily a material will flow by gravity. Generally, the lower the angle, the more freely the waste tends to flow when in a dry, loose condition.

3.2.2 Chemical and Mineral Characterization Methods

3.2.2.1 Bulk Chemical Composition

The chemical composition of a waste material can influence many important handling and disposal-related properties such as self-heating potential, self-hardening potential, pozzolanic reactivity, permeability, and leachate production potential. The usual method for determining the chemical composition of coal utilization wastes is to do a bulk chemical analysis. A standard bulk chemical analysis includes the following elements (all reported as oxides):

- Silicon, SiO₂
- Aluminum, Al₂O₃
- Sodium, Na₂O
- Potassium, K₂O
To do a bulk chemical analysis, the coal utilization waste was fused with lithium metaborate and then dissolved in dilute nitric acid. Silicon, aluminum, iron, calcium, magnesium, sodium, potassium, titanium, and phosphorous were analyzed from the dilute acid solution. Inductively coupled argon plasma (ICAP) spectrometry was used to determine the concentrations of titanium and phosphorous, and the remaining elements were determined by flame atomic absorption (AA) spectrometry. Matrix-matched standards were used for both spectrophotometric methods. Duplicate analyses were done. The results were reported as oxides on a weight percent basis according to standard bulk chemical reporting conventions.

Although the elements determined for a bulk chemical analysis are conventionally reported as oxides, these elements may or may not actually be present as oxides. For example, calcium in coal combustion wastes may be present as calcium oxide, calcium sulfate, calcium carbonate, and many other mineral forms.

To give a more thorough description of the chemical composition of each advanced process waste, additional compounds that could not be detected directly with the bulk chemical analysis were listed separately as "other constituents." The other waste constituents included compounds such as calcium carbonate, water of hydration, unburned carbon, anionic sulfur forms, and chloride. The amounts of these other constituents in a specific waste sample were determined by comparing the results of the bulk chemical analysis, mineralogical analysis, and thermogravimetric analysis.

3.2.2.2 Sulfur Forms

The total sulfur content of each advanced process waste was analyzed with a LECO induction furnace. The acid-labile sulfur was determined by extracting the sample with 40% hydrochloric acid and measuring the sulfur concentration of the extract by ICAP spectrometry. The acid extraction liberates nonpyritic sulfide as hydrogen sulfide and will solubilize the sulfite and sulfate that are not present as insoluble calcium or barium salts. Most of the hydrogen sulfide will escape to the atmosphere and thus be only a minor interference in the determination. The difference between the total sulfur value and the sulfate/sulfite value represents the acid-insoluble sulfide, such as pyrite, and the acid-insoluble sulfate/sulfite such as the Ca–Ba salts.

3.2.2.3 Chloride Content

The chloride content of the advanced process wastes was determined by extracting the chloride with distilled deionized water and then measuring the chloride concentration of the extract using an ion chromatograph.

3.2.2.4 X-Ray Diffraction Analysis

Qualitative x-ray powder diffraction analysis was used to identify the crystalline phases present in the advanced process wastes. The mineral composition of a waste is important because crystalline phases such as lime, tricalcium aluminate, and calcium sulfate can greatly affect the self-hardening and self-heating properties of the wastes.
To do the x-ray diffraction analysis, a representative aliquot of each waste was ground with ethyl alcohol and smeared onto a single-crystal, zero-background, quartz plate for analysis. Diffraction data were collected in 0.02° steps for a one-second dwell time using a Philips automated diffractometer equipped with a copper tube, theta-compensating slit, graphite-diffracted beam monochromator, and scintillation detector. Software supplied by Materials Data Incorporated was used for data collection, data reduction, and phase identification.

### 3.2.2.5 Scanning Electron Microscope Point Count

The scanning electron microscope point count (SE MPC) analysis technique was used to quantify the various mineral phases in the advanced process wastes. The SEMPC analysis is a valuable supplement to the x-ray diffraction analysis for determining the mineral composition of a waste.

The SEMPC analysis was done by collecting quantitative chemical composition data using a microprobe at many different points across the surface of a waste sample.

The data were collected using a stage automation system programmed according to operator-selected parameters to move in a raster pattern over a representative area of the sample. The system was programmed to halt the movement of the stage at regular intervals and collect an energy-dispersive spectrum for eight seconds. After eight seconds, the spectrum was integrated to determine the total number of x-ray counts collected. If the x-ray count was below a threshold selected by the operator, the computer moved the sample to the next point.

The chemical composition data were used to identify the mineral composition corresponding to each point. The mineral composition was determined by use of a computer program that compared the chemical composition data obtained at each point to various molar weight ratios for 43 different crystalline or amorphous phases known to be present in many coal utilization wastes.

The SEMPC technique is based on the point count technique used in quantitative optical mineralogy. In the optical technique, the sample is overlain with a optical grid. The mineral at each intersection of the grid is then classified and counted. By classifying a statistically significant number of grains, the mineral composition of the sample is determined. The SEMPC technique uses the same procedure, but the grid pattern is replaced by a programmed rastering of the electron microscope beam, and the optical identification is replaced by classification based on chemical composition.

### 3.2.2.6 Thermogravimetric Analysis

Thermogravimetric analysis (TGA) is useful for identifying certain mineral phases in wastes. For example, certain carbonate phases that cannot be identified with either bulk chemical or SEMPC analyses can be semiquantitatively indicated by a weight loss during the TGA run because they decompose when heated between 600°C and 900°C. The presence of reduced sulfur species such as sulfides and sulfites can be also indicated by a weight gain at the end of the TGA run when oxygen is introduced to the heated sample.

The instrument used for TGA analysis of the wastes was a DuPont Model 951 module interfaced with a DuPont 1090 thermoanalyzer and data processor. The instrument has a 100-mg capacity and a maximum heat up rate of 100°C/min.

To do the TGA analysis, the waste sample was heated to 1075°C while the weight, time, and temperature were logged by a computer. From this data, a plot of sample weight versus time (or
temperature) was prepared for each sample. The loss of weight from the sample corresponded to
dehydration, decomposition, or volatilization of various constituents as the temperature increased.
Depending on the temperature range where the weight loss occurred, the particular mineral phase
affected can be tentatively identified.

3.2.2.7 Coal Analysis

Proximate analysis of the coal samples was performed using an automated coal analyzer. Sulfur
content was determined using a LECO induction furnace, and the remaining parameters for the ultimate
analysis were determined using an automated carbon–hydrogen–nitrogen analyzer. The heating value
was determined by adiabatic calorimetry.

Representative aliquots of the coal samples were ashed, and elemental concentrations of the major
cations were determined using the analytical methods outlined in Section 3.2.2.1 for bulk chemical
analysis. Samples of the coal were digested with sulfuric and nitric acids for the determination of
arsenic, barium, cadmium, chromium, mercury, lead, selenium, and silver. Barium, cadmium, and
chromium were determined by ICAP. Arsenic and selenium were determined using hydride generation
AA. Cold vapor generation AA was used to determine mercury, and graphite furnace AA was used to
determine lead and silver.

3.2.2.8 Ceramicrete

Ceramicrete is a phosphate-based ceramic material made at room temperature. It is formed by
mixing magnesium oxide, a soluble phosphate powder, and waste ash with water. The phosphate
source used for the mixes was potassium dihydrogen phosphate (KH2PO4, Fisher certified reagent).
The magnesium oxide (MgO) used was also a Fisher certified reagent. The percentages of KH2PO4
and MgO used for the Ceramicrete mixes were selected based on mix proportions described in the
literature (6).

Each batch of Ceramicrete was made by first thoroughly mixing the dry ingredients and then
adding the appropriate volume of water. The moistened mixture was stirred 100 strokes with steel
spoon. Next, the mix was placed into a brass mold to make three identical specimens. Each specimen
was formed as a two inch cube. Depending on how much water was added to the mix, the material was
either poured into the mold or tamped in. Three specimens were prepared from each mix. The
specimens were cured for either 7 days (one specimen) or 21 days (two specimens) at room
temperature and then tested for unconfined compressive strength. One of the 21-day specimens was
placed in water for the last 14 days of its curing period to see if saturation conditions would affect
strength development.

An approximate determination of how much water should be added to the Ceramicrete mixes was
done by making several different batches of Ceramicrete using clean river sand. Four sand mixes were
prepared using different amounts of water. (See Mixes 1 through 4 in Table 19). The moisture content
and the associated mix consistency were correlated and the consistency that produced the highest
strength was noted. The results of the sand tests indicated that the highest strengths developed when just
enough water was added to bring the mix consistency to that of a pourable slurry. A similar consistency
was then used to prepare the advanced process waste mixes. Although mix consistency was used as a
guideline for batch preparation, its usefulness should not be overestimated. This was because all of the
mixes were quite exothermic and tended to stiffen in a matter of minutes when the water was added.
3.2.2.9 Ash Conversion to Zeolite

Zeolites were prepared from nine different ash samples by heating with aqueous NaOH using two different conditions. In the first method, ash (10 g) was mixed with 80 mL of 2.5 M NaOH in a plastic vessel and stirred for two days at ambient temperature, then heated at 80°C for six days with occasional shaking. The mixture was cooled and filtered. The collected product was washed repeatedly with deionized water until the pH reached 8. The residue was dried at 100°C. The weight yields were consistently close to 100% of the original.

In the second method, the same set of ashes were mixed with the same amount of 3.5 M NaOH and heated at 100°C for two days. The work up was the same, and product yields were again close to 100%. Products from both preparations were characterized with XRD and SEM and tested further for ion exchange capacity. Products were impregnated with a cationic surfactant and sorption isotherms for TCE were determined.

4.0 DATA

Raw data collected for the thirteen, advanced process wastes, one unreacted sorbent material, and six coals characterized for Task 3 of this project are contained in a set of ten appendices.

Appendix A - Waste Physical Property Data
Appendix B - Waste Chemical and Mineral Compositions
Appendix C - Waste Moisture-Density Curves
Appendix D - Waste Particle-Size Distribution Curves
Appendix E - Waste Compressibility/Consolidation Analysis
Appendix F - Waste Scanning Electron Microscope Photographs
Appendix G - Waste Bulk Chemical Composition Data
Appendix H - Waste Scanning Electron Microscope Point Counts
Appendix I - Waste X-Ray Diffraction Analyses
Appendix J - Waste Thermogravimetric Analyses
Appendix K - Coal Bulk Chemical Composition Data

5.0 RESULTS AND DISCUSSION

Advanced coal utilization processes currently being developed in the United States will be part of the next generation of energy production technologies. These processes will produce large amounts of solid wastes. To reduce the costs and potential adverse environmental impacts associated with the disposal of wastes from advanced processes, appropriate waste management techniques must be used.

Although waste management systems for advanced processes will be similar in many respects to those now being used for conventional coal combustion wastes, modifications may sometimes be needed to accommodate the unique properties of the advanced process wastes. In this section, the geochemical and geophysical properties of advanced process wastes are discussed, and the impacts of these properties on waste handling, transport, and disposal operations are evaluated. The evaluation was done by examining the waste properties and comparing them with ranges of values that are generally considered acceptable for conventional waste management operations, and by identifying waste characteristics such as extreme abrasiveness or self-hardening activity that might pose special problems for the operations.
5.1 Solid Waste Management Systems

Waste management systems for coal-fired power plants usually incorporate some or all of the following subsystems (3):

- A transfer subsystem to remove the waste from the primary collection device and transfer it to storage
- A storage subsystem to equalize the waste flow at the plant
- A conditioning subsystem to moisten the waste in preparation for transport and disposal
- A transport subsystem to convey the waste to an ultimate disposal site
- A disposal subsystem to contain the waste ultimately

Beyond these subsystems, additional handling and storage facilities may be needed if the waste has commercial value as a by-product so that it can be sold as demand arises

5.2 Transfer Subsystems

Waste transfer involves in plant movement of the waste from an initial collection point such as the ESP or the ash quench tank to some type of short-term storage facility. Waste transfer subsystems usually consist of feeder and transport components. The feeder removes the waste from the initial collection point, and the transport component moves it around the plant.

The selection of a transfer subsystem for an advanced process waste should be based on an analysis of the physical and chemical properties of the waste, the amounts of material to be handled, and the distances that the material must be moved. For the following discussion, the only information available was the physical and chemical property data collected during the testing phase of the project. Thus the conclusions drawn will be limited to general recommendations that concern the suitability of different transfer options for the advanced process wastes and the identification of specific transfer mechanisms that may not be compatible with certain wastes.

Transfer subsystems can be designed to handle wastes with moisture contents and consistencies ranging from a dry powder to a wet slurry. However, advanced process wastes will probably not be transferred short distances in slurry form because of their frequent self-hardening and/or self-heating behavior. Thus slurry transfer will not be examined in this section, although a discussion of slurry-handling is included in Section 5.5 (Transport Subsystems).

Dry transfer subsystems are classified as either pneumatic or mechanical processes. The most widely used pneumatic transfer processes are dilute-phase vacuum conveyors, dilute-phase positive-pressure conveyors, dilute-phase vacuum/positive-pressure conveyors, dense-phase vacuum conveyors, and air-activated gravity conveyors. The most widely used mechanical transfer processes are belt, screw, chain, and vibrating conveyors and bucket elevators.

5.2.1 Pneumatic Conveyors

Dilute-phase pneumatic conveyors use high-velocity air to move materials through a system of pipes. They are usually used in power plants to transfer wastes over relatively short distances. The
airstream for the pneumatic conveyor can be produced by either drawing air through the pipes under a vacuum or by pumping air through the system using positive pressure. Also, for certain applications, vacuum and positive-pressure air movement can be used in different sections of the same transfer subsystem. Dilute-phase pneumatic conveyors are the most commonly used types of fly ash transfer subsystems in U.S. power plants.

Materials conveyed with dilute-phase systems must be dry and relatively fine. Vacuum and positive-pressure conveyors can handle materials with particle sizes ranging from about one \( \mu m \) to 0.64 cm and bulk densities ranging from one to 200 lb/ft\(^3\). Moving particles as large as one inch may sometimes be possible if the bulk density of the waste does not exceed 60 lb/ft\(^3\). Generally, materials with a particle size of about 50 \( \mu m \) are easiest to transfer with these systems. The material being transferred should be kept dry to avoid problems with clogging in the pipes (3).

Dense-phase pneumatic conveyors are similar to dilute-phase systems, but use a higher material-to-air ratio. Dense-phase systems have been used in Europe with good results for handling fly ash, and they may be useful for transferring some advanced process wastes. Dense-phase conveyors should only be used for transferring fine, dry wastes because the material must be readily fluidized for the conveyor to operate properly. Generally, dense-phase conveyors cannot handle as broad a range of particle sizes as dilute-phase systems.

Air-activated gravity conveyors transfer materials pneumatically through a rectangular duct. This type of conveyor operates by fluidizing the waste with an airstream directed up through the porous bottom of the duct. When the duct is inclined slightly, the fluidized waste flows by gravity. Air-activated gravity conveyors are usually used for relatively short transfer distances. Since material movement depends on fluidization, many of the same requirements apply to an air-activated gravity conveyor as apply to a dense-phase conveyor. Air-activated systems generally require that 100% of the material being conveyed passes through a No. 20 sieve (which has 841-\( \mu m \) openings) and that 20% to 60% pass through a No. 200 sieve (which has 74-\( \mu m \) openings). The material must also be dry for the conveyor to work properly. Usually the moisture content should be less than 1\%(3).

The important material properties that affect the compatibility of advanced process wastes with pneumatic conveyors are moisture content, particle size distribution, bulk density, surface area, tackiness, abrasiveness, and corrosiveness. Table 6 summarizes some important physical properties for the advanced process wastes. Table 7 contains qualitative estimates of the abrasiveness and corrosiveness of the advanced process wastes.

If the waste produced an aqueous slurry with a pH >11.5 or <4.5, it was classified as potentially corrosive. Although slurry pH is a useful indicator of waste corrosiveness, the actual corrosive behavior of a waste will also depend on other factors such as the amount of free moisture in the waste and the presence of soluble anions like chloride and sulfate in the free moisture phase.

The abrasiveness of each waste was rated as either high, moderate, or low based on the amounts of quartz determined in the mineralogical analysis and the total SiO\(_2\) and Al\(_2\)O\(_3\) determined in the bulk chemical analysis. Generally, quartz is the most abrasive form of silicon oxide in the wastes. Other forms of silicon oxide contained in glassy phases may not be as abrasive as quartz. The properties listed in Table 7 do not necessarily indicate whether a specific transfer subsystem can or cannot handle a particular waste, but they may indicate whether special precautions should be taken in the selection of equipment to reduce future maintenance problems. For example, if a waste is extremely abrasive, the conveyor could be constructed with an abrasion-resistant alloy.
Wastes conveyed pneumatically should be dry because moisture can cause the particles to agglomerate and clog pipes. Since the bottom ashes from the GRSI, CR, and LNB processes and the spent FGD sorbent all have relatively high moisture contents, these are not compatible with pneumatic transfer systems. Since dilute-phase pneumatic conveyors can handle particle sizes up to one inch when the bulk density is less than 60 lb/ft³, dilute-phase conveyors can probably be used to transfer any of the dry advanced process wastes studied. Dense-phase and air activated conveyors differ from dilute-phase conveyors because they require that the waste be fluidized to operate properly. Because the waste must be fluidized, tighter limits on maximum particle size and bulk density are required for these types of conveyors. Based on this constraint, it appears that the PFBC bottom ash and the LNB economizer ash may not be suitable for transfer with dense-phase and air activated conveyors.

Clogging is a common problem with pneumatic systems. None of the dry advanced process wastes were tacky materials that would be expected to agglomerate and clog when transferred. However some materials can absorb moisture from the air and become tacky while being transferred. This problem can occur with a waste that contains a significant amount of quicklime (CaO) which can hydrate during transfer. The only advanced process waste that had a high enough quicklime content to suggest that this problem might occur was the GRSI fly ash.

Several advanced process wastes were classified as abrasive and potentially corrosive. However, these properties would probably not create any major problems for pneumatic conveyors. If necessary, additional equipment specific testing can be done to determine whether special alloys will be needed.

Table 8 shows the results of a compatibility analysis done by comparing the properties of the advanced process wastes to the various limitations specified for each type of pneumatic conveyor. Depending on the suitability of each type of conveyor for transferring a particular waste, either a "y" (for a yes) or an "n" (for a no) was placed in the column designated for that conveyor.

5.2.2 Mechanical Conveyors

Belt conveyors use a continuous belt loop supported by rollers to transfer material. The temperature of materials being transferred with a belt conveyor should not exceed 150°F with normal belt materials or 300°F with special belt materials. Materials being transferred by a belt conveyor should have a particle size greater than 0.125 inches to reduce dusting and slippage. If dusting is expected to be a problem, the belt can be enclosed or moisture can be added to the waste. Although adding too much moisture may cause the waste to become sticky and difficult to unload (3).

Screw conveyors consist of a long steel auger supported in a U-shaped steel trough. The turning auger moves the material through the trough. Materials transferred with a screw conveyor must be free-flowing, with particle sizes ranging from very fine to 4 inches in diameter. Dusting can be a problem with very fine wastes. Abrasion and corrosion can create wear problems with screw conveyors because of the moving parts.

Chain conveyors use a heavy steel chain to move materials through a trough. The chain is connected to a power drive and often has some type of blade attached for moving the materials. Various types of free-flowing materials can be transferred with chain conveyors. Generally, materials with particle sizes ranging from very fine to granular can be moved with some type of chain conveyor. Hot materials can also be handled with chain conveyors, although very hot materials may have to be cooled before being transferred. Generally, the temperature of wastes being transferred by chain or
### TABLE 6

**Important Physical Properties for Selection of Transfer Subsystems**

| Sample Designation | Maximum Particle Diameter (mm) | Mean Particle Diameter ($D_{50}$, mm) | Specific Surface Area ($m^2/g$) | Loose Dry Bulk Density (lb/ft$^3$) |
|--------------------|-------------------------------|--------------------------------------|---------------------------------|----------------------------------|
| GRSI-FA            | 0.02                          | 0.002                                | 3.93                            | 38.2                             |
| GRSI-BA            | 10.0                          | 1.06                                 | 8.32                            | 40.7                             |
| PFBC-FA            | 0.03                          | 0.014                                | 3.36                            | 23.1                             |
| PFBC-CA            | 2.0                           | 0.107                                | 1.76                            | 65.2                             |
| PFBC-BA            | 5.0                           | 0.9                                  | ND*                             | 80.3                             |
| CR-FA              | 0.1                           | 0.008                                | 0.83                            | 39.5                             |
| CR-BA              | 9.0                           | 2.07                                 | 16.43                           | 76.5                             |
| SNRB-FA            | 0.07                          | 0.006                                | 5.64                            | 21.1                             |
| SNRB-S             | 0.06                          | 0.005                                | 8.9                             | 24.2                             |
| LNB-FA             | 0.08                          | 0.03                                 | 2.13                            | 53.0                             |
| LNB-EA             | 20.0                          | 0.26                                 | 0.97                            | 59.5                             |
| LNB-BA             | 22.0                          | 7.2                                  | 2.02                            | 38.8                             |
| FGD-SS             | 0.1                           | 0.056                                | 13.82                           | 52.1                             |
| AAC-FA             | 0.13                          | 0.09                                 | 2.8                             | 35.5                             |

* Test could not be done on this sample.

### TABLE 7

**Estimated Abrasiveness and Corrosiveness of the Advanced Process Wastes**

| Sample Designation | Moisture Content$^1$ (wt. %) | Waste Abrasiveness$^2$ | Waste Corrosiveness$^3$ |
|--------------------|-------------------------------|------------------------|-------------------------|
| GRSI-FA            | 0.2                           | High                   | Potentially Corrosive   |
| GRSI-BA            | 54                            | High                   | —                       |
| PFBC-FA            | 0.1                           | Moderate               | —                       |
| PFBC-CA            | 0.1                           | Moderate               | Potentially Corrosive   |
| PFBC-BA            | 0.042                         | Low                    | —                       |
| CR-FA              | 1.15                          | High                   | Potentially Corrosive   |
| CR-BA              | SW$^4$                        | High                   | —                       |
| SNRB-FA            | 0.78                          | Low                    | Potentially Corrosive   |
| SNRB-S             | 1.84                          | Low                    | Potentially Corrosive   |
| LNB-FA             | 0.66                          | High                   | Potentially Corrosive   |
| LNB-EA             | 0.57                          | High                   | —                       |
| LNB-BA             | 41.8                          | High                   | Potentially Corrosive   |
| FGD-SS             | 25.6                          | Low                    | —                       |
| ACC-FA             | 1.65                          | High                   | —                       |

$^1$ As received moisture content  
$^2$ Basis for ranking abrasiveness:  
- Quartz Content  
  - <5%  
  - 5% to 10%  
  - >10%  
- or Total SiO$_2$ + Al$_2$O$_3$ Content  
  - <30%  
  - 30% to 50%  
  - >50%  
$^3$ Basis for ranking corrosiveness:  
Wastes were listed as "potentially corrosive" if the pH of a 50% aqueous slurry was either >11.5 or <4.5.  
$^4$ Sample received with standing water.
TABLE 8

Suitability of Pneumatic Systems for Transferring Advanced Process Wastes

| Sample Designation | Pneumatic Systems       |   |   |   | Comments                           |
|--------------------|-------------------------|---|---|---|------------------------------------|
|                    | Vacuum | Positive-Pressure | Vacuum/Positive-Pressure | Dense-Phase | Air-Activated Gravity |                     |
| GRSI-FA            | Y      | Y                 | Y                           | Y           | Y                     |                     |
| GRSI-BA            | N      | N                 | N                           | N           | N                     | Difficult to fluidize, High moisture content |
| PFBC-FA            | Y      | Y                 | Y                           | Y           | Y                     |                     |
| PFBC-CA            | Y      | Y                 | Y                           | N           | N                     | Difficult to fluidize  |
| PFBC-BA            | Y      | Y                 | Y                           | N           | N                     | Difficult to fluidize  |
| CR-FA              | Y      | Y                 | Y                           | Y           | Y                     |                     |
| CR-BA              | N      | N                 | N                           | N           | N                     | Difficult to fluidize, High Moisture content  |
| SNRB-FA            | Y      | Y                 | Y                           | Y           | Y                     |                     |
| SNRB-S             | Y      | Y                 | Y                           | Y           | Y                     |                     |
| LNB-FA             | Y      | Y                 | Y                           | Y           | Y                     |                     |
| LNB-EA             | Y      | Y                 | Y                           | N           | N                     | Difficult to fluidize  |
| LNB-BA             | N      | N                 | N                           | N           | N                     | Difficult to fluidize, High moisture content|
| FGD-SS             | N      | N                 | N                           | N           | N                     | High moisture content |
| ACC-FA             | Y      | Y                 | Y                           | Y           | Y                     |                     |
screw conveyors should not exceed 900°F. Abrasive materials may be difficult to handle with chain conveyors due to excessive wear.

Vibrating conveyors usually consist of a steel pan mounted on springs and vibrated by an electric motor. The vibration causes the material being transferred to move along the pan in a series of short hops. Vibrating conveyors are best suited to moving granular materials rather than fine powders. Hot materials can be transferred with this type of conveyor, but abrasive materials may cause wear problems.

Bucket elevators move materials up an incline or vertically with a series of buckets attached to a chain or belt. The elevator is usually enclosed to contain the material being conveyed. Bucket elevators having the proper bucket shape can move almost any type of material with a maximum particle size up to about 6 inches.

The important material properties that affect the compatibility of advanced process wastes with mechanical conveyors are temperature, moisture content, particle size distribution, tackiness, abrasiveness, and corrosiveness. Tables 6 and 7 summarize some important physical properties for the advanced process wastes that relate to compatibility with mechanical conveyors.

Very fine advanced process wastes such as fly ashes may be difficult to transfer with mechanical conveyors because of dusting problems. Dusting can be controlled by adding moisture to the waste, but the moisture may increase corrosiveness and tackiness. Extremely high temperatures such as those that occur with the bed ash from the PFBC process will be difficult to handle with mechanical conveyors. This waste may have to be cooled before it can be transferred by any means. Abrasiveness can be a real problem with mechanical conveyors particularly when moving parts are in constant contact with the waste. In this case the conveyor may have to be constructed with special abrasion resistant alloys.

5.3 Storage Subsystems

Storage facilities are usually needed for coal utilization wastes to equalize the flow to the conditioning, transport, and disposal subsystems. If the waste is transferred dry, it can often be stored in a bin or silo. These containers are usually cylindrical or square in cross section, enclosed, and may have a funnel shaped hopper at the bottom to control the discharge.

Design considerations for storage facilities include the rate at which the waste will be produced, how long it may have to be stored, and the physical and chemical properties that control its flow characteristics. Since specific production and storage data are not available for the advanced process wastes, this discussion will be limited to the pertinent waste properties. These include the angle of repose, packed dry bulk density, self-heating potential, self-hardening potential, abrasiveness, corrosiveness, and utilization potential.

The possible self-heating and/or self-hardening of a waste are important considerations for storage because these reactions can lead to troublesome clogging in the discharge hopper if the material is allowed to get wet. The self-hardening and self-heating behaviors of the advanced process wastes are indicated in Table 9. The self-hardening potential of each waste was rated as either high, moderate, or low based on the 7-day unconfined compressive strengths measured. The self-heating potential was rated as either high, moderate, low, or none based on the temperature increase recorded for each waste.
when it was mixed with water. Abrasiveness and corrosiveness are important considerations for selecting suitable materials for constructing storage facilities. If a waste is corrosive, it may be necessary to construct the silos and hoppers from concrete or stainless steel rather than mild steel, and if the waste is abrasive, it may be necessary to construct some parts of the storage system from abrasion-resistant steel alloys. Some other important properties of the advanced process wastes which relate to the design of storage facilities are listed in Table 10. Angle of repose is the angle formed between the side slope and bottom of the pile when dry waste is poured on a flat surface. Angle of repose is important because, typically, the smaller the angle, the more easily the material will flow by gravity. The packed dry bulk density indicates how much waste can be held in a given storage volume.

The utilization potential of a waste is also an important design consideration for the storage subsystem. If a waste has high utilization potential, building extra storage capacity to hold the waste until it can be sold may be desirable. The storage capacity needed will depend on the local coal combustion by-product market. Further, if utilization of a waste requires that it be chemically reactive, as is the case with many types of fly ash, keeping the waste dry while in storage will be important. Various utilization options for advanced process wastes are discussed in Section 5.7.

5.4 Conditioning Subsystems

Conditioning is usually done by mixing a very fine waste with just enough water to produce a moist, cohesive product. The purpose of waste conditioning is to improve the handling properties of the material before transport to an ultimate disposal site and to facilitate proper placement of the waste at the disposal site. Conditioning helps to control dusting, increase cohesiveness, and increase maximum compacted density. Instead of adding water directly to the waste, conditioning is sometimes done by mixing a dry waste with a relatively wet scrubber sludge to produce a moist product. Either method can be used, although conventional scrubber sludge may not be available at a plant that is producing an advanced process waste.

The amount of water used to condition a coal combustion waste is usually just enough to keep it from dusting. This is typically between 10 and 20 percent on a dry weight basis for a conventional fly ash. Most coal combustion plants try to keep the amount of added water low so that the waste does not become tacky and difficult to handle.

With most coal utilization wastes, an optimum moisture content produces the maximum compacted density. Conditioning the waste to its optimum moisture content is usually beneficial, because good compaction tends to reduce waste permeability, increase load-bearing capacity, and permit the maximum amount of material to be placed in a unit volume at the disposal site. Normally, adding the optimum moisture to the waste will not cause handling problems, but many managers at combustion plants keep the conditioning moisture below the optimum. Table 11 lists the optimum moisture contents determined for the advanced process wastes, along with their maximum compacted dry densities (using standard Proctor compaction).

Various types of mixers are used to condition conventional coal combustion wastes. These include pug mills, horizontal rotary drum mixers, and turbine mixers. A pug mill contains one or two shafts to which are attached short, heavy paddles. The shafts rotate in a horizontal trough. The water and dry waste continuously enter at one end of the trough, and the conditioned mixture is extruded at the other end. These mixers are efficient, durable, and relatively easy to clean. They work best when a fairly dry mixture is needed. For the advanced process wastes, pug mill mixers are best suited to the finer materials that are more difficult to wet and thus require more mixing energy.
TABLE 9
Estimated Self-Heating and Self-Hardening Potentials of the Advanced Process Wastes

| Sample Designation | Waste Self-Heating Potential | Waste Self-Hardening Potential |
|--------------------|-------------------------------|-------------------------------|
| GRSI-FA            | Moderate                      | Moderate                      |
| GRSI-BA            | None                          | Moderate                      |
| PFBC-FA            | Low                           | High                          |
| PFBC-CA            | None                          | High                          |
| PFBC-BA            | None                          | None                          |
| CR-FA              | Low                           | High                          |
| CR-BA              | None                          | None                          |
| SNRB-FA            | Low                           | High                          |
| SNRB-S             | Low                           | NA                            |
| LNB-FA             | Low                           | None                          |
| LNB-EA             | Low                           | None                          |
| LNB-BA             | Low                           | None                          |
| FGD-SS             | None                          | None                          |
| ACC-FA             | None                          | Moderate                      |

1 Self-heating potential was estimated from the maximum waste temperature after the waste was mixed with water. None = <70°F; Low = 70°F to 100°F; Moderate = 100°F to 200°F; and High = >200°F.

2 Self-hardening potential was estimated from the 7-day compressive strength of the wastes. None = <5 psi; Low = 5 to 10 psi; Moderate = 10 to 50 psi; and High = >50 psi.

3 Test was not applicable to this sample.

TABLE 10
Angle of Repose and Packed Dry Bulk Density of the Advanced Process Wastes

| Sample Designation | Angle of Repose (°) | Packed Dry Bulk Density (lb/ft³) |
|--------------------|---------------------|---------------------------------|
| GRSI-FA            | 35                  | 51.6                            |
| GRSI-BA            | 55                  | 55.1                            |
| PFBC-FA            | 40                  | 28.2                            |
| PFBC-CA            | 43                  | 79.5                            |
| PFBC-BA            | 35                  | 81.3                            |
| CR-FA              | 41                  | 47.0                            |
| CR-BA              | 57                  | 85.9                            |
| SNRB-FA            | 50                  | 25.4                            |
| SNRB-S             | 52                  | NA*                             |
| LNB-FA             | 25                  | 62.4                            |
| LNB-EA             | 30                  | 66.8                            |
| LNB-BA             | 40                  | 42.6                            |
| FGD-SS             | 40                  | 65.1                            |
| ACC-FA             | 35                  | 44.4                            |

*NA – Test was not applicable to this sample.
### TABLE 11

Optimum Moisture Content and Maximum Compacted Density of the Advanced Process Wastes

| Sample Designation | Optimum Moisture Content (% of dry wt) | Maximum Compacted Density (lb/ft³) |
|-------------------|---------------------------------------|-----------------------------------|
| GRSI-FA           | 31.6                                  | 75.0                              |
| GRSI-BA           | 24.5                                  | 78.9                              |
| PFBC-FA           | 19.5                                  | 105.4                             |
| PFBC-CA           | 19.7                                  | 105.9                             |
| PFBC-BA           | 20.5                                  | 96.0                              |
| CR-FA             | 31.8                                  | 85.3                              |
| CR-BA             | 17.6                                  | 117.8                             |
| SNRB-FA           | 58.8                                  | 58.2                              |
| SNRB-S            | NA²                                   | NA                                |
| LNB-FA            | 26.7                                  | 78.8                              |
| LNB-EA            | 36.0                                  | 70.5                              |
| LNB-BA            | 46.6                                  | 59.0                              |
| FGD-SS            | 48.5                                  | 72.8                              |
| ACC-FA            | 30.5                                  | 72.5                              |

1 This is the optimum moisture content using standard Proctor compaction.

2 NA – Test was not applicable to this sample.

A horizontal rotary drum mixer is simply a large diameter steel drum with some internal baffles. The water and dry waste are added at one end of the drum and mixed as it rotates. The baffles move the mixture continuously through the drum, and the conditioned waste exits at the other end. Rotary drum mixers do not supply as much mixing energy as pug mills, but they are durable and very easy to clean out. For the advanced process wastes, rotary drum mixers are probably best suited to the coarser materials that are easier to wet.

A turbine mixer consists of a circular trough with a housed shaft in the center. A set of radial arms projects from the shaft into the trough. A blade is attached to each arm to scrape the bottom of the trough. The dry waste and water are added to the trough and mixed by rotating the shaft. The mixer is emptied by opening the bottom of the trough and letting the contents fall through. For the advanced process wastes, a turbine mixer would work well for mixing fine materials to a relatively dry consistency.

Mixing techniques used to condition conventional coal combustion wastes may not be appropriate for all advanced process wastes. Wastes that are vigorously self-heating, for example, may require a significant amount of additional water to satisfy hydration reactions. To condition a highly reactive waste to the optimum moisture, it may be necessary to initially mix it as a slurry. As the waste hydrates and heats up, the free moisture content will decrease and the mixture will spontaneously stiffen. Usually it takes about 20 minutes after mixing for a self-heating waste to dry to its optimum moisture content.
Based on a review of their physical and chemical properties, it appears that none of the advanced process wastes studied should create any unique problems for conditioning subsystems. The GRSI fly ash was the only waste that got even moderately hot when mixed with water. However, this waste did not get hot enough to produce steam and thus should not be difficult to condition with an appropriate mixer. Several wastes did harden and develop strength when conditioned and cured. The PFBC cyclone ash actually attained a compressive strength of more than 2000 psi. However all these materials set up rather slowly, and thus should not cause any problems during conditioning.

5.5 Transport Subsystems

The purpose of a waste transport subsystem is to convey waste from the plant to a long-term storage facility or an ultimate disposal site. The waste can be transported as a wet slurry, in a moist conditioned form, or in a dry form. A waste slurry would probably contain over 100 percent moisture on a dry weight basis; a moist conditioned waste would normally contain between 10 and 20 percent moisture; and a dry waste would normally contain less than 1 percent moisture. A wet slurry will normally be hydraulically transported from the plant to a sedimentation basin. Dry or moist conditioned waste can be transported from the plant to the disposal site by truck, railroad, barge, belt conveyor, or aerial tram. Dry waste can also be transported by pneumatic conveyor.

5.5.1 Wet Transport

Wet transport of conventional coal combustion wastes typically begins at a central collection point in the plant. At that point, the waste is mixed with water to form a slurry and hydraulically transported from the plant. After transport, the slurry is sent to a basin where the solids are settled out. The slurry water can be recycled to the plant, stored, discharged, or evaporated. The waste can be left in the settling basin, transferred to a long-term storage facility, or placed in a landfill. Fly ash and bottom ash may or may not be mixed before transport. Transport distances from the plant to the settling pond are not usually more than one mile (3).

Wet transport has several advantages over conditioned or dry waste transport. Wet transport subsystems are not usually affected by transportation strikes or rising fuel costs. There is less noise, dust, and traffic associated with wet transport. And wet transport is usually less expensive than other types of transport. The disadvantages of wet transport include higher site development costs, larger quantities of water to control, a larger disposal site required for a given mass of waste, a possible reduction of the utilization potential of the waste, and less flexibility to change the system in the future.

Conventional fly ash and bottom ash are often transported as slurries, and so at least some advanced process wastes can probably also be transported in this manner. However, some characteristics of the advanced process wastes could present special problems for wet transport. Wastes that display self-heating and self-hardening activity may be difficult to handle, and the high pH associated with many advanced process waste slurries may cause corrosion problems.

Self-heating should not be a problem for the thirteen advanced process wastes studied for task three because none released a large amount of heat when wetted. However, several wastes were self-hardening and it could create serious problems if these were to set up while being sluiced through a transport channel. The advanced process wastes that exhibit the most significant self-hardening behaviors are the PFBC fly ash and cyclone ash, the CR fly ash, and the SNRB fly ash. Various additives can be used with wet transport subsystems to retard the set of cementitious wastes, but continuous use of such additives will increase transport costs. Further, several wastes produce a high pH mixture when slurried. If these slurries present a corrosion problem for the transport equipment,
the subsystem should be constructed with special corrosion-resistant materials that may significantly increase transport costs.

There is a general trend away from the use of wet transport subsystems for new power plants because of problems with managing the water used to slurry the wastes. If discharging excess water from the system is necessary, a discharge permit will be needed, and these are becoming more difficult to obtain. It is also possible that an episode of high precipitation will cause the settling pond to flood. If this happens, it may be necessary to discharge a large amount of water from the pond quickly. Since many advanced process wastes produce a high pH in water, an uncontrolled discharge from such a system could cause serious environmental damage. Further, controlling the movement of leachate to the groundwater is generally more difficult with ponds than with dry disposal sites.

5.5.2 Dry and Conditioned Transport

Trucks are the most widely used equipment for transporting both dry and conditioned wastes. Truck transport is flexible because it can be done with either utility-owned or contractor-owned equipment, and so the number of trucks being used can usually be quickly increased if greater transport capacity is needed. Another attractive feature of truck transport is that if an alternate disposal site is being used, the trucks can be rerouted to the new site with little disruption to the system. If the waste is conditioned at the plant, it is usually hauled in dump trucks. If the waste is to be conditioned at the disposal site or if it is to be transported to an alternate site for utilization, it is usually transported in pneumatic tank trucks or covered, sealed dump trucks. One disadvantage of truck transport is a relatively high operating cost. If the haul distance is long, fuel and personnel costs will be high. For this reason, truck transport may be better suited to short haul distances. Also, if the trucks must travel on public roads, spillage of waste may cause a public relations problem.

Railroad cars have not been widely used to transport coal utilization wastes, although rail transport would certainly be feasible in situations where long haul distances are required. Construction of a railroad system is expensive, and, once constructed, the system is not very flexible. It may be possible to use a common carrier system and existing track, which would minimize construction costs. Nevertheless, even when a common carrier is used, special loading and unloading facilities will need to be constructed at the plant and the disposal site.

There is a growing trend in the utility industry to ship wastes back to the coal mine for disposal. This approach is attractive because it greatly reduces the waste disposal burden for the utility. Mine disposal is particularly attractive when the coal is supplied to the plant by rail, in which case the same railroad cars that brought the coal can be used to transport the waste back to the mine. Since mine disposal is increasing, railroads may be an important mode of transportation for future utility plants that produce advanced process wastes. A possible problem with advanced process wastes, when being considered for mine disposal, is that they are often mixtures of ash and spent scrubber materials. Since spent scrubber material is usually perceived as having a greater potential adverse environmental impact than ash, obtaining a disposal permit for an ash-scrubber waste mixture will probably be more difficult than for ash alone.

In situations where both the plant that generates the waste and the disposal site are close to navigable waterways, barge transport may be feasible. Transportation by barge requires construction of special loading and unloading facilities, but it offers the advantages of large capacity and low
operating cost. If barges are used to transport advanced process wastes, care must be taken to avoid large waste spills into the waterway. And there is always the possibility that a barge might sink and create a major pollution incident on the waterway.

The use of belt conveyors for transporting coal utilization wastes is feasible, and although they are used in other industries to transport materials over long distances, they are not widely used at power plants for long distance transport. Belt conveyors are typically best suited to situations where the waste flow is constant, and the discharge point is stationary. The advantages of belt conveyors include low maintenance and operational costs. The disadvantages are that they have relatively high construction costs and they are difficult to change once the system is built. Also, conveyors cannot handle very hot materials. If the waste is conditioned before transport, it should not be so wet that it sticks to the belt, or unloading will be difficult. If the waste is transported dry, the conveyor should be enclosed to prevent problems with dust.

An aerial tram is a set of cars that travel above ground suspended from a cable. Aerial trams are not widely used in the utility industry to transport waste, but are used at some mining operations. However, aerial trams have some advantages for transport. For example, if the waste is contained in a tram car, there is less chance of it causing abrasive wear on moving parts. Also, a tram can travel up steep slopes, through rough terrain, and over long distances. The disadvantages of aerial trams for transporting wastes are similar to those discussed above for belt conveyors.

The use of pneumatic conveyors for transporting coal combustion wastes is limited because they are not economical for moving wastes more than about 7500 feet (3). However, if the transport distance is relatively short, pneumatic conveyors may be an excellent mode of transporting dry waste to a disposal site.

The physical and chemical properties of the advanced process wastes must be carefully considered when selecting an appropriate dry or conditioned waste transport subsystem. Abrasiveness, particle-size-distribution, and self-hardening are particularly important properties. Most of the advanced process wastes characterized appear to be quite abrasive, judging from their quartz contents and chemical compositions. The abrasive tendencies of the advanced process wastes were discussed in Section 5.2.1 for transfer subsystems, and the results are listed in Table 7. The same information can be used to assess the compatibility of the wastes with the various transport subsystems. Generally, if a waste is expected to be highly abrasive, the transportation equipment must be constructed with special materials that can resist aggressive wear conditions.

Particle-size-distribution is an important consideration for some types of transport equipment. For belt conveyors and pneumatic conveyors, the assessment done for transfer subsystems as summarized in Table 8 will also apply, with a few exceptions, to transport subsystems. Although very fine materials cannot be transported in a dry form with a belt conveyor, they can if they are first conditioned with water to reduce dusting. If wastes are to be transported pneumatically, they must be in a loose, dry form; thus, they should not be conditioned before transport.

Truck, railroad, barge, and aerial tram transport, have no prohibitive particle-size restrictions. However, if the waste is very fine and in a dry form, any container in which it is being transported must be closed to prevent leakage and dusting. If the waste is conditioned before transport, it can be carried in an open container for short distances. However, if the material will dry out during transport, a closed container should be used. For railroad and barge transport, shipping the waste in a closed container may not be possible. If the waste is to be shipped for a long distance in an open container,
precautions should be taken to ensure that the waste does not leak out or blow away. One such precaution may be to spray the top of the waste with a membrane-forming chemical.

If a waste is self-hardening, it must not be allowed to set up while being transported. None of the advanced process wastes studied are quick setting materials that could harden during a short haul. However for railroad or barge transportation, where the waste might be carried for several days, self-hardening could present a problem. The self-hardening potentials of the advanced process wastes are listed in Table 9.

5.6 Waste Disposal Subsystems

Ultimate disposal of a coal utilization waste requires permanent placement at a site designed to contain the waste and protect the surrounding groundwater. Disposal is usually done by either accumulating the waste in a settling pond, placing it in a landfill, or returning it to the mine site.

Coal combustion wastes transported by wet sluicing are usually sent to a pond where the solids settle out and the free water is drained off. Depending on how the system is operated, the waste can be periodically dredged from the pond and moved to a different site for disposal or else it can be left in the pond. When the pond is full, a decision must be made to either close the pond and convert it to a dry disposal site or dredge the waste and transport it to a landfill.

Landfilling a solid waste is done by spreading the material on the ground and compacting it. A landfill must contain the waste within defined boundaries and restrict the movement of leachate from the site into the surrounding groundwater. Landfills can be designed for heaped, sidehill, or valley fills. Sometimes these different fill configurations can be combined to suit the topography of the site and the properties of the waste. For a heaped fill configuration, the waste is simply stacked up on a level surface. To build the stack, the waste is spread out and compacted in lifts. Each lift is usually between six inches and one foot thick. For a sidehill fill configuration, the waste is placed and compacted along the side of a hill, and for a valley fill configuration, the waste is placed in a valley (3).

Mine disposal of coal utilization wastes is becoming increasingly popular because when the waste is returned to the mine, a new disposal site is not needed. This option is particularly attractive for minemouth operations where the distance between the plant and the mine is relatively short. Even in situations where the waste must be transported long distances, mine disposal still may be done economically if the same railcars or trucks that bring the coal to the plant are used to transport the waste back to the mine.

5.6.1 Disposal-Related Waste Properties

Important waste properties for evaluating disposal options for the advanced process wastes include shear strength, permeability, maximum compacted density, optimum moisture content, particle-size distribution, and consolidation. Optimum moisture and maximum compacted densities for the advanced process wastes are listed in Table 11. Particle-size data is summarized in Table 6. Strength and permeability data for the advanced process wastes are summarized in Table 12.

The shear strength that a coal combustion waste develops after it has been placed at a disposal site is important because it influences the stability of the entire waste deposit. Shear strength is particularly important when designing a heaped or sidehill landfill because it determines how high the waste can
safely be stacked and how steeply the side slopes can be constructed. High shear strength also usually indicates that the waste deposit will be resistant to erosion and freeze-thaw damage.

For self-hardening wastes, shear strength results from the development of interparticle cementitious bonds. The strength of a self-hardening waste is measured by applying an unconfined compressive load to a prepared specimen. The shear strength is usually assumed to be about 20 percent of the measured compressive strength. Of the thirteen wastes tested for task three, eight exhibited some degree of self-hardening behavior. Generally, the self-hardening wastes tended to be fine-grained materials with a high calcium content. Twenty-eight-day unconfined compressive strengths for compacted self-hardening wastes ranged from 9.8 to 2325 psi.

For wastes that are noncohesive and thus do not exhibit unconfined compressive strength, shear strength results mainly from the interlocking of individual particles. This type of waste only exhibits significant load bearing capacity when confined by surrounding material. The noncohesive wastes tended to be those with larger particle sizes such as the bottom ashes. The shear strength that a confined noncohesive waste exhibits is indicated by its angle of internal friction. Six of the wastes studied were noncohesive and the angle of internal friction measured for each is listed in Table 12. Usually, the higher the angle of internal friction, the greater will be the shear strength developed. Noncohesive wastes can be stacked at the disposal site, but they must usually be confined by a compacted soil berm or mixed with another self-hardening waste.

Waste permeability is an important factor in determining how rapidly water will pass through a waste deposit and how much leachate will be produced. Waste permeability is quantified with a permeability coefficient. Permeability coefficients were measured in the laboratory for all of the advanced process wastes, and the values ranged between \(5 \times 10^{-2}\) and \(2.5 \times 10^{-7}\) cm/sec. These values for the advanced process wastes indicate high to moderately low permeabilities, respectively. The permeability coefficients measured for the advanced process wastes are similar to coefficients measured in other studies for conventional coal combustion wastes (3). When evaluating the laboratory permeabilities measured for advanced process wastes, it should be noted that permeabilities exhibited in the field may differ significantly from the laboratory values. In field permeabilities will depend on factors such as the compacted density, moisture content, and age of the waste deposit. Generally, in field permeabilities tend to be higher than permeabilities measured in the laboratory.

The maximum compacted density of a waste indicates how much dry material can be placed in a unit volume at the disposal site using a standard compactive effort. The degree of compaction achieved for a waste will be influenced by its moisture content. Typically, the compacted density will increase as the moisture content is increased up to some maximum density, and then the density will begin to decrease as more moisture is added to the waste. The specific moisture content that produces the maximum compacted density for a waste is called the optimum moisture.

The maximum compacted densities and optimum moisture contents for the advanced process wastes are listed in Table 11. The density values ranged from 58.8 to 117.8 pounds per cubic foot on a dry weight basis. The maximum compacted densities measured for the advanced process wastes are similar to densities measured for conventional coal combustion wastes (4). Moisture-density curves for the advanced process wastes are contained in Appendix C.

Usually, wastes with a broad particle-size distribution tend to compact better, develop higher shear strength, and have lower permeabilities than wastes with narrow particle-size distributions. This is because the smaller particles fill the spaces between the larger particles and produce a more compact deposit. The relative spread of the particle-size distribution for an advanced process waste is
represented by its uniformity coefficient ($C_u$). The uniformity coefficient is the ratio between the sieve size through which 60 percent (by wt.) of the waste will pass and the sieve size through which 10 percent of the particles will pass. The particle-size distribution curves and the uniformity coefficients determined for the advanced process wastes can be found in Appendix D. The $C_u$ values ranged from 1.55 to 91.7.

The consolidation properties of a coal combustion waste deposit will control the rate and extent of settlement of the deposit under an applied load. For the advanced process wastes, only those wastes that did not self-harden were tested because the cementitious materials should not settle significantly under normal loads. The consolidation test was done by loading a waste specimen and then measuring the rate and extent of compression of the specimen. The data for the three suitable bottom ash samples (Appendix E) were analyzed to calculate a coefficient of consolidation ($C_v$).

### TABLE 12
Strength and Permeability Data for the Advanced Process Wastes

| Sample Designation | Permeability Coefficient\(^1\) (cm/sec) | Unconfined Compressive Strength (psi at 28 days) |
|--------------------|----------------------------------------|-----------------------------------------------|
| GRSI-FA            | 4.3x10\(^{-4}\)                        | 669                                           |
| GRSI-BA            | 4.2x10\(^{-3}\)                        | 51                                            |
| PFBC-FA            | 2.5x10\(^{-7}\)                        | 316                                           |
| PFBC-CA            | 7.3x10\(^{-5}\)                        | 2325                                          |
| PFBC-BA            | >5x10\(^{-2}\)                         | NC\(^1\)                                      |
| CR-FA              | 2.9x10\(^{-5}\)                        | 207                                           |
| CR-BA              | >5x10\(^{-2}\)                         | NC                                            |
| SNRB-FA            | 2.8x10\(^{-5}\)                        | 56.5                                          |
| SNRB-S             | NA\(^2\)                               | NA                                            |
| LNB-FA             | 6.3x10\(^{-5}\)                        | NC                                            |
| LNB-EA             | 1.3x10\(^{-3}\)                        | NC                                            |
| LNB-BA             | 1.7x10\(^{-3}\)                        | NC                                            |
| FGD-SS             | 1.4x10\(^{4}\)                         | 9.8                                           |
| ACC-FA             | 7.4x10\(^{-6}\)                        | 36\(^4\)                                      |

\(^1\) Cementitious samples were cured for 28 days before permeability tests were run.

\(^2\) NA - The test was not applicable to this sample.

\(^3\) NC - Noncohesive waste.

\(^4\) Strength measured at 14 days for this sample.

5.6.2 Disposal Options for Advanced Process Wastes

5.6.2.1 Pond Disposal

When a settling pond is to serve as an ultimate disposal site, steps must be taken to ensure the long-term stability of the deposit. To close a pond, the standing water must be drained, the waste must
be dewatered to stabilize it, and the deposit must be capped. The waste can be dewatered to some extent by driving wells into the deposit and then pumping out the free water. Once the waste has been stabilized, the deposit can be sealed with a soil cap. The purpose of the cap is to confine the waste and to limit infiltration of surface water into the deposit.

The procedures for closing a pond will be much the same for an advanced process waste as for conventional coal combustion wastes. Opportunities may exist, however, for utilizing additional quantities of advanced process wastes for the closure process. For example, large quantities of self-heating wastes could possibly be used to partially dewater a disposal pond. This would be done by hauling the self-heating waste in a dry form to the pond, spreading it on the surface, and then tilling it into the deposit. The hydration reactions will chemically bind some free moisture in the pond, and some moisture will simply be absorbed by the dry waste. If the advanced process waste being used is also self-hardening, it could also help to stabilize the surface of the waste deposit by increasing shear strength.

Self-hardening wastes could also be used to form part of the cap for the deposit. This would require that the waste be placed and compacted on the surface of the deposit. A cap formed in this manner would have to meet the same permeability criteria specified for a conventional soil cap, but this may be possible if the waste cap is well compacted. Another option may be to stabilize the surface of a pond using an advanced process waste in the manner described above and then to convert the deposit to a landfill by stacking additional waste on top of the cap. The advantage of this approach is that if the pond already has a good liner system, a new liner will not be needed for the landfill.

Disposing of any of the advanced process wastes using a pond should be possible if the site is properly designed. Although a disadvantage of pond disposal is that the waste cannot be compacted as it is placed. The relatively low density of pond-disposed waste means that less material can be placed in a given disposal volume compared with landfill. Another potential problem associated with pond disposal is the difficulty of obtaining environmental permits for constructing new ponds. Sometimes state regulatory agencies require more stringent environmental controls for new ash disposal ponds and occasionally suggest that alternate disposal methods be used.

5.6.2.2 Landfill Disposal

Disposal of the advanced process wastes should be possible using either a heaped, sidehill, or valley landfill. Self-hardening wastes are better suited for a heaped or sidehill landfill because they develop long-term strength for a stable deposit. A valley landfill configuration however can probably be used for any of the advanced process wastes because the sides of the valley will confine the deposit even if it is not a self-hardening material.

An advantage of the sidehill and valley fill configurations over the heaped fill configuration is that they usually blend in better with the surrounding terrain once they have been capped and revegetated; however, sidehill and valley landfills are usually more difficult to construct because the natural drainage in the area has to be rerouted around the landfill site (4).

5.6.2.3 Mine Disposal

Active surface coal mines are the best candidates for in mine waste disposal because the disposal activities can be incorporated into the overall operation of the mine. This can be done in several ways. The simplest method is to place the waste in a worked out section of the pit bottom. Another possibility is to place the waste in the v-notch of the spoil banks. Placing the waste in the notches is
more difficult than placing it on the pit bottom, but waste placed in the v-notch is usually well above the groundwater table. Another alternative is to place the waste in the spoil bank with the overburden.

One aspect of mine disposal that could present a problem is the containment of leachate since constructing a liner at the site may be difficult or even impossible. Constructing a liner may not be a problem for pit bottom placement, but if the pit bottom is below the groundwater table, the liner may not be effective. For v-notch placement, using a liner may be possible, but it could be difficult. For placement in the overburden, using a liner probably would not be possible.

Mine disposal can probably be used for any of the advanced process wastes, if the site design provides sufficient protection for groundwater.

5.7 Utilization Potential of Advanced Process Wastes

Any beneficial use for a coal utilization waste that serves as an alternative to ultimate disposal is considered by-product utilization. A by-product utilization strategy should be an important component of the overall waste management plan developed for any advanced process. By-product utilization can reduce the total volume of waste requiring disposal and produce additional revenue for the waste generator through sales of the material. (Since this section will discuss utilization options for the advanced process wastes, the terms waste and by-product will often be used interchangeably.)

Utilization options can be roughly separated into two groups, those that use by-products for manufacturing various building materials and those that use large volumes of by-products for construction or agricultural applications. Although these groups do not include all by-product utilization options, most can be classified as one or the other. Typically, by-products used for manufacturing are required to meet tight material specifications, while those used for high-volume applications are subjected to less stringent specifications. An example of a manufacturing related application is the use of fly ash for partial replacement of Portland cement in concrete. An example of a high-volume application is the use of bottom ash or fly ash for a construction fill material. Usually, manufacturing related options with tight specifications support higher prices for by-products.

When evaluating utilization options for a particular by-product, the following factors are usually considered:(7)

- chemical and mineral composition,
- physical properties,
- market demand,
- amounts of waste produced, and
- shipping distance between the plant where the by-product is produced and the location where the market exists.

Since many advanced process wastes are not yet being produced on a commercial scale, only the first three of these factors were considered in the following discussion of utilization options.

5.7.1 Manufacturing Related By-Product Utilization Options

5.7.1.1 Utilization for Concrete Admixture

One of the most common and most profitable uses for coal combustion fly ash is for concrete admixtures. Fly ash can be added to a concrete mix to replace some Portland cement, to act as a
pozzolan, and for various other reasons. To use fly ash for concrete admixtures, at a minimum, it should meet the criteria listed in ASTM C-618, "Specification for Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete." Several key material properties included in ASTM C-618 were measured for the advanced process wastes and the results are listed in Table 13. Of the thirteen wastes studied, the only one that appeared to meet the specification was the fly ash from the coal-reburning process (CR-FA). Although it cannot be concluded that CR-FA met the full specification because some relevant properties were not measured.

The fly ash from the low NO$_x$ burner process (LNB-FA) met most of the requirements for the properties listed in Table 13, except that the unburned carbon content was 7.1% (as measured by thermogravimetric analysis). This exceeded the 5% limit specified in ASTM C-618. Since advanced low NO$_x$ processes often involve a starved air combustion step, the question arises will by-products from these processes typically have high unburned carbon contents? If the answer is yes, utilizing these by-products for concrete admixtures may be difficult. Three of the processes studied in task three, the GRSI, CR, and LNB processes, used some type of starved air combustion step to control NO$_x$ production. Of these, only the LNB process produced a fly ash with an unusually high unburned carbon content. However, the other two processes both produced fly ash that contained spent sorbent, which makes detection of unburned carbon more difficult.

Another study that examined the unburned carbon content of fly ash from a retrofit low NO$_x$ burner process was reported in the literature (8). Fly ashes from two low NO$_x$ pulverized coal furnaces were characterized. The results of this study indicated that the carbon content of fly ash collected from one or the furnaces approximately doubled after the retrofit, but the carbon content of fly ash from the other furnace increased only slightly after the retrofit. At this time, drawing any general conclusions about the impact of advanced low NO$_x$ processes on the composition of fly ash is difficult.

The fly ashes from the GRSI, SNRB, and PFBC processes clearly did not meet the C-618 specification. A common problem with these fly ashes was high SO$_3$. All three had SO$_3$ contents that exceeded 5 percent by weight, which is the maximum allowed by the C-618 specification. The reason the GRSI, SNRB, and PFBC processes produced fly ashes with high SO$_3$ percentages is that they all used a lime-based sorbent to control SO$_2$ emissions and some spent sorbent was collected with the ash.

5.7.1.2 Utilization for Aggregate

Advanced process wastes that contain spent sorbents could possibly be utilized for manufacturing lightweight aggregate, even if they are not suitable for concrete admixtures. A distinction is made here between lightweight aggregate used for structural concrete and lightweight aggregate used for masonry units such as cast blocks. The relevant specifications are ASTM C-330 "Standard Specification for Lightweight Aggregates for Structural Concrete" and ASTM C-331 "Standard Specification for Lightweight Aggregates for Concrete Masonry Units." Comparing the specifications, it appears that the advanced process wastes are better suited for aggregate for masonry units because the specification for structural concrete (C-330) contains a fairly high strength criteria that might be difficult to meet. The specification for masonry units (C-331) does contain criteria relating to the chemical composition and physical properties of the aggregate but it does not indicate a minimum compressive strength. Although C-331 does require that the loss on ignition of the aggregate not exceed 12 percent by weight, none of the advanced process wastes studied exceeded that level. The presence of spent scrubber material in the advanced process wastes is not necessarily a problem either, since C-331 does not specifically limit the SO$_3$ content of the aggregate.
The physical properties specified in C-331 are mainly concerned with the particle size and durability of the aggregate. Some advanced process wastes such as the bottom ashes may meet the particle size requirements for aggregate after sieving. However, the fly ashes must be mixed with some type of binder and formed into the proper particle sizes. Several processes exist to manufacture lightweight aggregate from various coal combustion by-products. The Poz-O-Lite™ process has been developed for manufacturing lightweight aggregate from stabilized scrubber sludge. This process relies on cementitious stabilization and reports indicate that the product meets the C-311 specification (9). Other processes have been described that use sintering of pelletized fly ash to manufacture lightweight aggregate (10).

**TABLE 13**

Comparison of Waste Properties to ASTM C-618 Specifications

| Sample Designation | Total SiO₂+ Al₂O₃+ Fe₂O₃ Content, (wt%) | SO₃ Content, (wt%) | Pozzolanic Activity Index, (% of control) | Unburned Carbon Content (wt%) | % Retained on a No. 325 Sieve, (wt%) |
|--------------------|-----------------------------------------|-------------------|------------------------------------------|-------------------------------|-----------------------------------|
| GRSI-FA            | 52.2                                    | 8.0               | 83                                       | WG                            | 0?                                |
| GRSI-BA            | 74.9                                    | 2.4               | 49                                       | 0.62                          | 92                                |
| PFBC-FA            | 48.3                                    | 23.7              | 64                                       | WG                            | 20                                |
| PFBC-CA            | 36.4                                    | 10.3              | 71                                       | 1.0                           | 83                                |
| PFBC-BA            | 11.2                                    | 8.7               | 41                                       | 0.51                          | 98                                |
| CR-FA              | 73.4                                    | 2.2               | 85                                       | WG                            | 10                                |
| CR-BA              | 82.9                                    | 0.0               | ND                                       | WG                            | 99                                |
| SNRB-FA            | 21.4                                    | 12.0              | 81                                       | WG                            | 0?                                |
| SNRB-S             | 2.6                                     | 0.1               | 74                                       | NA                            | 0?                                |
| LNB-FA             | 78.2                                    | 0.7               | 76                                       | 7.1                           | 0?                                |
| LNB-EA             | 87.8                                    | 0.4               | 62                                       | 3.1                           | 75                                |
| LNB-BA             | 85.3                                    | 0.01              | 52                                       | 0.68                          | 95                                |
| FGD-SS             | 0.5                                     | 45.5              | ND                                       | NA                            | 80                                |
| ACC-FA             | 75.5                                    | 0.6               | 85                                       | 11.1                          | 79                                |

1 - Samples were cured for 28 days.
2 - Percent waste retained on a No. 325 sieve was estimated from the particle-size analysis.
ND - These wastes were not tested for pozzolanic activity.
NA - Test not applicable to this sample.
WG - Sample gained weight when oxidized during thermogravimetric analysis.

Note: Some requirements to meet ASTM C618 specifications include the following:
- Total SiO₂ + Al₂O₃ + Fe₂O₃ content must be >70% for Class F ash and >50% for Class C ash.
- SO₃ content must be <5%.
- Pozzolanic activity index (for cement) must be >75% of control after a 28-day cure.
- Percent retained on a No. 325 sieve cannot exceed 34%.
- LOI must be <5%.
Manufacturing aggregates with advanced process wastes for applications where higher strengths are required has also been studied (11). An atmospheric fluidized bed combustion waste was mixed with a Class C fly ash and water to form a moderately high strength, self-cementing material. The mixes used either 15 or 25 percent AFBC waste and the rest of the solids were Class C fly ash. The various mixes were cured, crushed and then sieved to produce a lightweight aggregate. These aggregates had good strength characteristics and could possibly be used for road subbase construction. It was reported that efflorescence of sodium sulfate from the aggregate could cause a problem when it is used beneath Portland cement concrete, but it should be suitable for use with asphalitic concrete.

Usually, the chemical and physical properties of the advanced process wastes indicate that they may be suitable for manufacturing lightweight aggregates. However each by-product should be evaluated individually to determine whether it can be used for aggregate.

5.7.1.3 Other Utilization Options Related to Manufacturing

Other possible utilization options for the advanced process wastes are for manufacturing brick, mineral wool, blasting grit, road deicer, and cement clinker. Some advanced process wastes should be suitable for all or most of these applications. However wastes that contain high percentages of SO3 may be limited to use for manufacture of cement clinker.

| Sample Designation | SiO2 (%) | Al2O3 (%) | Fe2O3 (%) | CaO (%) | MgO (%) | Na2O (%) | K2O (%) |
|--------------------|----------|-----------|-----------|---------|---------|----------|---------|
| GRSI-FA            | 32.1     | 12.1      | 8.0       | 28.6    | 2.8     | 1.4      | 0.7     |
| GRSI-BA            | 43.0     | 15.0      | 16.9      | 11.0    | 1.2     | 1.4      | 0.7     |
| PFBC-FA            | 26.5     | 13.8      | 8.0       | 16.7    | 9.3     | 0.4      | 2.2     |
| PFBC-CA            | 20.4     | 7.5       | 8.5       | 21.5    | 15.1    | 0.2      | 1.0     |
| PFBC-BA            | 5.9      | 2.1       | 3.2       | 31.0    | 23.5    | 0.0      | 0.0     |
| CR-FA              | 36.7     | 16.7      | 20.0      | 8.0     | 1.3     | 0.8      | 0.0     |
| CR-BA              | 44.0     | 17.9      | 21.0      | 21.0    | 0.6     | 0.4      | 0.0     |
| SNRB-FA            | 11.4     | 4.5       | 5.5       | 43.0    | 1.8     | 0.1      | 0.3     |
| SNRB-S             | 1.9      | 0.5       | 0.2       | 71.2    | 2.8     | 0.0      | 0.1     |
| LNB-FA             | 45.0     | 22.1      | 11.0      | 1.2     | 0.9     | 0.3      | 2.4     |
| LNB-EA             | 47.5     | 22.6      | 18.2      | 1.3     | 0.9     | 0.3      | 2.4     |
| LNB-BA             | 48.1     | 23.6      | 13.6      | 0.9     | 0.9     | 0.3      | 2.5     |
| FGD-SS             | 0.2      | 0.14      | 0.14      | 38.1    | 0.0     | <0.2     | <0.2    |
| ACC-FA             | 38.5     | 29.7      | 7.3       | 2.5     | 0.6     | 0.2      | 1.1     |

* All elements are reported as oxides on a weight percent basis.
5.7.2 High Volume By-product Utilization Options

5.7.2.1 Utilization for Construction Fill Material

Fill materials are often used at construction sites to fill depressions and create a level working surface. Construction fills may be either compacted or uncompacted, depending on the type of structure being supported. Coal combustion by-products make good fill materials for several reasons. Large amounts of by-products are available at low cost in many areas of the U.S. By-products usually have a lower compacted unit weight than soil, and so they can be used to advantage in situations where the underlying soil has a low bearing capacity. Self-hardening by-products are useful because they tend to develop high shear strength when compacted with an appropriate moisture content. Fly ash is a particularly good fill material because it can be placed and compacted using equipment and procedures similar to those used for natural soils. Fly ash has been used extensively as a fill material in situations where natural soil was either unavailable or unusually expensive.

Some important physical properties that indicate whether an advanced process waste can be used as a fill material are its particle size, maximum compacted density, unconfined compressive strength, angle of internal friction, pozzolanic activity, compressibility and permeability. Much of this information for the advanced process wastes is summarized in Appendix A. For a self-hardening material, unconfined compressive strength is a primary indicator of the expected strength and bearing capacity of the fill. For a non self-hardening material, angle of internal friction, compressibility and compacted density are all important indicators of the expected shear strength and bearing capacity of the fill. Generally, a good fill material will be well-graded (i.e., have a relatively broad particle-size distribution), have a medium to high maximum compacted density, have a high shear strength, and have a moderate to high permeability to promote good drainage.

Some important chemical properties of the advanced process wastes are total silicon, aluminum, and iron oxide content; sulfur content (measured as SO3); free lime content; and leachate composition. A finely divided material with high total silicon, aluminum, and iron oxide contents will tend to be pozzolanic. When a pozzolanic by-product is used as a fill material it will usually gain significant shear strength over time if free lime and sufficient moisture are also present. Data on the chemical composition of the advanced process wastes is contained in Table 14.

Usually, a high SO3 content (as determined from a bulk chemical analysis) and high corrosiveness (as indicated by a highly acidic or alkaline waste slurry pH) are undesirable for a fill material because these properties may promote rapid corrosion of concrete or steel structures buried in the fill. However the results of a recent study indicate that the corrosiveness of fly ash and bottom ash fill materials to buried concrete structures is highly dependent on the type of cation that the SO3 (or SO4) is paired with and on the pH of the pore water in the fill (12). The study measured corrosion to concrete specimens buried in fly ash and bottom ash fills for ten years. It was found that sodium sulfate was much more corrosive to concrete than calcium sulfate and that acidic pore water was much more corrosive than alkaline pore water. This finding should help to promote the use of advanced process wastes for fills because, for those materials that contain spent lime-based sorbents, the sulfur form should be predominantly calcium sulfate and the pore water should be alkaline rather than acidic. This means that although many advanced process wastes have a relatively high measured SO3 content, they may not pose a significant corrosion problem for buried concrete structures when used for fills. Thus it appears that under the proper conditions, all of the advanced process wastes characterized for Task 3 could be used for fill materials.
Another potential problem associated with the use of advanced process wastes for fill material is expansion of the material after placement. If the material expands too much, it will heave and destroy the integrity of the fill. By-products that contain high percentages of lime (CaO) and anhydrite (CaSO₄) tend to expand when these minerals hydrate and may expand further with the eventual formation of secondary mineral phases like ettringite. Expansive behavior has been observed with some FBC by-products and spray dryer by-products. However, it is unlikely that any of the advanced process wastes characterized for task three would be expansive because none contain large amounts of lime or anhydrite. Even if a by-product does tend to be expansive, steps can be taken to reduce the problem. For one thing, enough water should be added to the by-product to fully rehydrate the oxides before placement. Also, the hydrated by-product should be allowed to cool before it is placed and compacted.

The expansive properties of an advanced process waste were evaluated in a recent research project. The project evaluated the effects of long-term stockpiling on the utilization properties of an advanced process waste (13). The by-product involved was a dry scrubber residue from the Lime Injected Multistage Burner Process (LIMB). A 1500 ton "temporary storage pile" was constructed. The stockpile was sampled over a 30-month period to characterize changes in the physical, mineralogical, chemical and engineering properties of the material. Results showed that a gradual decrease occurred in the free lime content and the related strength producing potential of the by-product. Much of the stored by-product was converted to calcium silicate, calcium carbonate and ettringite through spontaneous chemical reactions. These results indicate that when the by-product is being used as a liming agent or a cementing agent, as with soil stabilization, storage will decrease its effectiveness. Alternatively, when the by-product is being used as a fill material, storage may increase its usefulness, because the expansive hydration reactions will have already occurred during storage and thus will not adversely affect the fill deposit.

A recent study reported on the successful use of an advanced process waste for a fill material (14). For the application described, a dry scrubber by-product from a PFBC process (the same site that generated the PFBC-FA sample) was used to rebuild and stabilize a failed highway embankment. The by-product was placed and compacted in sequential lifts. The authors reported that the PFBC by-product was easy to place, achieved high strength gain and at the time of writing had not caused any adverse environmental impacts.

5.7.2.2 Utilization for Soil Stabilization

A combination of lime and fly ash is often used to stabilize soil for construction of pavement subgrades. The lime helps to improve the mechanical properties of fine-grained soils by decreasing plasticity and increasing shear strength. The fly ash serves to promote pozzolanic reactions that further increase the shear strength of the soil. An additional benefit of fly ash, when it contains a high percentage of free lime, is that it can reduce the amount of commercial lime needed for stabilization. Sometimes, if the fly ash contains enough free lime (typically this would be a Class C fly ash), little or no commercial lime will be needed to stabilize the soil.

The key properties measured for this study that may indicate whether an advanced process waste will be an effective soil stabilization additive are particle-size-distribution, pozzolanic activity index, self-hardening behavior and free lime content. The relevant specification is ASTM C-593 "Standard Specification for Fly Ash and Other Pozzolans for Use with Lime." This specification contains criteria for compressive strength, freeze-thaw durability and wet-dry durability of stabilized soil specimens. The minimum compressive strength specified for a mixture of lime, fly ash and soil after compaction and curing is 400 psi. Pozzolanic activity index is probably the best parameter (of those measured for Task 3) for evaluating usage of advanced process wastes for soil stabilization. The activity index
indicates (as a percentage of control) the compressive strength developed by a mixture of fly ash and lime compared with the compressive strength developed by a standard control mix. A high index value (75% of control and higher) generally indicates that the by-product being tested has useful pozzolanic strength-gain properties. The pozzolanic activities of selected advanced process wastes were measured and the results are listed in Table 9.

The self-hardening properties of selected advanced process wastes were determined by measuring the unconfined compressive strengths of compacted and cured waste specimens. The self-hardening potentials of the wastes are listed in Table 11. Waste free-lime content was estimated by comparing the acid titration data, chemical and mineral composition data, and thermogravimetric data obtained for each material. Estimates of the waste free-lime contents are contained in Appendix B. From an examination of the pozzolanic activities, self-hardening properties, and free-lime contents of the advanced process wastes, it was determined that six of the wastes characterized for Task 3 were potentially useful soil-stabilization additives. These wastes are listed in Table 15 along with descriptions of their useful properties.

An interesting project that utilized an advanced process waste for soil stabilization was reported in the literature (15). For this research, a dry scrubber by-product from a PFBC process (the same process from which the PFBC-FA sample was obtained) was used to stabilize soil for several cattle pens. The PFBC by-product was mixed with the natural soil and compacted. Three cattle pens with a total of 1300 m³ were treated. Rapid strength gain was observed in the stabilized soil. A wear surface of compacted by-product was then placed on top of the stabilized soil. The results of the study indicate that the modified cattle pens are performing quite well.

5.7.2.3 Utilization for Pavement Base Course

The base course of a highway is the foundation for the paved surface. The base course must have sufficient bearing capacity to support the traffic load, and must be sufficiently durable to withstand weather-related stresses such as freezing and thawing cycles. Mixtures of coal combustion fly ash, lime or Portland cement, and aggregate are commonly used for constructing base courses. If the fly ash is not self-hardening, lime or cement must be added to achieve the necessary strength. However if the fly ash is self-hardening, using it without adding any lime or cement may be possible (7).

A strength criterion that is commonly applied for evaluating mixtures of fly ash, cement and aggregate for use as pavement base course is that the mix has an unconfined compressive strength of 1000 to 2000 psi after curing. Since this strength criterion is much higher than that used for soil stabilization (i.e., 400 psi), CR-FA and LNB-FA may be the only advanced process wastes studied that are suitable for base course applications. The two samples both meet the pozzolanic activity and SO₃ criteria in ASTM C-618. The GRSI-FA and SNRB-FA wastes may also be useful for base course mixtures since both have relatively high pozzolanic activity indexes, however these wastes should be carefully tested before use because they do not meet the SO₃ criteria in ASTM C-618.

5.7.2.4 Utilization for Agricultural Soil Amendment

Coal combustion by-products can be used for agricultural soil-amendment to raise soil pH, eliminate trace element deficiencies, and increase the moisture-holding capacity of soil. A common use for alkaline by-products has been to neutralize acidic soils when reclaiming strip-mined lands in the eastern United States (7). Acid-buffering capacity is an important property for determining whether an advanced process waste can be used to neutralize soil acidity. The acid-buffering capacities of the advanced process wastes were measured by titrating 10 grams of the waste with a sulfuric acid solution.
to an endpoint pH of 5.0. The test results are listed in Table 16. From an examination of these results, it appears that samples GRSI-FA, PFBC-FA, PFBC-CA, CR-FA, and SNRB-FA would be effective soil-neutralizing additives.

Soil amendment with coal combustion by-products can also be done to enhance production of commercial crops. A study was reported which evaluated the effect of several different by-products on the growth of corn (16). Conventional fly ash, FBC fly ash, and flue gas desulfurization sludge were separately added to soil in various percentages. The by-products were thoroughly mixed with soil and then the soil was used to grow corn. Corn plants grown in soil containing up to 2 to 3 percent FBC fly ash yielded 2-fold higher dry matter than plants grown in unamended acid soil. However corn yield decreased when higher percentages of FBC fly ash were added. Conventional fly ash produced about the same degree of enhanced corn growth as FBC fly ash. Although it was possible to sustain this growth with higher percentages of conventional fly ash in the soil mix.

Another study reported on the use of a PFBC dry scrubber by-product as an agricultural liming material (17). The by-product used had a CaCO$_3$ equivalency of 60%. It was surface applied to low pH soils and then alfalfa and corn were planted. Within one year, the pH of the soil had increased down to a depth of 30 cm. Trace element concentrations did not increase in the soil with the exception of Boron which was increased in the zone of incorporation. The PFBC by-product increased alfalfa yield on all three soils tested, but had no effect on corn yield.

### TABLE 15

| Sample Designation | Useful Soil Stabilization Properties |
|--------------------|--------------------------------------|
| GRSI-FA            | Self-hardening, moderately pozzolanic and 4 wt.% free lime$^2$ |
| PFBC-FA            | Self-hardening and moderately pozzolanic |
| PFBC-CA            | Self-hardening and moderately pozzolanic |
| CR-FA              | Moderately pozzolanic and 2.4 wt% free lime |
| SNRB-FA            | Self-hardening and moderately pozzolanic |
| LNB-FA             | Moderately pozzolanic |
| ACC-FA             | Moderately pozzolanic |

$^1$ Self-hardening – the 28-day unconfined compressive strength was greater than 50 psi.

$^2$ Moderately Pozzolanic – the 28-day pozzolanic activity index was between 70% and 100% of the control.
Other agricultural uses for coal combustion by-products are being studied and some encouraging results have been reported. For example, a recent research project successfully used FBC by-products for a soil "cap" material for orchards. For this application, approximately 100 tons per acre of spent FBC bed material was applied to the soil surface beneath the trees (18). The by-product was not tilled into the soil, but it served as a surface barrier to hold in soil moisture and inhibit growth of weeds. The FBC bed material also served as a liming agent supplying calcium to the trees and raising soil pH. This project also evaluated a similar usage for FBC by-products for growing tomatoes. The results of this work indicate that the growth and production of tomato plants were enhanced by using FBC bed material as a soil cap. Surface application of coal combustion by-products has some advantages over direct incorporation into the soil. For certain crops, previous studies have shown that incorporation of high percentages of by-products into soil has caused problems with elevated soil pH and salt concentrations. Surface application appears to mitigate these problems and may allow for usage of large amounts of advanced process wastes.

Agricultural uses may be the most promising utilization applications for advanced process wastes. This is because many advanced process wastes contain spent sorbents that can supply calcium carbonate, free lime and gypsum. All these compounds are desirable additives for certain types of soils. The prices paid for wastes being used for agricultural uses will likely not be as high as those paid for some other utilization options, but the potential exists for using very large volumes of waste. Thus the major cost benefit associated with agricultural usage of advanced process wastes may be the disposal costs avoided when the waste is put to use.

**TABLE 16**

Summary of Advanced Process Wastes with High Acid-Neutralizing Capacities

| Sample Designation | Sulfuric Acid-Neutralizing Capacity, g H₂SO₄/g waste |
|--------------------|--------------------------------------------------|
| GRSI-FA            | 0.34                                             |
| PFBC-FA            | 0.05                                             |
| PFBC-CA            | 0.29                                             |
| CR-FA              | 0.06                                             |
| SNRB-FA            | 0.46                                             |

5.7.2.5 Utilization as Landfill Cover Material

Coal combustion fly ash has been used as cover material at several landfills in the United States. Fly ash often makes a good cover material because it has a moderately low permeability when compacted at optimum moisture content, it does not shrink appreciably when it dries out, and many types of fly ash develop significant shear strength after they have been placed (7). Generally the properties that indicate a particular by-product will be a suitable landfill cover material are the same as those discussed in Section 5.7.2.1 for fill materials.
The following are several possible drawbacks to the use of combustion by-products for cover material. One is that the by-product may contribute significant amounts of regulated trace elements to the landfill leachate. However, advanced process wastes are not expected to release higher levels of trace elements than conventional fly ashes. Another possible drawback is that a by-product with a high free-lime content will produce a leachate with an unacceptably high pH. A high pH could be corrosive to the leachate collection system at the landfill or possibly degrade the quality of the surrounding groundwater. Also, a high pH within the landfill will tend to inhibit decay of municipal waste and methane production, a definite disadvantage if the landfill includes a system for collecting and using methane. Although in some situations, a high leachate pH may actually be beneficial. For example, if the material being placed in the landfill contains trace metals such as lead and cadmium, which are more soluble at low pH, an advanced process waste that contains free lime could serve to stabilize these trace metals and reduce their movement into the leachate.

If an advanced process waste is being considered for use as a landfill cover material, evaluating the chemical compatibility between the waste being placed in the landfill and waste being considered as a cover material will be necessary. This should be done on a case-by-case basis, since the chemical interactions between the two materials can be complex.

5.7.2.6 Utilization for Waste Stabilization and Treatment

Many processes that use coal combustion by-products to stabilize wastes have been developed. Waste stabilization processes usually involve mixing a dry stabilizing agent (i.e., the by-product) with a wet sludge to improve handling properties, increase compacted density and shear strength, reduce permeability, and possibly reduce the amounts of trace metals that leach out (7). The POZ-O-TEC® processes, which uses fly ash to stabilize FGD scrubber sludge, is already well developed and widely accepted. Other processes intended to stabilize a wide range of different waste materials are being studied, but in many cases have not yet reached widespread commercial usage. These developing applications include fixation of toxic metals in various wastes, stabilization of municipal wastewater treatment sludges, and stabilization of municipal incinerator wastes.

The use of fly ash to remove toxic metals from wastewater has been reported in several studies. One such study found that fly ashes from several different sources can remove toxic metals from electroplating wastewaters (18). The authors suggest that fly ash may be used as a pretreatment step to remove metals like chromium, lead and nickel from wastewater. Another study evaluated the use of fly ash for fixation of lead in contaminated soil (20). In this case, a mixture of pozzolanic fly ash and Portland cement was used to stabilize soil and reduce the amounts of lead that leached from the stabilized product. Similar studies have examined the use of fly ash for stabilization of hazardous wastes produced from municipal waste incinerators.

The use of fly ash to condition municipal wastewater treatment sludge has also been studied (21). Sludge conditioning is done to enhance the dewatering characteristics of the sludge. It is usually done by adding lime, coagulants such ferric chloride and/or various polyelectrolytes to the sludge before dewatering. The research has indicated that a mixture of fly ash and lime can be used in place of ferric chloride and lime to achieve effective conditioning of municipal wastewater sludge.

In a related application, a mixture of fly ash and municipal wastewater treatment sludge has been used to reclaim thousands of acres of defoliated and contaminated land near a zinc smelter in eastern
Pennsylvania (22). A mixture of conventional fly ash, municipal sludge, limestone and potash was used to make an artificial soil that was spread over the contaminated land. This mixture served to stabilize toxic metals in the native soil, promote revegetation, reduce wind erosion, reduce runoff, and increase evapotranspiration. Legal issues concerning use of fly ash at a listed Superfund site were a major holdup for this project. This issue was overcome when the EPA granted the suppliers special status to protect them from liability. This project is scheduled to use as much as 16,250 tons of fly ash per year. Although the fly ash used for this application was from a conventional combustion process, many advanced process wastes could probably have been used with similar results.

Many advanced process wastes appear to have properties that would make them valuable waste-stabilization additives. For example, all of the wastes listed in Table 15 with self-hardening and/or pozzolanic properties should be excellent additives for reducing the permeability and increasing the shear strength of stabilized sludges. Further, when a particular waste stabilization process requires lime addition along with fly ash, advanced process wastes with significant free lime contents may reduce the amount of commercial lime that would otherwise have to be added.

5.7.2.7 Utilization of FGD Gypsum

The largest single use for gypsum in the United States is for wallboard manufacture. Most wallboard is produced from natural gypsum, but the use of FGD gypsum is increasing. A key criterion for determining the suitability of FGD gypsum for wallboard is the amount of calcium sulfite present. A typical FGD waste is a mixture of calcium sulfite and calcium sulfate (gypsum). However, the sulfite can be converted to sulfate by various forced oxidation processes. The CT-121 FGD process includes a forced oxidation step and the waste product is approximately 99 percent calcium sulfate. Therefore, the CT-121 waste should be an excellent raw material for wallboard manufacture. A typical set of quality criteria for wallboard gypsum is listed in Table 17 along with the corresponding values for the CT-121 waste (23). The CT-121 waste appears to meet all criteria except moisture content, but this can be corrected by drying.

The second largest use for gypsum is for manufacture of cement clinker. The quality criteria for this application are less stringent than those applied to wallboard, so the CT-121 waste should also be acceptable for cement manufacturing. The third largest use for gypsum is for agricultural soil amendment. It is used to loosen heavy, compacted soils and sometimes it is used to supply supplemental amounts of sulfur and calcium for specific crops such as peanuts, legumes, potatoes and cotton. When FGD wastes are used for soil amendment, the best results have been obtained with materials that contained predominantly gypsum (calcium sulfate) rather than calcium sulfite.

5.7.2.8 Bottom Ash and Boiler Slag Utilization

Boiler slag from wet-bottom coal combustion processes is a granular material produced when molten slag from a boiler is quenched in a water tank. The material typically has a black, glassy composition. Boiler slag is commonly marketed as aggregate for bituminous pavement, blasting grit, and road deicing material. One of the advanced process wastes characterized for Task 3, sample CR-BA, had a composition similar to a conventional boiler slag. This sample seems usable for all of the markets normally associated with boiler slag.
TABLE 17
Quality Criteria for Gypsum Used for Wallboard Manufacture (23)

| Quality Criteria | Wallboard Gypsum (Required) | CT-121 Spent Sorbent Composition |
|------------------|-----------------------------|---------------------------------|
| CaSO₄· 2H₂O (wt. %, dry) | >93                         | 99                              |
| CaSO₃· 1/2H₂O (wt. %, dry) | <2.0                        | <0.5                            |
| SiO₂ (wt. %, dry) | <2.5                        | 0.25                            |
| Fe₂O₃ (wt. %, dry) | <3.5                        | 0.14                            |
| Chlorides (ppm) | <120                        | <200                            |
| Total Water Soluble Salts (ppm) | <600           | ND¹                            |
| Free H₂O (wt. %) | <10                         | 3                               |
| Mean Particle Size (microns) | >20                        | 56                              |

¹ ND – Parameter not determined.

Bottom ash produced from dry-bottom coal combustion processes is a granular material that often has a porous, cinder-like composition. Bottom ash is useful for some high-volume applications discussed above, and it is also widely used as a road deicer. Wastes GRSI-BA, PFBC-BA and LNB-BA could probably be used as road deicers.

5.8 Summary

In this section, the characteristics of the advanced process wastes are evaluated on a site-by-site basis, and potential problems associated with the handling and disposal of the wastes are summarized.

5.8.1 Site 1 – Gas-Reburning Sorbent Injection Process

Two solid waste streams were sampled from the GRSI process demonstration. Sample GRSI-BA was a crushed bottom ash collected from a pulverized coal fired boiler, and sample GRSI-FA was a fly ash collected from an ESP.

The GRSI bottom ash was a granular material, similar to a conventional pulverized coal process bottom ash. However since calcium hydroxide sorbent was injected into the boiler during the test run, the GRSI bottom ash contained higher percentages of calcium and sulfur than would typically be found in conventional bottom ashes. Handling and disposal of the GRSI bottom ash can be done with the methods currently being used for conventional bottom ashes. This often involves either sluicing the ash to a settling pond or trucking it to a landfill. Although the GRSI bottom ash was slightly self-hardening, transferring the waste by wet sluicing should be possible if it is kept moving and not allowed to accumulate in the sluice channel. Utilizing the GRSI bottom ash for many same by-product applications associated with conventional bottom ashes should also be possible.
For the GRSI fly ash, the most important considerations for selecting appropriate handling and disposal methods are 1) that the material is self-hardening, and 2) that it produces a leachate with a relatively high pH. Although the material was self-hardening, it did not set up quickly and so would probably not pose any problems for conventional transfer or conditioning operations. Although care should be taken with the conditioned waste not to let it sit for an extended time and set up in a truck or other container while being transported to a disposal site.

Since the GRSI fly ash does produce a high pH leachate, handling this material in as dry a form as possible is suggested. The waste should, therefore, be transferred dry and conditioned with just enough water to achieve its maximum compacted density.

5.8.2 Site 2 – Pressurized Fluidized-Bed Combustion Process

Three solid waste streams were sampled from the PFBC process demonstration. Sample PFBC-BA was a granular bottom ash collected from the bed of the combustor. Samples PFBC-CA and PFBC-FA were fly ashes removed from the flue gas stream with a mechanical cyclone and an ESP respectively. A dolomite sorbent was injected into the combustor during the run that produced these wastes.

The PFBC bottom ash had a chemical composition similar to a conventional pulverized coal combustion bottom ash. However, due to the presence of spent sorbent, it does contain a higher sulfur content than would typically be found in a conventional bottom ash. Since the bottom ash was not self-hardening or self-heating, handling and transport should be possible using the same types of systems that are currently being used for conventional bottom ashes. The bottom ash can be utilized for a fill material, but precautions should be taken so that it does not corrode buried concrete pipes and footings.

Both PFBC fly ashes were self-hardening, the cyclone ash more so than the ESP fly ash. The cyclone fly ash actually developed a compressive strength of 2325 psi in 28 days, which is similar to the strength developed by a low-strength concrete. Since these fly ashes are self-hardening, they should not be allowed to set up while being stored or transported for an extended time. Both the PFBC fly ashes contain too much SO$_3$ to be used for cement replacement. However, they could be used as fill material in some situations. They should also be well suited for uses such as soil stabilization, soil amendment, sludge stabilization, and pavement base course.

5.8.3 Site 3 – Coal-Reburning Process

Two solid waste streams were sampled from the CR process demonstration. Sample CR-BA was a slag-type bottom ash produced from a cyclone-fired boiler, and sample CR-FA was a fly ash collected with an ESP. Since a sorbent was not used with the CR process, both the bottom ash and the fly ash were similar to the types of wastes produced from a conventional cyclone-fired boiler. Therefore handling and transporting both the CR wastes should be possible using the same systems currently being used for conventional cyclone-fired boilers. The fly ash appeared to meet the ASTM C618 specification for use as a cement replacement additive. The bottom ash could possibly be marketed as an aggregate for bituminous pavements, a blasting grit, and a road deicing material.
5.8.4 Site 4 – SO\textsubscript{2}, NO\textsubscript{x}, RO\textsubscript{x}, BOX Process

One solid waste stream was sampled from the SO\textsubscript{2}, NO\textsubscript{x}, RO\textsubscript{x}, BOX process demonstration. Sample SNRB-FA was a fly ash collected in a baghouse. Because a calcium hydroxide sorbent was injected into the flue gas duct during the demonstration, this waste had a high calcium content and a high sulfur content. Even though the waste did have a high calcium content, it did not display significant self-heating behavior. This was because the temperature in the flue gas duct was not high enough to transform the unreacted calcium hydroxide sorbent to calcium oxide. Therefore, the sorbent in the fly ash did not rehydrate with an accompanying release of heat when the waste was mixed with water.

Handling and transporting the SNRB fly ash should be possible using the same types of systems that are currently being used for conventional coal combustion fly ashes. The waste was moderately self-hardening and so care should be taken not to let it set up in storage bins or transport vehicles. It also should be noted that the waste had an unusually low compacted density. The low density is probably due to the high calcium content. A low compacted density means that this waste will require a larger landfill volume to dispose of a unit mass of material than would be required for a waste with a higher compacted density. Since the SNRB fly ash had a high acid-neutralizing capacity, it can be utilized as a soil amendment in situations where an acidic soil is to be neutralized.

5.8.5 Site 5 – Low NO\textsubscript{x}/Advanced Over-Fire Air Process

Three solid waste streams were sampled from the low NO\textsubscript{x} burner process. Sample LNB-FA was a fly ash collected from an ESP, sample LNB-EA was an economizer ash, and sample LNB-BA was a bottom ash. The LNB wastes were quite similar to typical ashes produced by conventional pulverized coal boilers burning bituminous coal. The LNB wastes were composed largely of silicon, aluminum and iron oxides with very little calcium present. None of the wastes were either self-heating or self-hardening and should not pose any unusual problems for storage or conditioning subsystems. The samples did produce low pH slurries that could be corrosive to some handling equipment.

The LNB wastes should be suitable for some high volume utilization options. They would all be acceptable fill materials when corrosiveness is not a concern. The bottom ash could be used for road deicer. The fly ash was pozzolanic and thus could be used for soil or road subbase stabilization when mixed with lime. The fly ash may not be suitable for pozzolanic cement replacement, however, because of high loss on ignition.

5.8.6 Site 6 – CT-121 Flue Gas Desulfurization Process

One solid waste was sampled from the CT-121 advanced flue gas desulfurization process. Sample FGD-SS was a spent sorbent material. Since the waste was 99 percent calcium sulfate, handling and disposal should be possible using conventional waste management methods. The waste should also be suitable for utilization for wallboard manufacture, cement production, and soil amendment applications.

5.8.7 Site 7 – Advanced Coal-Cleaning Process

One solid waste was sampled from the ACC process demonstration. Sample ACC-FA was a fly ash obtained from burning a specially cleaned Carefree Coal\textsuperscript{TM}. The composition and characteristics
of the ACC fly ash were very similar to those of a typical pulverized coal fly ash. One unusual feature of the ACC fly ash was a high loss-on-ignition. Handling and disposal of the ACC fly ash should be feasible using conventional waste management methods. The waste should be suitable for utilization as a pozzolanic fill material.

5.9 An Evaluation of Ceramicrete Mixtures Prepared with Advanced Process Wastes

An innovative utilization option for advanced process wastes was suggested by the recent development of a new material called Ceramicrete™. The idea is to use Ceramicrete made with advanced process wastes as an alternative to Portland cement concrete for various construction applications. Ceramicrete is a phosphate-based ceramic material made at room temperature. It is formed by mixing magnesium oxide and a soluble phosphate powder with water. These ingredients react quickly to form a hard ceramic product. Other materials such as sand, aggregate or coal combustion ash can be added to the mixture as inert fillers. Work done at Argonne National Laboratory has demonstrated that Ceramicrete mixtures can have compressive strengths similar to Portland cement concrete (24). Some additional benefits of Ceramicrete are that it will set up in cold temperatures, is highly impermeable to water, and tends to bind quite well to other surfaces.

A number of uses have been suggested for Ceramicrete. The material could be used as a binder for hazardous wastes or radioactive wastes. Another possibility is to prepare the material using conventional sand and aggregate to produce a structural building material similar to Portland cement concrete. Since the hydration reactions associated with Ceramicrete are quite exothermic, this material can be placed and cured at lower temperatures than conventional Portland cement concrete.

Ceramicrete mixes having relatively high compressive strengths have also been made using up to 65 weight percent conventional coal combustion ash (5). Assuming that materials with similar strengths can be produced using advanced coal utilization wastes instead of conventional ash, development of such materials might create a significant utilization Option for the advanced wastes. In order to evaluate this possibility, a research task was performed. The objective of the task was to determine 1) whether a high percentage of advanced process wastes could be utilized in Ceramicrete mixtures and 2) what were the strength properties of these mixtures. The hypothesis was that at least some of the advanced process wastes would work as well as conventional coal combustion ash in the Ceramicrete mixtures. Experimental work for the task involved preparing numerous small batches of Ceramicrete materials using different advanced process wastes, curing the mixtures, and then testing their unconfined compressive strength. Some of the mixtures were soaked in water for part of the curing cycle to test their resistance to water saturation. The performance of the Ceramicrete mixes containing advanced process wastes were evaluated by comparing the results of their strength tests to strengths obtained for Ceramicrete mixes containing conventional ash and to typical strengths obtained for conventional Portland cement concrete.

Five of the advanced process wastes were selected for testing in Ceramicrete mixes. Selection of wastes was dependent on whether enough material was available to make the three specimens needed for the strength tests. It was decided that at least 1000 grams of waste was needed to make a set of specimens. The five wastes used are listed in Table 18.
TABLE 18

Sample Descriptions

| Waste Designation | Advanced Process            | Waste Description       |
|-------------------|-----------------------------|-------------------------|
| CR-BA             | Coal-Recirculating          | Black glassy slag       |
| PFBC-BA           | Pressurized Fluidized Bed   | Tan granular bottom ash |
| PFBC-FA           | Pressurized Fluidized Bed   | Reddish-brown fly ash   |
| PFBC-CA           | Pressurized Fluidized Bed   | Greyish-brown cyclone ash|
| LNB-FA            | Low NO x Burner with Over-Fire Air | Grey fly ash |

5.9.1 Ceramicrete Results

The mix proportions used for each of the Ceramicrete batches are listed in Table 19. For the reasons stated above, just enough water was added to each mix to just bring the consistency to pourable.

TABLE 19

Ceramicrete Mix Proportions

| Mix No. | Filler Type | Filler content (wt.%) | Water Added (% dry wt.) | KH$_2$PO$_4$ Added (wt.%) | MgO Added (wt.%) |
|---------|-------------|-----------------------|-------------------------|---------------------------|-----------------|
| 1       | Sand        | 70                    | 23                      | 23                        | 7               |
| 2       | Sand        | 70                    | 24.5                    | 23                        | 7               |
| 3       | Sand        | 70                    | 25                      | 23                        | 7               |
| 4       | Sand        | 70                    | 26.5                    | 23                        | 7               |
| 5       | Sand        | 70                    | 23                      | 23                        | 7               |
| 6       | PFBC-BA     | 70                    | 28                      | 23                        | 7               |
| 7       | PFBC-BA     | 70                    | 30                      | 23                        | 7               |
| 8       | PFBC-FA     | 70                    | 58                      | 23                        | 7               |
| 9       | LNB-FA      | 70                    | 46                      | 23                        | 7               |
| 10      | PFBC-CA     | 70                    | 28                      | 23                        | 7               |
| 11      | PFBC-CA     | 70                    | 32                      | 23                        | 7               |
slurry. The actual percentage moisture addition (percent of dry weight) needed to do that depended largely on the particle size of the waste. Wetting a powder required much more water than wetting a granular material.

The unconfined compressive strengths developed by the Ceramicrete mixes are shown in Table 20. With only one exception, the strengths developed by the Ceramicrete mixes were all less than 1000 psi. The additional curing time from seven to twenty-one days did not seem to cause a consistent increase in the strength of the specimens nor did the soaking of the specimens seem to affect the strength. The strengths developed by all of the Ceramicrete specimens were much lower than strengths typically exhibited by a similar sized specimen produced with Portland cement. For example, ASTM C150 indicates that a Type 1 Portland cement should have an unconfined compressive strength greater than 2800 psi after a 7-day cure. The strengths of the materials made with advanced process wastes were also much lower than those reported in the literature for Ceramicrete mixes made with conventional fly ashes (6).

TABLE 20
Strengths Developed by the Ceramicrete Mixes

| Mix No. | Filler Type | Water Added (% dry wt.) | 7-Day Strength (psi) | 21-Day Strength (psi) | 21-Day Strength Wet Cure (psi) |
|---------|-------------|-------------------------|----------------------|-----------------------|-------------------------------|
| 1       | Sand        | 23                      | 205                  | 165                   | 155                           |
| 2       | Sand        | 24.5                    | 830                  | 795                   | 920                           |
| 3       | Sand        | 25                      | 350                  | 600                   | 515                           |
| 4       | Sand        | 26.5                    | 645                  | 645                   | 745                           |
| 5       | Sand        | 23                      | 650                  | 605                   | 630                           |
| 6       | PFBC-BA     | 28                      | 588                  | 245                   | 350                           |
| 7       | PFBC-BA     | 30                      | 930                  | 760                   | 730                           |
| 8       | PFBC-FA     | 58                      | 275                  | 375                   | 150                           |
| 9       | LNB-FA      | 46                      | 260                  | 230                   | 280                           |
| 10      | PFBC-CA     | 28                      | 910                  | 525                   | 665                           |
| 11      | PFBC-CA     | 32                      | 1380                 | ND                    | 985                           |
5.10 Preparation and Testing of Base Conversion Products from Combustion Waste

5.10.1 Characterization of Conversion Products

5.10.1.1 X-ray powder diffraction (XRD)

XRD data for the conversion products from the SNRB fly ash show that the major component is still calcite (from the lime sorbent injection). Other components of the 2θ plot match those of a calcium aluminum iron silicate and a sodium calcium aluminosilicate. The plots for the two samples prepared at different temperatures are similar. These data show that the original amorphous and anhydrite composition was altered in the treatment, and predicts that sodium and perhaps calcium ions in the resulting structures should be exchangeable.

XRD data for the conversion products from the GRSI fly ash show that the major component is calcite (from the lime sorbent injection). Other components are a calcium aluminum iron silicate and a sodium calcium aluminosilicate, as in the SNRB-FA product. The plots for the two samples prepared at different temperatures are similar.

XRD data for the lower temperature conversion product from the PFBC fly ash show that the major components are calcite (from the dolomite-limestone injection) and quartz. Other components of the 2θ plot match those of a sodium calcium aluminosilicate, as well as some of the original hematite and mullite. The higher temperature conversion product from the PFBC ash contains a calcium aluminum iron silicate as the major phase and sodium calcium aluminosilicates, calcite, maghemite and quartz as minor phases.

The conversion product from the PFBC cyclone ash shows a similar composition. Calcite is the major phase present in products from both temperatures and sodium calcium aluminosilicate and calcium aluminum iron silicate as minor phases.

The LNB combustion system did not use lime injection, consequently low amounts of calcium are present in the products from the process ashes. XRD data for the low temperature conversion product from the LNB fly ash show that the amorphous materials were converted to a mixture of sodium aluminosilicates. Mullite and quartz from the original composition were still present as minor components. Similar results were obtained from the higher temperature conversion.

The LNB economizer ash also contained low calcium. The major component of the low temperature conversion product was sodium aluminosilicate, with minor amounts of quartz and mullite. The higher temperature product had a similar composition, by quartz was the major phase and lower amounts of aluminosilicates were present.

XRD data for the conversion products from the CR fly ash show that the amorphous materials were converted to a mixture of sodium aluminosilicates. Mullite, quartz, and hematite from the original composition were still present. Since no lime injection was used in the combustion, low calcium was present in the products.

XRD data for the conversion products from the CR bottom ash show that the sample is completely amorphous. No phases can be identified, and it is unlikely that any conversion occurred.
XRD data for the conversion products from the ACC fly ash show that the amorphous materials were converted to a mixture of sodium aluminosilicates. Mullite from the original composition was still present. Since no lime injection was used in the combustion, small amounts of calcium were present as calcium aluminosilicates.

5.10.1.2 SEM

The high temperature conversion product from SNRB fly ash exhibited a great deal of fine or fluffy crystalline growth around a dense particle core. Microprobe analyses indicated that the particles were CaCO₃, consistent with the XRD data. The fine crystalline portion of the sample is the aluminosilicate zeolite structure.

The low temperature conversion product from SNRB fly ash also consisted of fluffy crystalline growth. Microprobe analyses indicated the presence of CaCO₃ and sodium aluminosilicate, iron aluminosilicate, and sodium iron aluminosilicate.

The high temperature conversion product from the LNB fly ash consisted of agglomerated spheres stitched together by a lattice structure. Microprobe analyses showed that some of the spheres were sodium aluminosilicates, others were the iron aluminum silicates. Some titanium was present in both. Low amounts of sulfur and alkaline earths were present.

The low temperature conversion product from the LNB fly ash also had clusters of spheres, not nearly as well formed as those from the high temperature conditions. Microprobe analyses indicated that aluminosilicates were present. A flake consisting of iron oxide, iron silicate, and iron aluminum silicate was found.

The conversion products from PFBC fly ash also consisted of a fluffy spherical crystalline growth. Microprobe analyses indicated the presence of calcium carbonate, calcium aluminosilicates, sodium aluminosilicates, and iron aluminosilicates.

The PFBC cyclone ash conversion product appeared to be composites of all kinds of particles with little definition. It was not possible to get distinctive microprobe data from individual portions of these composites.

The high temperature ACC fly ash conversion product consisted of the fuzzy spheres as well as some interesting larger spheres clearly exhibiting a crystalline cage-like lattice structure. Microprobe analyses of the smaller spheres indicated sodium aluminosilicates as well as sodium calcium iron aluminosilicates. The larger lattice sphere also was a sodium calcium iron aluminosilicate.

The lower temperature ACC fly ash conversion product also consisted of agglomerated spheres and smaller spheres nested inside larger ones. The microprobe data indicated that some spheres were sodium aluminosilicates, some calcium aluminosilicates, some iron aluminosilicates, and some were mixed cation aluminosilicates.
5.10.2 Reactivity Tests for Conversion Products

5.10.2.1 Cu (II) Exchange

Zeolites prepared by conversion of ash samples were tested for removal of heavy metal ions from solution by determining the capacities for exchange of copper ion. The results for zeolite preparations conducted under the two conditions were compared with determinations performed with the original unconverted ash samples. In these tests, converted and original ash samples were equilibrated with 0.10 M copper sulfate solution for 48 hours at 25°C and washed free of solution. The unexchanged copper was determined by colorimetric titration (addition of KI and titration with Na$_2$S$_2$O$_3$ to pale yellow endpoint). The results are shown in Table 21. The results with unconverted ash samples show that only the PFBC and the ACC fly ashes have a significant capacity for Cu ion exchange.

The results with unconverted ash samples show that only the PFBC and the ACC fly ashes have a significant capacity for Cu ion exchange. The amount of Cu ion exchanged was low for these two ash samples.

After conversion by heating in 2.5 M NaOH for 6 days at 80°C, all of the zeolite products exhibited significant exchange of Cu ion. The highest exchange capacity was obtained with the SNRB fly ash-derived product (1.25 meq Cu$^{2+}$/g zeolite). Intermediate exchange was obtained with the zeolites obtained from GRSI fly ash, PFBC fly ash, PFBC cyclone ash, and ACC fly ash (0.90 to 0.65 meq Cu$^{2+}$/g zeolite). Lower exchange was observed with preparations from the CR fly ash, CR bottom ash, LNB fly ash, and LNB economizer ash.

The higher temperature conversions (3.5 M NaOH at 100°C for 2 days) gave products with higher exchange capacities. The zeolite from SNRB fly ash again gave the best results (1.45 meq Cu$^{2+}$/g zeolite). Reasonably good exchange was obtained with the zeolites obtained from GRSI fly ash, PFBC fly ash, PFBC cyclone ash, CR fly ash, LNB fly ash, and ACC fly ash (1.06 to 0.69). Only the CR bottom ash-derived products showed poor exchange.

The SNRB fly ash was produced in a system employing a relatively large injection of lime sorbent and consequently contained a large amount of calcium and smaller amounts of silicon and aluminum. The characterization of the conversion products showed that aluminosilicates were formed as fine crystals on the calcite particles. Thus, the high exchange capacity observed for the zeolite conversion products could be attributed to effective exposure of the aluminosilicate phase to the Cu ion solution. The high calcite content does not significantly affect the development of exchange capacity in the treated ash.

Since the high-calcium GRSI fly ash and PFBC fly ash also generated conversion products with good exchange capacities, there is no correlation of exchange activity with calcium content resulting from lime addition in the combustion system. Although the cyclone ash appeared to be more compacted, the higher temperature conversion was able to produce a material suitable for exchange. Thus, virtually any fly ash has potential for zeolite sorbent formation, any differences in activity of these products may be due to some as chemical composition factor that is not yet understood. Only the bottom ash was not converted to aluminosilicate sorbents.
TABLE 21

Cu⁺² Ion Exchange Capacities of Ashes and Conversion Products

| Precursor Ash | Ash Capacity (meq Cu⁺²/g) | Low-T Zeol. Cap. (meq Cu⁺²/g) | High-T Zeol. Cap. (meq Cu⁺²/g) |
|---------------|----------------------------|-------------------------------|-------------------------------|
| SNRB-FA       | 0.02                       | 1.25                          | 1.45                          |
| GRSI-FA       | 0                          | 0.90                          | 0.89                          |
| PFBC-FA       | 0.16                       | 0.73                          | 0.78                          |
| PFBC-CA       | 0                          | 0.79                          | 0.95                          |
| CR-FA         | 0                          | 0.39                          | 0.70                          |
| CR-BA         | 0                          | 0.20                          | 0.06                          |
| LNB-FA        | 0                          | 0.30                          | 1.06                          |
| LNB-EA        | 0                          | 0.34                          | 0.46                          |
| ACC-FA        | 0.14                       | 0.65                          | 0.69                          |

5.10.2.2 Ammonium Exchange

The same two sets of ash-derived zeolites were utilized in tests to determine capacities for ammonium ion exchange. In these tests, the zeolite preparations were equilibrated with 0.10 M ammonium hydroxide solution at 25°C for 48 hours. The supernatant solution was removed and unexchanged ammonium determined by the indophenol method. The results are shown in Table D.

The exchange capacities for ammonium parallel those described above for Cu⁺² ion, and are generally a little more than twice the values, as expected for a monovalent ion. Thus, for the zeolites prepared at 80°C, the SNRB fly ash showed the highest capacity (2.75 meq NH₄⁺/g zeolite). Other capacity values were in the range 2.2 to 1.5 meq NH₄⁺/g zeolite, except for the CR bottom ash which was very poor (0.05 meq NH₄⁺/g zeolite).

As in the Cu ion exchange tests, the zeolites prepared at 100°C exhibited better performance. The SNRB fly ash zeolite exhibited an ammonium exchange capacity of 3.0 meq NH₄⁺/g zeolite, but the LNB fly ash zeolite was also 3.0 meq NH₄⁺/g zeolite. Again the CR bottom ash product was very poor.

The consistency in these data sets for Cu and ammonium ions for the members of the set convinces us that the products are behaving predictably. Literature values for exchange of monocations in fly ash-derived zeolites range from 1.6 to 3.0 meq/g, exactly the range observed in this project. The zeolites could be produced at low cost and in very small particle sizes. Thus, many uses for the zeolite...
products with these exchange capacities are feasible. These uses range from environmental clean up applications such as nuclear waste to soil amendments.

TABLE 22
NH\textsubscript{4}\textsuperscript{+1} Ion Exchange Capacities of Ashes and Conversion Products

| Precursor Ash | Low-T Zeol. Cap. (meq NH\textsubscript{4}\textsuperscript{+1} /g) | High-T Zeol. Cap. (meq NH\textsubscript{4}\textsuperscript{+1} /g) |
|---------------|-------------------------------------------------|-------------------------------------------------|
| SNRB-FA       | 2.8                                             | 3.0                                             |
| GRSI-FA       | 1.5                                             | 1.6                                             |
| PFBC-FA       | 1.7                                             | 1.7                                             |
| PFBC-CA       | 2.1                                             | 2.2                                             |
| CR-FA         | 2.2                                             | 1.7                                             |
| CR-BA         | 0.05                                            | 0.1                                             |
| LNB-FA        | 1.6                                             | 3.0                                             |
| LNB-EA        | 1.8                                             | 1.7                                             |
| ACC-FA        | 2.7                                             | 2.5                                             |

5.10.2.3 Sorption of Organic Contaminants

Surfactant-modified zeolites have been utilized effectively as sorbents for the removal of chlorinated organic solvents from water (25). In this application the zeolite serves as a supporting surface for a cationic surfactant layer. The contaminants therefore partition into the hydrophobic organic phase formed by the surfactant. Previous studies (25) utilized a natural zeolite (clinoptilolite) with a particle size range 0.42-0.83 mm (20-40 mesh). The partitioning coefficients \( K_d \) varied with surfactant loading on the clinoptilolites and \( K_d \) up to 17.4 L/kg were obtained.

The zeolite prepared by conversion of the GRSI fly ash by heating in 2.5 M NaOH for 6 days and 80°C was impregnated with two different cationic surfactants, tricaprylmethylammonium chloride (TCMA) and hexadecyltrimethylammonium bromide (HDTMA). Owing to the large number of experiments, one of the ash-derived zeolite products was selected for the testing. Each of the cationic surfactants was loaded at five concentrations on the zeolite to give two sets of sorbents.

Isotherm sorption tests were conducted for each set of impregnated zeolites with aqueous solutions of trichloroethylene (TCE) containing 800 mg/L of TCE. A set of weighed amounts (0.5g, 1.0g, 1.5g, 2.0g, 2.5g) of each impregnated zeolite were stirred in a 50 ml bottle for 24 hours with 50 ml of the
TCE solution at 25°C. An aliquot of the solution was removed from the zeolite and internal standard (MTBE) added. The unsorbed TCE (equilibrium TCE concentration) was analyzed by a calibrated GC, and the sorbed TCE calculated by difference. Results were plotted as amount of TCE sorbed/weight of sorbent (mg/kg) versus equilibrium TCE concentration (mg/L). A typical plot is shown in Figure 8. The slope of each plot gives the $K_d$ for each loading of the sorbent.

![Figure 8. Linear sorption plot for HDTMA-zeolite (GRSI-FA high-temp) at 24g/kg load.](image)

For the HDTMA-Br surfactant loaded on the GRSI-FA zeolite, three of the plots were fairly linear with high $R^2$, but two of the plots showed a poor linear correlation. Log-log plots (Freundlich plots) gave considerably poorer fits to a linear regression, thus the linear sorption isotherm expression (Eqn. 1) was used, where $C_s$ is amount of solute sorbed per unit mass of sorbent, $C_w$ is the equilibrium aqueous solute concentration, and $K_d$ is the sorption coefficient.

**Equation 1.**

$$C_s = K_d C_w$$

The range of $K_d$s (9.1 to 28.6 L/kg) were considerably higher than those obtained for perchloroethylene with the clinoptilolite-HDTMA-Br (25) for similar loadings of surfactant. A plot of the $K_d$s versus HDTMA loading (Figure 9) showed the same type of leveling out at higher surfactant loadings that was observed earlier (25). But the maximum $K_d$ value for the fly ash derived zeolite sorbent (29 L/kg obtained at 55 mmol/kg surfactant loading) occurred at nearly twice the maximum value for the clinoptilolite sorbent (17 L/kg at a loading of 150 mmol/kg). In addition, the slope of the line representing the lower loadings (0.72 L/mmol) on the ash-derived sorbent was 4.8 times larger.
than the slope for the clinoptilolite, indicating better sorption per unit mass of sorbent when low surfactant loadings are used and where maximum efficiency of surfactant use is desired.

![Figure 9. Plot of $K_d$ versus surfactant loading for HDTMA-zeolite (GRSI-FA).](image)

In contrast to the results obtained by loading HDTMA on the zeolite, isotherm studies with the sorbents prepared by impregnating TCMA into the GRSI fly ash zeolite resulted in sorption plots (amount of TCE adsorbed versus equilibrium concentration) that were highly linear. In the case of the TCMA loaded zeolites, the $K_d$ versus surfactant loading plot (Figure 10) did not exhibit the leveling out effect that was observed for the HDTMA surfactant on the zeolite, at least over the range of surfactant loadings used. In fact, a very high $K_d$ (89 L/kg) was observed for the 98 mmol/kg loading of TCMA. At lower loadings the $K_d$s were a little higher than those obtained with HDTMA surfactant. The slope of the $K_d$ versus surfactant loading curve was 0.84 L/mmol for the TCMA-GRSI FA sorbent.

The success of the surfactant loaded fly ash-derived zeolites might be attributed to higher surface areas available. The surfactant is bulky and cannot readily penetrate micropores in the zeolite but spreads out attaching to cation binding sites on the surface. The larger the surface area, the more surfactant is spread out in a monolayer, offering the most efficient binding. Present in the fly ash derived zeolites are spherical lattices produced from the original glassy cenospheres. These structures as well as needle clusters can bind surfactant over a very large surface area. It may be that the surfactant-coated spherical lattices can promote a kind of solid micelle formation that is effective for organic contaminant binding.

Further work is needed with a variety of organic contaminants. Testing should be performed over a much greater range of organic concentrations, so that Freundlich behavior can be examined and
better predictions can be obtained for treatment conditions. Only one fly ash zeolite was examined in the organic sorption tests, the set of surfactant loaded sorbents should be expanded. Although the morphologies and structures of the zeolite products from fly ash are complex, they may offer greater possibilities for contaminant control. Further empirical testing is warranted.

![Figure 10. Plot of $K_d$ versus surfactant loading for TCMA-zeolite (GRSI-FA)](image)

6.0 CONCLUSIONS

Thirteen solid wastes, six coals and one unreacted sorbent produced from seven advanced coal utilization processes were characterized for task three of this project. The advanced processes from which samples were obtained included a gas-reburning sorbent injection process, a pressurized fluidized-bed coal combustion process, a coal-reburning process, a $SO_x$, $NO_x$, ROX, BOX process, an advanced flue desulphurization process, and an advanced coal cleaning process. The waste samples ranged from coarse materials, such as bottom ashes and spent bed materials, to fine materials such as fly ashes and cyclone ashes.

Based on the results of the waste characterizations, an analysis of appropriate waste management practices for the advanced process wastes was done. The analysis indicated that using conventional waste management technology should be possible for disposal of all the advanced process wastes studied for task three. However, some wastes did possess properties that could present special problems for conventional waste management systems. Several task three wastes were self-hardening materials and one was self-heating. Self-hardening is caused by cementitious and pozzolanic reactions that occur when water is added to the waste. All of the self-hardening wastes set up slowly (in a matter
of hours or days rather than minutes). Thus these wastes can still be handled with conventional management systems if care is taken not to allow them to set up in storage bins or transport vehicles.

Waste self-heating is caused by the exothermic hydration of lime when the waste is mixed with conditioning water. If enough lime is present, the temperature of the waste will rise until steam is produced. It is recommended that self-heating wastes be conditioned in a controlled manner so that the heat will be safely dissipated before the material is transported to an ultimate disposal site.

Waste utilization is important because an advanced process waste will not require ultimate disposal when it is put to use. Each task three waste was evaluated for utilization potential based on its physical properties, bulk chemical composition, and mineral composition. Only one of the thirteen materials studied might be suitable for use as a pozzolanic concrete additive. However, many wastes appeared to be suitable for other high-volume uses such as blasting grit, fine aggregate for asphalt concrete, road deicer, structural fill material, soil stabilization additives, waste stabilization additives, landfill cover material, and pavement base course construction.

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APPENDIX A

SUMMARY OF THE WASTE PHYSICAL PROPERTY DATA
Gas Reburning Sorbent Injection - ESP Fly Ash

Color: Consistency - Gray powder
Initial Moisture Content - 0.2%
pH of 50% Slurry - 12.2
Acid-neutralizing Capacity (to pH 5.0) - 3167 meq/lb
Particle Specific Surface Area - 3.93 m²/g
Particle Specific Gravity - 2.44
Dry Bulk Density (poured) - 38.2 lbs/ft³
Dry Bulk Density (packed) - 51.6 lbs/ft³
Blaine Fineness - 8022 cm²/g

Particle-size Data:
- D₃₀ - 0.0024 mm
- Uniformity Coefficient (D₉₀/D₁₀) - 1.55

Maximum Compacted Dry Density (ASTM D698-78) - 75.0 lbs/ft³

Optimum Moisture Content - 31.6% dry wt.
Pozzolanic Activity Index (with cement) - 83% of control (7-day)
- 87% of control (28-day)

Self-cementing Behavior - Moderately cementitious
Unconfined Compressive Strength - 7 day - 48 psi
- 14 day - 67 psi
- 28 day - 669 psi

Angle of Repose - 35°
Self-heating Behavior - Moderately exothermic, the temperature increased 60° in 5 minutes
Permeability Coefficient - 4.3 x 10⁻⁴ cm/s
Compressibility (Cᵥ) - NA
Angle of Internal Friction - NA

NA - The test was not applicable to this sample.
Gas Reburning Sorbent Injection - Bottom Ash

- **Color: Consistency**: Dark gray and granular
- **Initial Moisture Content**: 54% (wet)
- **pH of 50% Slurry**: 10.9
- **Acid-neutralizing Capacity (to pH 5.0)**: 136 meq/lb
- **Particle Specific Surface Area**: 8.32 m²/g
- **Particle Specific Gravity**: 1.63
- **Dry Bulk Density (poured)**: 40.7 lbs/ft³
- **Dry Bulk Density (packed)**: 55.1 lbs/ft³
- **Blaine Fineness**: 143 cm²/g

**Particle-size Data:**

| Particle-size Data               | Value       |
|----------------------------------|-------------|
| D₅₀                             | 1.06 mm     |
| Uniformity Coefficient (D₆₀/D₁₀) | 22.4        |

- **Maximum Compacted Dry Density (ASTM D698-78)**: 78.9 lbs/ft³
- **Optimum Moisture Content**: 24.5% dry wt.
- **Pozzolanic Activity Index (with cement)**: 49% of control (7-day), 56% of control (28-day)
- **Self-cementing Behavior**: Slightly cementitious
- **Unconfined Compressive Strength**:
  - 7 day - 46 psi
  - 14 day - 56 psi
  - 28 day - 51 psi
- **Angle of Repose**: 55°
- **Self-heating Behavior**: None, no temperature increase after one hour
- **Permeability Coefficient**: 4.2 x 10⁻⁵ cm/s
- **Compressibility (Cᵥ)**: 3.26 sq.in./min @ 8000 psf
- **Angle of Internal Friction**: 44.5°

*NA - The test was not applicable to this sample.*
Pressurized Fluidized Bed - Bottom Ash

Color:Consistency - Tan and granular
Initial Moisture Content - 0.042%
pH of 50% Slurry - 11.2
Acid-neutralizing Capacity (to pH 5.0) - 102 meq/lb
Particle Specific Surface Area - ND
Particle Specific Gravity - 2.73
Dry Bulk Density (poured) - 80.3 lbs/ft³
Dry Bulk Density (packed) - 83.1 lbs/ft³
Blaine Fineness - ND

Particle-size Data:
\[ D_{50} \] - 0.9 mm
Uniformity Coefficient \( \left( \frac{D_{50}}{D_{10}} \right) \) - 2.99

Maximum Compacted Dry Density (ASTM D698-78) - 96.0 lbs/ft³

Optimum Moisture Content - 20.5% dry wt.
Pozzolanic Activity Index (with cement) - 41% of control (7-day), 42% of control (28-day)
Self-cementing Behavior - None
Unconfined Compressive Strength - None, sample was noncohesive
Angle of Repose - 35°
Self-heating Behavior - None, no temperature increase after one hour
Permeability Coefficient - Highly permeable, greater than \( 5 \times 10^{-2} \) cm/sec
Compressibility \( (C_v) \) - 7.61 sq.in./min @ 8000 psf
Angle of Internal Friction - 39°

ND - No data, The test could not be done on this sample.
Pressurized Fluidized Bed - Cyclone Ash

Color: Consistency - Gray-brown powder
Initial Moisture Content - 0.1%
pH of 50% Slurry - 11.9
Acid-neutralizing Capacity (to pH 5.0) - 2714 meq/lb
Particle Specific Surface Area - 1.76 m²/g
Particle Specific Gravity - 2.76
Dry Bulk Density (poured) - 65.2 lbs/ft³
Dry Bulk Density (packed) - 79.5 lbs/ft³
Blaine Fineness - 4004 cm²/g

Particle-size Data:

\[ D_{50} \] - 0.107 mm
Uniformity Coefficient (\(D_{60}/D_{10}\)) - 3.34

Maximum Compacted Dry Density (ASTM D698-78) - 105.9 lbs/ft³
Optimum Moisture Content - 19.7% dry wt.
Pozzolanic Activity Index (with cement) - 71% of control (7-day)
- 84% of control (28-day)
Self-cementing Behavior - Highly cementitious
Unconfined Compressive Strength
- 7 day - 1089 psi
- 14 day - 2056 psi
- 28 day - 2325 psi

Angle of Repose - 43°
Self-heating Behavior - None, no temperature increase after one hour
Permeability Coefficient - 7.3 x 10⁻⁵ cm/sec
Compressibility (Cₜ) - NA
Angle of Internal Friction - NA

NA - The test was not applicable to this sample.
Color: Consistency - Red-brown powder
Initial Moisture Content - 0.1%
pH of 50% Slurry - 8.9
Acid-neutralizing Capacity (to pH 5.0) - 452 meq/lb
Particle Specific Surface Area - 3.36 m²/g
Particle Specific Gravity - 2.69
Dry Bulk Density (poured) - 23.1 lbs/ft³
Dry Bulk Density (packed) - 28.2 lbs/ft³
Blaine Fineness - 16,321 cm²/g

Particle-size Data:

\[ D_{50} \] - 0.014 mm
\[ \text{Uniformity Coefficient } (D_{60}/D_{10}) \] - 3.17

Maximum Compacted Dry Density (ASTM D698-78) - 105.9 lbs/ft³

Optimum Moisture Content - 19.5% dry wt.
Pozzolanic Activity Index (with cement) - 64% of control (7-day)
- 92% of control (28-day)

Self-cementing Behavior - Moderately cementitious

Unconfined Compressive Strength - 7 day - 440 psi
- 14 day - 534 psi
- 28 day - 316 psi

Angle of Repose - 40°

Self-heating Behavior - Slightly exothermic, temperature increased 2°C after one hour

Permeability Coefficient - \( 2.5 \times 10^{-7} \) cm/sec

Compressibility (Cv) - NA

Angle of Internal Friction - NA

NA - The test was not applicable to this sample.
Coal Reburning - ESP Fly Ash

Color: Consistency - Brown: Powder
Initial Moisture Content - 1.15%
pH of 50% Slurry - 12.1
Acid Neutralizing Capacity (to pH 5.0) - 565.6 meq/lb
Particle Specific Surface Area - 16.43 m²/g
Particle Specific Gravity - 2.54
Dry Bulk Density (poured) - 39.5 lbs/ft³
Dry Bulk Density (packed) - 47.0 lbs/ft³
Blaine Fineness - 7841 cm²/gm
Particle Size Data:
  \( D_{50} \) - 0.008 mm
  Uniformity Coefficient, \( D_{60}/D_{10} \) - 8.7
Maximum Compacted Density (Standard Proctor) - 85.3 lbs/ft³
Optimum Moisture Content - 31.8% dry weight
Pozzolanic Activity Index - 85% of control, 7 day
  94% of control, 28 day
Self-Cementing Behavior - Moderately Cementitious
Unconfined Compressive Strength - 7 day - 130 psi
  14 day - specimen broke
  28 day - 207 psi
Angle of Repose - 41° (dry)
Self-Heating Behavior - Slightly exothermic, the temperature increased 12°F after one hour.
Permeability Coefficient - 2.9 x 10⁻⁵ cm/s
Compressibility - NA

NA - Test was not applicable to this sample.
## Coal Reurning - Bottom Ash (Slag)

| Property                                      | Value                        |
|-----------------------------------------------|------------------------------|
| Color: Consistency                            | Black: glassy granules       |
| Initial Moisture Content                      | Wet, standing water          |
| pH of 50% Slurry                              | 7.2                          |
| Acid-neutralizing Capacity (to pH 5.0)        | 22.6 meq/lb                  |
| Particle Specific Surface Area                | 0.83 m²/g                    |
| Particle Specific Gravity                     | 2.9                          |
| Dry Bulk Density (poured)                     | 76.5 lbs/ft³                 |
| Dry Bulk Density (packed)                     | 85.9 lbs/ft³                 |
| Blaine Fineness                               | NA                           |
| Particle-size Data:                           |                              |
| \( D_{20} \)                                  | 2.1 mm                       |
| Uniformity Coefficient (\( D_{60}/D_{20} \)) | 2.1                          |
| Maximum Compacted Dry Density (ASTM D698-78) | 117.8 lbs/ft³                |
| Optimum Moisture Content                      | 17.6% dry wt.                |
| Pozzolanic Activity Index (with cement)       | NA                           |
| Self-cementing Behavior                       | None                         |
| Unconfined Compressive Strength               | None, sample was noncohesive |
| Angle of Repose                               | 57°                          |
| Self-heating Behavior                         | None, no temperature increase after one hour |
| Permeability Coefficient                      | Highly permeable, greater than \( 5 \times 10^{-2} \) cm/sec |
| Compressibility (\( C_v \))                  | 3.31 sq.in./min @ 8000 psf   |
| Angle of Internal Friction                    | ND                           |

NA - Test was not applicable to this sample.  
ND - No data, The test could not be done on this sample.
Color: Consistency - Off White: Powder

Initial Moisture Content - 1.84%

pH of 50% Slurry - 11.9

Acid Neutralizing Capacity (to pH 5.0) - NA

Particle Specific Surface Area - 8.9 m²/g

Particle Specific Gravity - 2.24

Dry Bulk Density (poured) - 24.2 lbs/ft³

Dry Bulk Density (packed) - 27.8 lbs/ft³

Blaine Fineness - 20,671 cm²/g

Particle Size Data:

D₅₀ - 0.0052 mm

Uniformity Coefficient, D₅₀/D₁₀ - 3.6

Maximum Compacted Density (Standard Proctor) - NA

Optimum Moisture Content - NA

Pozzolanic Activity Index - 74% of control, 7 day
76% of control, 28 day

Self-Cementing Behavior - NA

Unconfined Compressive Strength - NA

Angle of Repose - 52° (dry)

Self-Heating Behavior - Slightly Exothermic, the temperature increased 1°F after one hour.

Permeability Coefficient - NA

Compressibility - NA

NA - The test was not applicable to this sample.
SOx, NOx, ROx, Box - Baghouse Fly Ash

Color: Consistency - Grey: Powder
Initial Moisture Content - 0.78%
pH of 50% Slurry - 11.6
Acid Neutralizing Capacity (to pH 5.0) - 4299 meq/lb
Particle Specific Surface Area - 5.64 m²/g
Particle Specific Gravity - 2.26
Dry Bulk Density (poured) - 21.1 lbs/ft³
Dry Bulk Density (packed) - 25.4 lbs/ft³
Blaine Fineness - 10,773 cm²/gm

Particle Size Data:

\[ D_{50} \]
\[ \text{Uniformity Coefficient, } D_{60}/D_{10} \]
- 0.0057 mm
- 5.6

Maximum Compacted Density (Standard Proctor) - 58.2 lbs/ft³
Optimum Moisture Content - 58.8% dry weight
Pozzolanic Activity Index - 81% of control, 7 day
99% of control, 28 day
Self-Cementing Behavior - Slightly Cementitious
Unconfined Compressive Strength - 7 day - 60 psi
14 day - specimen broke
28 day - 56.5 psi
Angle of Repose - 50° (dry)
Self-Heating Behavior - Slightly Exothermic, the temperature increased 3°F after one hour.
Permeability Coefficient - 2.8 x 10⁻⁵ cm/s
Compressibility - NA

NA - Test was not applicable to this sample.
LNB/AOFA ESP Fly Ash - Physical Data Summary

Color: Consistency - Dark Grey Powder
Initial Moisture Content - 0.66%
pH of 50% Slurry - 4.09
Acid-neutralizing Capacity (to pH 5.0) - 0 meq/lb
Particle Specific Surface Area - 2.13 m²/g
Particle Specific Gravity - 2.27
Dry Bulk Density (poured) - 53.0 lbs/ft³
Dry Bulk Density (packed) - 62.4 lbs/ft³
Blaine Fineness - 3549 cm²/g

Particle-size Data:

| D₅₀ | Uniformity Coefficient (D₆⁰/D₅₀) |
|-----|---------------------------------|
| 0.03 mm | 4.4 |

Maximum Compacted Dry Density (ASTM D698-78) - 78.8 lbs/ft³
Optimum Moisture Content - 26.7% dry wt.
Pozzolanic Activity Index (with cement) - 60% of control (7-day) - 76% of control (28-day)
Self-cementing Behavior - None
Unconfined Compressive Strength - None, waste did not develop strength when cured
Angle of Repose - 25°
Self-heating Behavior - None, no temperature increase after one hour
Permeability Coefficient - 6.3 x 10⁻⁵ cm/s
Compressibility - NA
Angle of Internal Friction - 19°

NA - The test was not applicable to this sample.
LNB/AOFA Economizer Ash - Physical Data Summary

Color: Consistency
- Assorted Granular Fractions (Tan, Gray, Black, Redish)

Initial Moisture Content
- 0.57%

pH of 50% Slurry
- 8.86

Acid-neutralizing Capacity (to pH 5.0)
- 10 meq/lb

Particle Specific Surface Area
- 0.97 m²/g

Particle Specific Gravity
- 2.06

Dry Bulk Density (poured)
- 59.5 lbs/ft³

Dry Bulk Density (packed)
- 66.8 lbs/ft³

Blaine Fineness
- NA

Particle-size Data:

\[ D_{10} \]
- 0.26 mm

Uniformity Coefficient \( (D_{60}/D_{10}) \)
- 23.9

Maximum Compacted Dry Density (ASTM D698-78)
- 70.5 lbs/ft³

Optimum Moisture Content
- 36.0% dry wt.

Pozzolanic Activity Index (with cement)
- 49% of control (7-day)
- 62% of control (28-day)

Self-cementing Behavior
- None

Unconfined Compressive Strength
- None, sample was not sufficiently cohesive to form cylinders

Angle of Repose
- 30°

Self-heating Behavior
- None, no temperature increase after one hour

Permeability Coefficient
- \( 1.3 \times 10^{-3} \) cm/sec

Compressibility
- NA

Angle of Internal Friction
- 32°

NA - The test was not applicable to this sample.
LNB/AOFA Bottom Ash - Physical Data Summary

| Property                                      | Value                              |
|-----------------------------------------------|------------------------------------|
| Color: Consistency                            | Assorted Granular Fractions (Tan, Gray, Black, Redish) |
| Initial Moisture Content                      | 41.8%                              |
| pH of 50% Slurry                              | 4.4                                |
| Acid-neutralizing Capacity (to pH 5.0)        | 0 meq/lb                           |
| Particle Specific Surface Area                | 0.42 m²/g                          |
| Particle Specific Gravity                     | 2.02                               |
| Dry Bulk Density (poured)                     | 38.8 lbs/ft³                       |
| Dry Bulk Density (packed)                     | 42.6 lbs/ft³                       |
| Blaine Fineness                               | NA                                 |
| Particle-size Data:                           |                                    |
| \(D_{50}\)                                   | 7.2 mm                             |
| Uniformity Coefficient (\(D_{50}/D_{10}\))   | 91.7                               |
| Maximum Compacted Dry Density (ASTM D698-78)  | 59.0 lbs/ft³                       |
| Optimum Moisture Content                      | 46.6% dry wt.                      |
| Pozzolanic Activity Index (with cement)       | 40% of control (7-day), 52% of control (28-day) |
| Self-cementing Behavior                       | None                               |
| Unconfined Compressive Strength               | None, sample was not sufficiently cohesive to form cylinders |
| Angle of Repose                               | 40°                                |
| Self-heating Behavior                         | None, no temperature increase after one hour |
| Permeability Coefficient                      | \(1.7 \times 10^{-3}\) cm/s       |
| Compressibility (\(C_v\))                    | 6.9 in²/min @ 8000 psf             |
| Angle of Internal Friction                    | 42°                                |

NA - The test was not applicable to this sample.
Advanced FGD Scrubber Waste - Physical Data Summary

Color: Consistency - Off-white powder
Initial Moisture Content - 25.6%
pH of 50% Slurry - 7.8
Acid-neutralizing Capacity (to pH 5.0) - 381 meq/lb (dry wt.)
Particle Specific Surface Area - 13.82 m²/g
Particle Specific Gravity - 2.55
Dry Bulk Density (poured) - 52.1 lbs/ft³
Dry Bulk Density (packed) - 65.1 lbs/ft³
Blaine Fineness - 1095 cm²/g

Particle-size Data:
- D₅₀ - 0.056 mm
- Uniformity Coefficient (D₅₀/D₁₀) - 8.9
- Maximum Compacted Dry Density (ASTM D698-78) - 72.3 lbs/ft³
- Optimum Moisture Content - 44.6% dry wt.
- Pozzolanic Activity Index (with cement) - 76% of control
- Self-cementing Behavior - None
- Unconfined Compressive Strength - 7 day - 9.8 psi (additional curing time did not increase strength)
- Angle of Repose - 40°
- Self-heating Behavior - None, no temperature increase after one hour
- Permeability Coefficient - 2 x 10⁻⁴ cm/sec (specimen cured for 7 days)
- Compressibility - NA

NA - The test was not applicable to this sample.
### Advanced Coal Cleaning Fly Ash - Physical Data Summary

| Property                                      | Value   |
|-----------------------------------------------|---------|
| Color: Consistency                            | Dark Grey Powder |
| Initial Moisture Content                      | 0.06%   |
| pH of 50% Slurry                              | 5.0     |
| Acid-neutralizing Capacity (to pH 5.0)        | 0 meq/lb|
| Particle Specific Surface Area                | 2.8 m²/g|
| Particle Specific Gravity                     | 2.3     |
| Dry Bulk Density (poured)                     | 35.5 lbs/ft³|
| Dry Bulk Density (packed)                     | 44.37 lbs/ft³|
| Blaine Fineness                               | 3960 cm²/g|
| Particle-size Data:                           |         |
| $D_{90}$                                      | 0.09 mm |
| Uniformity Coefficient ($D_{90}/D_{10}$)      | 4.9     |
| Maximum Compacted Dry Density (ASTM D698-78) | 72.5 lbs/ft³|
| Optimum Moisture Content                      | 30.5% dry wt. |
| Pozzolanic Activity Index (with cement)       | 79% of control (7-day) 85% of control (28-day) |
| Self-cementing Behavior                       | None    |
| Unconfined Compressive Strength               | 7 day - 20 psi 14 day - 36 psi |
| Angle of Repose                               | 35°     |
| Self-heating Behavior                         | None, no temperature increase after one hour |
| Permeability Coefficient                      | 7.4 x 10⁻⁶ cm/sec |
| Compressibility ($C_v$)                       | NA      |
| Angle of Internal Friction                    | 23.5°   |

NA - The test was not applicable to this sample.
APPENDIX B

SUMMARY OF THE WASTE CHEMICAL AND MINERAL COMPOSITIONS
GRSI ESP Fly Ash

Mineral Composition

| Phase                  | Percentage |
|------------------------|------------|
| Crystalline Phases     | 36.8%      |
| Amorphous Phases       | 63.2%      |

Crystalline Fraction Composition

- Dicalcium Silicate: 0.4%
- Calcium Silicate: 1.2%
- Wollastonite: 0.4%
- Montmorillonite: 2.4%
- Illite: 3.6%
- Altered Kaolinite: 1.6%
- Kaolinite: 2.8%
- Quartz (SiO₂): 3.2%
- Ankerite: 10.4%
- Altered Calcite: 4.4%
- Calcite (CaCO₃): 4.0%
- Hematite (Fe₂O₃): 2.0%
- Lime (CaO): 4.0%
GRSI ESP Fly Ash

Chemical Composition

%  

100  80  60  40  20  0

SiO₂ 32.1%
Al₂O₃ 12.1%
Fe₂O₃ 8.0%
CaO 25.0%
Other Oxides & Components 19.2%

Other Oxides and Components

1500 ppb Cl⁻¹
CO₃²⁻ (as CO₂)
SO₄²⁻ or SO₃²⁻ (as SO₃)
0.5% TiO₂
0.1% P₂O₅
K₂O
Na₂O
MgO

Bulk Composition
GRSI Bottom Ash

Mineral Composition

Crystalline Phases

Amorphous Phases

Phases

Crystalline vs. Noncrystalline

Crystalline Fraction Composition

0.4% Hematite (Fe₂O₃)
0.4% Calcite (CaCO₃)
2.4% Quartz (SiO₂)
0.8% Alt. Kaolinite
0.4% Illite
PFB Cyclone Fly Ash

Mineral Composition

Phases
Crystalline vs. Noncrystalline

Crystalline Phases
- Montmorillonite 3.6%
- Illite 0.8%
- Altered Kaolinite 0.4%
- Kaolinite 4.0%
- Quartz (SiO₂) 7.2%
- Dolomite 1.6%
- Calcite (CaCO₃) 4.0%
- Anhydrite (CaSO₄) 2.4%
- Lime (CaO) 0.4%
- Iron Oxide 2.0%
- Periclase (MgO) 0.4%

Amorphous Phases
- 72.8%

Crystalline Fraction Composition
- 27.2%
PFB ESP Fly Ash

Mineral Composition

1.66%

Crystalline Phases

0.4%

Altered Kaolinite

0.8%

Anhydrite (CaSO₄)

98.4%

Amorphous Phases

Crystalline vs. Noncrystalline Phases

100

%
PFB Bottom Ash

Mineral Composition

| Phases | Crystalline vs. Noncrystalline |
|--------|-------------------------------|
| Crystalline Phases | 10% |
| Amorphous Phases | 90% |

| Crystalline Fraction Composition |
|----------------------------------|
| Montmorillonite | 1.6% |
| Quartz (SiO₂) | 1.2% |
| Dolomite | 1.8% |
| Calcite (CaCO₃) | 3.2% |
| Anhydrite (CaSO₄) | 2.8% |
| Periclase (MgO) | 0.4% |
PFB Bottom Ash

Chemical Composition

Bulk Composition

- CaO: 31.0%
- Fe₂O₃: 3.2%
- Al₂O₃: 2.1%
- SiO₂: 5.9%

Other Oxides & Components

- 57.8% (Unidentified)
- 15.8% (Other Oxides and Components)
- 9.3% (Unburned Carbon)
- 8.7% (CO₃⁻² (as CO₂))
- 23.5% (MgO)
- 343 ppb S²⁻ or SO₃⁻² (as SO₃)
- 0.1% TiO₂
- 87 ppb Cl⁻
Coal Reburning - Bottom Ash (Slag)

Mineral Composition

Amorphous Phases

Phases
Crystalline vs. Noncrystalline
Coal Reburning - Bottom Ash (Slag)

Chemical Composition

- **CaO**
  - 14.8%

- **Fe₂O₃**
  - 21.0%

- **Al₂O₃**
  - 17.9%

- **SiO₂**
  - 44.0%

1.7% Other Oxides & Components

- **TiO₂**
  - 0.7%

- **Na₂O**
  - 0.4%

- **MgO**
  - 0.6%

20 ppb Cl⁻¹
Coal Reburning - ESP Fly Ash

Mineral Composition

Crystalline Phases

30.8%

Amorphous Phases

69.2%

Phases
Crystalline vs. Noncrystalline

Crystalline Fraction Composition

Dicalcium Silicate
Montmorillonite
Illite
Altered Kaolinite
Kaolinite
Quartz (SiO₂)
0.4% Ankerite
Calcite (CaCO₃)
Anhydrite (CaSO₄)
Hematite (Fe₂O₃)
Lime (CaO)
Coal Reburning - ESP Fly Ash

Chemical Composition

- SiO₂: 36.7%
- Al₂O₃: 16.7%
- Fe₂O₃: 24.0%
- CaO: 8.0%
- Other Oxides & Components: 18.6%

Other Oxides & Components:
- SO₄²⁻ or SO₃²⁻ (as SO₃): 2.2%
- MgO: 1.31%
- Na₂O: 0.3%
- P₂O₅: 0.2%
- TiO₂: 0.8%
- CO₃²⁻ (as CO₂): 1.0%
- Cl⁻: 26 ppb

Unidentified: 12.3%
SO\textsubscript{x}, NO\textsubscript{x}, RO\textsubscript{x}, Box - Sorbent

Mineral Composition

| Component            | Percentage |
|----------------------|------------|
| Portlandite (Ca(OH)\textsubscript{2}) | 87.4%      |
| Periclase (MgO)      | 10.3%      |
| Dicalcium Silicate   | 0.4%       |

Crystalline Phases: 100%

Phases: Crystalline vs. Noncrystalline

Crystalline Fraction Composition
SO\textsubscript{x}, NO\textsubscript{x}, RO\textsubscript{x}, Box - Sorbent

Chemical Composition

Bulk Composition
- CaO: 71.2%
- Other Oxides: 27.5%

Other Oxides and Components
- 310 ppb Cl\textsuperscript{-1}
- 21.0% Water of Hydration
- 0.2% Fe\textsubscript{2}O\textsubscript{3}
- 0.5% Al\textsubscript{2}O\textsubscript{3}
- 1.9% SiO\textsubscript{2}
- 3.0% MgO
- 0.1% SO\textsubscript{4}\textsuperscript{2-}
- 0.1% K\textsubscript{2}O

0.5% Moisture
SO$_x$, NO$_x$, RO$_x$, Box - Fly Ash

Mineral Composition

- **Crystalline Phases**
  - 22.9%

- **Amorphous Phases**
  - 77.1%

- **Phases**
  - Crystalline vs. Noncrystalline

- **Crystalline Fraction Composition**
  - Illite: 0.8%
  - Kaolinite: 0.4%
  - Altered Calcite: 2.0%
  - Calcite (CaCO$_3$): 2.4%
  - Anhydrite (CaSO$_4$): 17.3%
SO\textsubscript{X}, NO\textsubscript{X}, RO\textsubscript{X}, Box - Fly Ash

Chemical Composition

- **CaO**: 43.0%
- **Fe\textsubscript{2}O\textsubscript{3}**: 5.5%
- **Al\textsubscript{2}O\textsubscript{3}**: 4.5%
- **SiO\textsubscript{2}**: 11.4%
- **Other Oxides & Components**: 35.6%

Other Oxides and Components

- **Unidentified**: 6.3%
- **CO\textsubscript{3}\textsuperscript{2-} (as CO\textsubscript{2})**: 13.7%
- **SO\textsubscript{4}\textsuperscript{2-} or SO\textsubscript{3}\textsuperscript{2-} (as SO\textsubscript{3})**: 12.0%

Minerals in Fly Ash

- 0.2% TiO\textsubscript{2}
- 0.3% K\textsubscript{2}O
- 0.1% Na\textsubscript{2}O
- MgO
Advanced FGD Process - Spent Scrubber Waste
Chemical and Mineral Composition

- 20.3% Water of Hydration
- 22.5% Ca
- 54.1% SO₄

Bulk Chemical Composition

- 0.25% SiO₂
- 0.14% Al₂O₃
- 0.14% Fe₂O₃
- 3% Moisture

Mineral Composition

- 1.2% Calcite (CaCO₃)
- 98.4% Gypsum (CaSO₄·2H₂O)
LNB-AOFA Fly Ash
Chemical and Mineral Composition

Chemical Composition

- 11.0% Fe₂O₃
- 22.1% Al₂O₃
- 45.0% SiO₂
- 0.91% MgO
- 1.16% CaO
- 0.34% Na₂O
- 0.44% K₂O
- 0.22% P₂O₅
- 1.13% TiO₂
- 0.72% SO₄
- 11.3% Unburned Carbon
- 0.43% Moisture

Mineral Composition

- 3.6% Quartz
- 2.4% Montmorillonite
- Tr. Mullite
- Tr. Maghemite
- Tr. Ferrite Spinel
- 4.4% Iron Oxide
- 5.2% Altered Kaolinite
- 8% Kaolinite
- 23.2% Illite
- 54% Amorphous Phases
LNB-AOFA Economizer Ash
Chemical and Mineral Composition

Weight Percent

- 18.2% Fe₂O₃
- 22.6% Al₂O₃
- 47.5% SiO₂
- 0.87% MgO
- 1.34% CaO
- 0.29% Na₂O
- 2.37% K₂O
- 0.14% P₂O₅
- 1.1% TiO₂
- 0.41% SO₄
- 2.7% Unburned Carbon
- 0.19% Moisture

1.2% Iron Oxide
0.4% Ferrite Spinel
4.8% Altered Kaolinite
Tr. Mullite
Tr. Maghemite
5.2% Montmorillonite
6% Quartz
6% Kaolinite
13.6% Illite
62% Amorphous Phases
LNB-AOFA Bottom Ash
Chemical and Mineral Composition

Weight Percent

 Bulk Chemical Composition

- 13.6% Fe₂O₃
- 23.6% Al₂O₃
- 48.1% SiO₂
- 0.92% MgO
- 0.94% CaO
- 0.33% Na₂O
- 2.5% K₂O
- 0.16% P₂O₅
- 1.15% TiO₂
- 0.01% SO₄
- 4.02% Unburned Carbon
- 0.29% Moisture

Mineral Composition

- 4.4% Quartz
- 4.8% Illite
- 5.2% Kaolinite
- 0.8% Iron Oxide
- 2.4% Altered Kaolinite
- 0.4% Montmorillonite
- Tr. Mullite
- Tr. Maghemite
- Tr. Ferrite Spinel

80% Amorphous Phases
Advanced Coal Cleaning Process - Fly Ash
Chemical and Mineral Composition

1.65% Moisture
2.46% CaO
1.76% P_2O_5
1.1% K_2O
1.45% TiO_2
0.16% Na_2O
39 µg/g Cl
11.1% Unburned Carbon
7.3% Fe_2O_3
23.7% Al_2O_3
38.5% SiO_2

1.2% Montmorillonite
3.6% Hematite
1.6% Quartz
0.8% Anorthite
15.6% Illite
19.6% Mullite
40% Kaolinite
16.4% Amorphous Phases
APPENDIX C

WASTE MOISTURE–DENSITY CURVES
**GAS REBURNING SORBENT INJECTION - ESP FLY ASH**

**MOISTURE - DENSITY CURVE**

Using Standard Proctor Method

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**Maximum Dry Density = 75.0 pcf**

**Optimum Moisture Content = 31.6%**

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**COLLAR WEIGHT = 2022.7 lbs**

| SPECIMEN CONTAINER | CONTAINER WEIGHT (grams) | INITIAL NET WT. (grams) | FINAL NET WT. (grams) | MOLD & SPECIMEN WEIGHT (grams) | PERCENT MOISTURE CONTENT | DRY DENSITY |
|--------------------|--------------------------|-------------------------|-----------------------|--------------------------------|--------------------------|--------------|
| S                  | 0.45                     | 49.19                   | 37.71                 | 3496.3                         | 30.81                    | 74.4         |
| M                  | 0.45                     | 61.69                   | 46.62                 | 3509.5                         | 32.64                    | 74.1         |
| I                  | 0.44                     | 59.17                   | 44.6                  | 3503.2                         | 32.99                    | 73.6         |
| II                 | 0.44                     | 65.62                   | 49.82                 | 3511.9                         | 32                       | 74.5         |
| H                  | 0.46                     | 46.02                   | 35.21                 | 3505                           | 31.11                    | 74.7         |
| Y                  | 0.45                     | 46.02                   | 35.21                 |                                |                          |              |
| C                  |                          |                         |                       |                                |                          |              |
GAS REBURNING SORBENT INJECTION - BOTTOM ASH
MOISTURE - DENSITY CURVE

Using Standard Proctor Method

Maximum Dry Density = 79.0 pcf

Optimum Moisture Content = 25.5 %

| SPECIMEN | CONTAINED WEIGHT (grams) | INITIAL NET WT. (grams) | FINAL NET WT. (grams) | MOLD & SPECIMEN WEIGHT (grams) | PERCENT MOISTURE CONTENT | DRY DENSITY (lbs per cu. ft.) |
|----------|-------------------------|-------------------------|-----------------------|-------------------------------|--------------------------|-------------------------------|
| S        | 0.42                    | 39.4                    | 34.05                 | 3185.2                        | 15.91                    | 66.3                          |
| M        | 0.42                    | 58.2                    | 46.85                 | 3509.5                        | 24.45                    | 78.9                          |
| I        | 0.46                    | 53.5                    | 41.5                  | 3503.2                        | 29.24                    | 75.7                          |
| II       | 0.43                    | 42.3                    | 32.09                 | 3511.9                        | 32.25                    | 74.4                          |
| H        | 0.4                     | 48.4                    | 40.67                 | 3386                          | 19.2                     | 75.6                          |
| Y        |                         |                         |                       |                               |                          |                               |
| C        |                         |                         |                       |                               |                          |                               |
Using Standard Proctor Method

**Max. Dry Density**

= 96 pcf

**Moisture Content**

= 20.5%

| COLLAR | WEIGHT = 4227.9 |
|--------|----------------|
| S      | 0  | 201.8 | 168.1 | 5790.5 | 20.05 | 86 |
| N      | 0  | 200   | 171.9 | 5727.2 | 16.35 | 85.2 |
| I      | 0  | 200   | 155   | 5803.3 | 21.21 | 85.9 |
| II     | 0  | 200   | 160.2 | 5844.1 | 24.84 | 85.5 |
PRESSURIZED FLUIDIZED BED - ESP FLY ASH
MOISTURE - DENSITY CURVE

Using Standard Proctor Method

Maximum Dry Density = 104.5 pcf

Optimum Moisture Content = 19.0 %

| COLLAR | WEIGHT = 2021.7 |
|--------|-----------------|
| SPECIMEN | CONTAINWEIGHT | INITIALNET WT. | FINALNET WT. | MOLD & SPECIMENWEIGHT | PERCENTMOISTURECONTENT | (lbs percu. ft.)DRYDENSITY |
| SPECIMEN | (grams) | (grams) | (grams) | (grams) | | |
| H | 0.48 | 44.3 | 36.1 | 3965.7 | 23.02 | 104.4 |
| I | 0.5 | 48.08 | 40.9 | 3875.6 | 17.77 | 104 |
| M | 0.47 | 60.46 | 48.21 | 3927.8 | 25.66 | 100.2 |
| C | 0.47 | 34.9 | 26.54 | 3899.4 | 32.07 | 93.9 |
PRESSURIZED FLUIDIZED BED - CYCLONE ASH
MOISTURE - DENSITY CURVE

Using Standard Proctor Method

Maximum Dry Density = 105.5 pcf

Optimum Moisture Content = 18.9 %

| SPECIMEN | CONTAINED WEIGHT (grams) | INITIAL NET WT. (grams) | FINAL NET WT. (grams) | MOLD & SPECIMEN WEIGHT (grams) | PERCENT MOISTURE CONTENT | (lbs per cu. ft.) DRY DENSITY |
|----------|--------------------------|-------------------------|-----------------------|-------------------------------|--------------------------|------------------------------|
| S        | 0.46                     | 39.82                   | 35.28                 | 3628.4                        | 13.04                    | 93.9                         |
| M        | 0.47                     | 37.57                   | 32.52                 | 3820.6                        | 15.76                    | 102.7                        |
| I        | 0.47                     | 44.3                    | 37.35                 | 3909.5                        | 18.84                    | 105                          |
| II       | 0.47                     | 50.63                   | 42.15                 | 3926.3                        | 20.35                    | 104.6                        |
| H        |                          |                         |                       |                               |                          |                              |
| Y        |                          |                         |                       |                               |                          |                              |
| C        |                          |                         |                       |                               |                          |                              |

COLLAR WEIGHT = 2021.7
**COAL REBURNING – ESP FLY ASH**

**MOISTURE – DENSITY CURVE**

*Using Standard Proctor Method*

| SPECIMEN | CONTAINER WEIGHT (grams) | INITIAL NET WT. (grams) | FINAL NET WT. (grams) | MOLD & SPECIMEN WEIGHT (grams) | PERCENT MOISTURE CONTENT | DRY DENSITY (lbs per cu. ft.) |
|----------|--------------------------|-------------------------|-----------------------|-------------------------------|--------------------------|-------------------------------|
| S        | 0                        | 213.2                   | 166.4                 | 5814.7                        | 28.12                    | 81.8                          |
| M        | 0                        | 228.7                   | 185                   | 5480.8                        | 23.62                    | 67                            |
| I        | 0                        | 195.1                   | 142.49                | 5864                          | 35.32                    | 79                            |
| II       | 0                        | 200                     | 144.7                 | 5795                          | 38.22                    | 75                            |

**M.D.D. = 85.3 PCF**

**OPT. = 31.8%**
**SO\(_2\), NO\(_x\), RO\(_x\), BOX - BAGHOUSE FLY ASH**

**MOISTURE - DENSITY CURVE**

*Using Standard Proctor Method*

| Specimen | Container | Initial Net Wt. (grams) | Final Net Wt. (grams) | Specimen Weight (grams) | Percent Moisture Content | (lbs per cu. ft.) Dry Density |
|----------|-----------|-------------------------|-----------------------|-------------------------|--------------------------|-------------------------------|
| S        | 0         | 254.8                   | 172.3                 | 5426.4                  | 47.88                    | 53.6                          |
| W        | 0         | 247                     | 160                   | 5565.3                  | 54.38                    | 57.3                          |
| I        | 0         | 235.1                   | 150                   | 5604.9                  | 56.73                    | 58.1                          |
| II       | 0         | 230.6                   | 143.3                 | 5638.7                  | 60.92                    | 57.9                          |
| H        | 0         | 200                     | 120.7                 | 5634.4                  | 65.7                     | 56.1                          |
COAL REBURNING - BOTTOM ASH (SLAG)  
MOISTURE - DENSITY CURVE  

Using Standard Proctor Method

| SPECIMEN | CONTAINER WEIGHT (grams) | CONTAINER INITIAL NET WT. (grams) | CONTAINER FINAL NET WT. (grams) | MOLD & SPECIMEN WEIGHT (grams) | PERCENT MOISTURE CONTENT | DENSITY (lbs per cu. ft.) |
|----------|--------------------------|---------------------------------|--------------------------------|-------------------------------|--------------------------|--------------------------|
| S        | 0                        | 224.2                           | 215                             | 5849.6                        | 4.28                     | 102.8                   |
| M        | 0                        | 214.5                           | 198.6                           | 5968.5                        | 8.01                     | 106.5                   |
| I        | 0                        | 235.4                           | 210.2                           | 6183.5                        | 11.99                    | 115.4                   |
| II       | 0                        | 244.3                           | 203.6                           | 6332.5                        | 19.99                    | 115.9                   |
| H        | 0                        | 232.6                           | 200.5                           | 6315                          | 16.01                    | 118.9                   |
| Y        |                          |                                 |                                 |                               |                          |                         |
| C        |                          |                                 |                                 |                               |                          |                         |
LNB/AOFA - ESP FLY ASH
MOISTURE - DENSITY CURVE

Maximum Dry Density = 78.8 pcf

Optimum Moisture Content = 26.7%

Harvard Compaction
SAMPLE # 94-18

| SPECIMEN CONTAIN | CONTAIN重量 (grams) | INITIAL NET WT. (grams) | FINAL NET WT. (grams) | MOLD & SPECIMEN WEIGHT (grams) | PERCENT MOISTURE CONTENT | (lbs per cu. ft.) DRY DENSITY |
|------------------|--------------------|-------------------------|-----------------------|-------------------------------|--------------------------|----------------------------|
| A1               | 0.45               | 44.3                    | 37.2                  | 229.7                         | 19.32                    | 76.2                       |
| A2               | 0.45               | 44.5                    | 35.9                  | 237.3                         | 24.26                    | 79.3                       |
| A3               | 0.45               | 76.1                    | 58                    | 239.5                         | 31.45                    | 76.6                       |
| A4               | 0.45               | 58.1                    | 45.6                  | 238.7                         | 27.69                    | 78.2                       |
LNB/AOFA - ECONOMIZER ASH
MOISTURE - DENSITY CURVE

Maximum Dry
Density = 70.5 pcf

Optimum Moisture
Content = 36.0 %

Harvard Compaction
SAMPLE # 94-20

| SPECIMEN | WEIGHT (grams) | INITIAL NET WT. (grams) | FINAL NET WT. (grams) | MOLD & SPECIMEN WEIGHT (grams) | PERCENT MOISTURE CONTENT | DRY DENSITY |
|----------|----------------|-------------------------|-----------------------|--------------------------------|---------------------------|-------------|
| A1       | 0.45           | 40.5                    | 32.4                  | 223.8                          | 25.35                     | 67.8        |
| A2       | 0.45           | 52.5                    | 39.3                  | 234                            | 33.98                     | 71.1        |
| A3       | 0.45           | 59.4                    | 43.6                  | 234.4                          | 36.62                     | 70          |
| A4       | 0.45           | 41.9                    | 35.1                  | 216.6                          | 19.62                     | 65          |
LNB/AOFA - BOTTOM ASH
MOISTURE - DENSITY CURVE

Maximum Dry Density = 59 pcf

Optimum Moisture Content = 46.6%

Harvard Compaction
SAMPLE # 94-19

| SPECIMENT | CONTAIN CONTENT | INITIAL NET WT. | FINAL NET WT. | MOLD & SPECIMEN WEIGHT | PERCENT MOISTURE CONTENT | (lbs per cu. ft.) DRY DENSITY |
|-----------|-----------------|-----------------|---------------|-------------------------|--------------------------|-------------------------------|
| A1        | 0.45            | 28.6            | 24            | 201.3                   | 19.53                    | 52.3                          |
| A2        | 0.45            | 31.8            | 26.6          | 206.8                   | 19.89                    | 56.7                          |
| A3        | 0.45            | 27.1            | 22            | 205.7                   | 23.67                    | 54.1                          |
| A4        | 0.45            | 29.9            | 23.3          | 212.6                   | 28.88                    | 57.3                          |
| A5        | 0.45            | 46.7            | 33.1          | 222.6                   | 41.65                    | 59.2                          |
| A6        | 0.45            | 42.4            | 28.1          | 228                     | 51.72                    | 58.8                          |
Advanced FGD Process - Spent Scrubber Waste
Moisture - Density Curve

Maximum Compacted Density = 72.8 lb/ft³
Optimum Moisture Content = 48.4%
Advanced Coal Cleaning Process - Combustion Fly Ash
Moisture - Density Curve

![Graph showing the relationship between moisture content and dry density.](image)

- **Maximum Dry Density**: 72.5 pcf
- **Optimum Moisture Content**: 30.5 %
APPENDIX D

WASTE PARTICLE-SIZE DISTRIBUTION CURVES
GAS REBURNING SORBENT INJECTION - ESP FLY ASH
PARTICLE SIZE DISTRIBUTION

D_{10} = 0.00174 mm
D_{50} = 0.00244 mm
D_{60} = 0.00269 mm
C_U = D_{60}/D_{10} = 1.55

PARTICLE SIZE (mm)

PERCENT FINER %
Particle Size Distribution
Gas Reburning Sorbent Injection - Bottom Ash

\[ C_n = \frac{D_{50}}{D_{10}} = 22.4 \]

- \( D_{50} = 1.7 \text{ mm} \)
- \( D_{50} = 1.86 \text{ mm} \)
- \( D_{10} = 8.76 \text{ mm} \)
PRESSURIZED FLUIDIZED BED - ESP FLY ASH
PARTICLE SIZE DISTRIBUTION

D_{10} = 0.005 mm
D_{50} = 0.0144 mm
D_{60} = 0.0158 mm
Cu = D_{60}/D_{10} = 3.16
\[ C_u = \frac{D_{60}}{D_{10}} = 3.34 \]
\[ D_{60} = 0.117 \text{ mm} \]
\[ D_{50} = 0.107 \text{ mm} \]
\[ D_{10} = 0.835 \text{ mm} \]
PRESSURIZED FLUIDIZED BED - BOTTOM ASH
PARTICLE SIZE DISTRIBUTION

D_{10} = 0.375 mm
D_{50} = 0.9 mm
D_{60} = 1.127 mm
C_{u} = D_{60}/D_{10} = 3.0
COAL REBURNING - ESP FLY ASH
PARTICLE SIZE DISTRIBUTION

D_{10} = 0.0013 mm
D_{50} = 0.008 mm
D_{60} = 0.013 mm
C_u = D_{60}/D_{10} = 10.0
COAL REBURNING - BOTTOM ASH (SLAG)
PARTICLE SIZE DISTRIBUTION

\[ \begin{align*}
D_{10} &= 1.13 \text{ mm} \\
D_{50} &= 2.073 \text{ mm} \\
D_{60} &= 2.42 \text{ mm} \\
C_u &= \frac{D_{60}}{D_{10}} = 2.14
\end{align*} \]
SOX, NOX, ROX, BOX - BAGHOUSE FLY ASH
PARTICLE SIZE DISTRIBUTION

\[ D_{10} = 0.00162 \text{ mm} \]
\[ D_{50} = 0.0057 \text{ mm} \]
\[ D_{60} = 0.00915 \text{ mm} \]
\[ C_u = D_{60}/D_{10} = 5.6 \]
SO$_x$, NO$_x$, RO$_x$, BO$_x$ - SORBENT
PARTICLE SIZE DISTRIBUTION

$D_{10} = 0.00162$ mm
$D_{50} = 0.00515$ mm
$D_{60} = 0.00588$ mm
$C_U = D_{60}/D_{10} = 3.36$
LNB/AOFA - ESP FLY ASH
PARTICLE SIZE DISTRIBUTION

\[ D_{10} = 0.008 \text{ mm} \]
\[ D_{50} = 0.03 \text{ mm} \]
\[ D_{80} = 0.035 \text{ mm} \]

\[ C_u = \frac{D_{80}}{D_{10}} \cdot 4.38 \]
LNB/AOFA - ECONOMIZER ASH
PARTICLE SIZE DISTRIBUTION

Percent Finer, %

Particle Size, mm

$D_{10} = 0.018 \, \text{mm}$

$D_{50} = 0.26 \, \text{mm}$

$D_{68} = 0.43 \, \text{mm}$

$C_u = 23.9$
LNB/AOFA - BOTTOM ASH
PARTICLE SIZE DISTRIBUTION

\[ D_{10} = 0.12 \text{ mm} \]
\[ D_{50} = 7.2 \text{ mm} \]
\[ D_{90} = 11.0 \text{ mm} \]

\[ C_u = \frac{D_{80}}{D_{10}} = 91.7 \]
Advanced FGD Process - Spent Scrubber Waste

Particle Size Distribution

- $D_{10} = 0.0071$ mm
- $D_{50} = 0.056$ mm
- $D_{90} = 0.063$ mm
- $C_v = \frac{D_{90}}{D_{10}} = \frac{0.063}{0.0071} = 8.9$
APPENDIX E

WASTE COMPRESSIBILITY/CONSOLIDATION ANALYSIS
CV for 2000 psf load = 4.83 sq. in./min

2000 psf Consolidation Curve

Gas Refurning - Bottom Ash
Gas Reburning - Bottom Ash

4000 psf Consolidation Curve

Cv for 4000 psf load = 3.32 sq.in/min
Gas Reburning - Bottom Ash

8000 psf Consolidation Curve

Dial Reading (0.0001 In.)

Time (Sq. Root Min.)

Cv for 8000 psf load = 3.26 sq.in/min
Gas Reburning - Bottom Ash

16000 psf Consolidation Curve

Cv for 16000 psf load = 3.2 sq.in/min
**Gas Reburning - Bottom Ash**

32000 psf Consolidation Curve

![Graph showing consolidation curve for 32000 psf load]

\[ Cv \text{ for } 32000 \text{ psf load} = 3.85 \text{ sq.in/min} \]
PFBC - Bottom Ash

2000 psf Consolidation Curve

Cv for 2000 psf load = 5.8 sq.in/min
PFBC - Bottom Ash
4000 psf Consolidation Curve

Cv for 4000 psf load = 4.17 sq.in/min
PFBC - Bottom Ash

8000 psf Consolidation Curve

Dial Reading (0.00001 In.)

Time (Sq. Root Min.)

Cv for 8000 psf load = 7.61 sq.in/min
PFBC - Bottom Ash
16000 psf Consolidation Curve

Cv for 16000 psf load = 7.64 sq.in/min
PFBC - Bottom Ash

32000 psf Consolidation Curve

Dial Reading (0.0001 In.)

Time (Sq. Root Min.)

Cv for 32000 psf load = 7.39 sq.in/min
Coal Reburning - Bottom Ash

2000 psf Consolidation Curve

Dial Reading (0.0001 in.)

Time (Sq. Root Min.)

Cv for 2000 psf load = 3.06 sq.in/min
Coal Reburning - Bottom Ash

4000 psf Consolidation Curve

\[ Cv \text{ for 4000 psf load} = 3.34 \text{ sq.in/min} \]
Coal Reburning - Bottom Ash

8000 psf Consolidation Curve

Cv for 8000 psf load = 3.31 sq.in/min
Coal Reburning - Bottom Ash
16000 psf Consolidation Curve

Cv for 16000 psf load = 4.01 sq.in/min
Coal Reburning - Bottom Ash
32000 psf Consolidation Curve

Cv for 32000 psf load = 5.49 sq.in/min
APPENDIX F

WASTE SCANNING ELECTRON MICROSCOPE PHOTOGRAPHS
SCANNING ELECTRON MICROGRAPHY
GAS REBURNING SORBENT INJECTION - BOTTOM ASH
PRESSURIZED FLUIDIZED BED - ESP FLY ASH
SCANNING ELECTRON MICROGRAPH

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[Image of microscopic details with labels 10 and 100 microns]
PRESSURIZED FLUIDIZED BED - BOTTOM ASH
SCANNING ELECTRON MICROGRAPH

1 MILLIMETER

200 MICRONS
COAL REBURNING - BOTTOM ASH (SLAG)
SCANNING ELECTRON MICROGRAPH
Advanced FGD Process - Spent Scrubber Waste
Scanning Electron Micrograph

Scale: 1 cm = 50 microns

Scale: 1 cm = 200 microns
Scanning Electron Micrograph
Advanced Coal Cleaning Process - Combustion Fly Ash
APPENDIX G

WASTE BULK CHEMICAL COMPOSITION DATA
| Parameter | Lab # | Sample ID | Date Submitted | UEDA | Sample Info | Proj. # | Requestor | Analysis Report Form |
|-----------|-------|-----------|----------------|------|-------------|--------|-----------|---------------------|
| 92-072    |       | 5-21-92   |                |      |             |        |           |                     |
| 92-071    |       |           |                |      |             |        |           |                     |
| 92-072    |       | 5-22-92   |                |      |             |        |           |                     |
| 92-071    |       |           |                |      |             |        |           |                     |
| 92-072    |       |           |                |      |             |        |           |                     |
| 92-071    |       |           |                |      |             |        |           |                     |
| 92-072    |       |           |                |      |             |        |           |                     |
| 92-071    |       |           |                |      |             |        |           |                     |

The table contains data for various parameters, but the specific details are not legible. The data includes percentages and other values, and there are notes and logos visible on the page.
# ANALYSIS REPORT FORM

**REQUESTOR**: Ed Olson  
**PROJ. #**: 5420  
**SAMPLE INFO**: UFDA  
**DATE SUBMITTED**: 6-23-92

| SAMPLE ID. | ESP Fly Ash | Cyclone Ash | Bottom Ash |
|------------|-------------|-------------|------------|
| 92-076     | 42265       | 42266       | 42267      |
| 92-075     |             |             |            |
| 92-074     |             |             |            |

**PARAMETER**

| PARAMETER | ESP Fly Ash | Cyclone Ash | Bottom Ash |
|-----------|-------------|-------------|------------|
| SiO2 (%)  | 26.5        | 20.4        | 5.90       |
| Al2O3 (%) | 13.8        | 7.47        | 2.11       |
| Fe2O3 (%) | 8.02        | 8.50        | 3.18       |
| CaO (%)   | 16.7        | 21.5        | 31.0       |
| MgO (%)   | 9.31        | 15.1        | 23.5       |
| Na2O (%)  | 0.43        | 0.18        | <.20       |
| K2O (%)   | 2.21        | 1.03        | <.20       |
| P2O5 (%)  | 0.09        | <.09        | <.09       |
| TiO2 (%)  | 0.76        | 0.36        | 0.07       |
| SO4 (%)   | 28.4        | 12.4        | 10.4       |
| CO2 (%)   | *           | 14.0        | 9.15       |
| Sulfide ug/g | <5.0 | 104 | 343 |
| Chloride ug/g | 43 | 110 | 87 |

* Not Determined

**DATE REPORTED**: 9-9-92

**REPORTED BY**: [Signature]

**DISTRIBUTION**: 9/19/92 [Signature]
ANALYSIS REPORT FORM

REQUESTOR: Ed Olson
PROJ. #: 5420
SAMPLE INFO: UFDA DOE Site "E"
DATE SUBMITTED: 1-14-93

SAMPLE ID.

|          | BULK | BAGHOUSE |
|----------|------|----------|
| SORBANT  |      |          |
| ASH      |      |          |
| 1        |      |          |
| 2        |      |          |
| 3        |      |          |
| 4        |      |          |
| 5        |      |          |
| 6        |      |          |
| 7        |      |          |

LAB #

|     | 43621 | 43622 |

PARAMETER

| Parameter | BULK | BAGHOUSE |
|-----------|------|----------|
| SiO2 %    | 1.89 | 11.39    |
| Al2O3 %   | 0.52 | 4.47     |
| Fe2O3 %   | 0.22 | 5.51     |
| CaO %     | 71.20| 43.09    |
| MgO %     | 2.78 | 1.80     |
| Na2O %    | 0.00 | 0.10     |
| K2O %     | 0.09 | 0.33     |
| P2O5 %    | 0.01 | 0.04     |
| TiO2 %    | 0.02 | 0.21     |
| SO4 %     | 0.10 | 12.00    |
| Sulfide ug/g | <0.5 | <0.5    |
| Chloride ug/g | 310 | 1200    |
| LOI %     | 23.47| 13.30    |
| MOISTURE %| 0.54 | 0.24     |

ANALYSIS AS RECEIVED

DATE REPORTED: 5-13-93

REPORTED BY: [Signature]
DISTRIBUTION: 5-13-93
**REQUESTOR**
**PROJ. #**
**SAMPLE INFO**
Advanced FGD Process Spent Scrubber Waste - Bulk Chemical Analysis
**DATE SUBMITTED**
10/23/95

| PARAMETER | units | value |
|-----------|-------|-------|
| SiO2      | %     | 0.25  |
| Al2O3     | %     | 0.14  |
| Fe2O3     | %     | 0.14  |
| CaO       | %     | 38.1  |
| Na2O      | %     | < 0.2 |
| K2O       | %     | < 0.2 |
| P2O5      | %     | < 0.1 |
| TiO2      | %     | < 0.1 |
| SO4       | %     | 43.3  |
| LOI       | %     | 7.60  |
| Moisture  | %     | 22.36 |
| Sulfide   | ug/g  | < 0.5 |
| Chloride  | ug/g  | < 200 |

Analysis based on dry basis.

**DATE REPORTED**
11/16/95

**REPORTED BY**

**DISTRIBUTION**

UFDA8967.XLS
**Advanced Coal Cleaning Process - Combustion Fly Ash**  
**Bulk Chemical Analysis**

### Final Results

**Set Number:** 49309  
**Fund#:** 5420  
**PI:** Chuck Moretti  
**Request Date:** Wednesday, November 27, 1996  
**Due Date:** Wednesday, December 18, 1996  
**Set Description:** Geochemical/Geotechnical Characterization of Advanced Coal Utilization Wastes

**Contact Person:** Chuck Moretti

| Sample     | 49309-01   | clean coal ash |
|------------|------------|----------------|
| Aluminum   | 29.7 % Al2O3 |
| Calcium    | 2.46 % CaO  |
| Chloride   | 39 µg/g     |
| Iron       | 7.30 % Fe2O3 |
| Phosphorus | 1.76 % P2O5 |
| Potassium  | 1.1 % K2O   |
| Silicon    | 38.5 % SiO2 |
| Sodium     | 0.18 % Na2O |
| Sulfide    | <1 µg/g     |
| Titanium   | 1.45 % TiO2 |

---

1  
**Distribution:** 3  
**Date:** 12-16-96
APPENDIX H

WASTE SCANNING ELECTRON MICROSCOPE POINT COUNTS
| Mineral Name          | Frequency | Percent |
|-----------------------|-----------|---------|
| Silicon Rich          |           |         |
| Quartz                | 2.4       |         |
| Albite                | 0.0       |         |
| Anorthite             | 0.0       |         |
| Potassium Feldspar    | 0.0       |         |
| Nepheline             | 0.0       |         |
| Hauyne                | 0.0       |         |
| Leucite               | 0.0       |         |
| Kaolinite             | 0.0       |         |
| Altered Kaolinite     | 0.8       |         |
| Illite                | 0.4       |         |
| Montmorillonite       | 67.6      |         |
| Pyroxene              | 0.0       |         |
| Wollastonite          | 0.0       |         |
| CaSilicate            | 0.0       |         |
| DiCalcium Silicate    | 0.0       |         |
| NaCaSiO3              | 0.0       |         |
| Gehlenite             | 0.0       |         |
| Akermanite            | 0.0       |         |
| Merwinite             | 0.0       |         |
| Spurrite              | 0.0       |         |
| Mullite               | 0.0       |         |
| Mixed Silicon Rich    | 24.8      |         |
| Total for group       | 96.0      |         |
| Mixed Phosphorous Rich| 0.0       |         |
| User defined list     | 0.0       |         |
| Ettringite            | 0.0       |         |
| Calcium Aluminate     | 0.0       |         |
| Total for group       | 0.0       |         |
| Carbon Rich           | 0.4       |         |
| Calcite               | 0.0       |         |
| Altered Calcite       | 0.0       |         |
| Dolomite              | 0.0       |         |
| Sulfated Dolomite     | 0.0       |         |
| Ankerite              | 0.0       |         |
| Sulphated Ankerite    | 0.0       |         |
| Mixed Carbon Rich     | 1.2       |         |
| Total for group       | 1.6       |         |
| Metal Rich            | 0.0       |         |
| Aluminum              | 0.0       |         |
| Titanium              | 0.0       |         |
| Iron                  | 0.0       |         |
| Nickel                | 0.0       |         |
| Copper                | 0.0       |         |
| Chromium              | 0.0       |         |
| Mixed Metal Rich      | 0.4       |         |
| Total for group       | 0.4       |         |

Total number of points analysed = 250
Carbon threshold for analysis = 250
Oxygen threshold for analysis = 100
### BULK CHEMICAL COMPOSITION

|     | A   | B   | C    | D    | E   | F   | G   |
|-----|-----|-----|------|------|-----|-----|-----|
| SiO2| 4.8 | 6.7 | 69.9 | 93.0 | 49.8| 55.2| 55.4|
| Al2O3| 36.6| 6.7 | 17.2 | 1.2  | 16.0| 17.8| 17.8|
| Fe2O3| 38.9| 29.4| 3.9  | 2.9  | 20.7| 13.6| 13.7|
| TiO2| 1.1 | 0.0 | 0.8  | 0.0  | 1.0 | 0.8 | 0.8 |
| P2O5| 0.0 | 0.0 | 0.0  | 0.0  | 0.1 | 0.1 | 0.1 |
| CaO | 9.7 | 38.3| 4.9  | 0.6  | 7.8 | 7.8 | 8.0 |
| MgO | 2.6 | 0.9 | 0.8  | 0.0  | 1.1 | 1.0 | 1.0 |
| Na2O| 1.9 | 0.0 | 1.5  | 0.1  | 1.0 | 1.1 | 1.1 |
| K2O | 3.6 | 0.3 | 0.6  | 0.0  | 1.9 | 2.1 | 2.1 |
| Cl2O7| 0.0 | 16.8| 0.1  | 0.8  | 0.1 | 0.3 | 0.1 |
| Cr2O3| 0.6 | 0.0 | 0.0  | 0.5  | 0.2 | 0.1 | 0.0 |
| BaO | 0.0 | 0.4 | 0.0  | 0.0  | 0.1 | 0.1 | 0.0 |

A). Cumulative bulk composition of OTHER

B). Cumulative bulk composition of Mixed_Sulfur_Rich

C). Cumulative bulk composition of Mixed_Carbon_Rich

D). Cumulative bulk composition of Mixed_Metal_Rich

E). Cumulative bulk composition of Mixed_Silicon_Rich

F). Cumulative bulk composition of the entire sample

G). SO3, Cl2O7, Cr2O3, BaO Free composition of the entire sample
## GAS REBURNING SORBENT INJECTION - ESP FLY ASH
## SEM POINT COUNTS

**54205241 Fly ash 92-71  25JAN93**

| MINERAL NAME                  | FREQUENCY PERCENT |
|-------------------------------|-------------------|
| Oxide_Rich                    | Silicon_Rich      |
| MagnesiumOxide                | 3.2               |
| AluminumOxide                 | 0.0               |
| CalciumOxide                  | 0.0               |
| TitaniumOxide                 | 0.0               |
| ChromiumOxide                 | 0.0               |
| IronOxide                     | 0.0               |
| Spinel                        | 0.0               |
| CaTiOxide                     | 0.0               |
| CaAlOxide                     | 2.8               |
| Mixed_Oxide_Rich              | 1.6               |
| Total for group               | 18.8              |
| Sulfur_Rich                   | Mixed_Sulfur_Rich |
| Pyrite                        | 1.2               |
| Pyrrhotite                    | 0.0               |
| IronSulfate                   | 0.0               |
| SodiumSulfate                 | 0.0               |
| CalciumSulfate                | 0.0               |
| NaCaSulfate                   | 0.0               |
| Barite                        | 0.0               |
| Mixed_Sulfur_Rich             | 22.4              |
| Total for group               | 38.0              |
| Phosphorous_Rich              | User_defined_list|
| Apatite                       | 0.0               |
| Mixed_Phosphorous_Rich        | 0.0               |
| Total for group               | 0.0               |
| Carbon_Rich                   | Other             |
| Calcite                       | 4.4               |
| AlteredCalcite                | 10.4              |
| Dolomite                      | 0.0               |
| SulfatedDolomite              | 0.0               |
| Ankerite                      | 0.4               |
| SulphatedAnkerite             | 0.0               |
| Mixed_Carbon_Rich             | 20.0              |
| Total for group               | 35.2              |
| Metal_Rich                    |                   |
| Aluminum                      | 0.0               |
| Titanium                      | 0.0               |
| Iron                           | 0.0               |
| Nickel                        | 0.0               |
| Copper                         | 0.0               |
| Chromium                      | 0.0               |
| Mixed_Metal_Rich              | 0.8               |
| Total for group               | 0.8               |

**TOTAL NUMBER OF POINTS ANALYSED = 250**
**Carbon threshold for analysis = 250**
**Oxygen threshold for analysis = 100**
### GAS REBURNING SORBENT INJECTION - ESP FLY ASH
### SEM POINT COUNTS

#### BULK CHEMICAL COMPOSITION

|       | A   | B   | C   | D   | E   | F   | G   | H   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| SiO₂  | 1.4 | 5.5 | 3.2 | 54.9| 99.4| 58.4| 36.6| 37.7|
| Al₂O₃ | 32.1| 4.1 | 1.2 | 21.7| 0.0 | 24.9| 13.5| 14.0|
| Fe₂O₃ | 24.4| 2.4 | 1.0 | 5.4 | 0.0 | 6.7 | 5.4 | 5.8 |
| TiO₂  | 1.5 | 0.0 | 0.1 | 2.2 | 0.2 | 1.4 | 0.9 | 1.1 |
| P₂O₅  | 0.0 | 0.7 | 0.2 | 0.3 | 0.0 | 0.0 | 0.1 | 0.2 |
| CaO   | 27.2| 71.9| 63.3| 4.9 | 0.0 | 1.3 | 30.3| 36.8|
| MgO   | 3.7 | 0.7 | 1.3 | 1.4 | 0.0 | 1.7 | 1.5 | 1.7 |
| Na₂O  | 2.1 | 0.3 | 0.3 | 1.6 | 0.0 | 1.7 | 1.0 | 1.1 |
| K₂O   | 4.8 | 0.1 | 0.2 | 2.2 | 0.0 | 3.1 | 1.6 | 1.6 |
| S₀₃   | 2.4 | 12.6| 25.7| 2.0 | 0.2 | 0.2 | 7.1 | 0.0 |
| Cl₂O₇ | 0.0 | 1.0 | 3.1 | 3.0 | 0.3 | 0.2 | 1.7 | 0.0 |
| Cr₂O₃ | 0.5 | 0.0 | 0.1 | 0.2 | 0.0 | 0.1 | 0.2 | 0.0 |
| BaO   | 0.0 | 0.8 | 0.1 | 0.2 | 0.0 | 0.1 | 0.1 | 0.0 |

A). Cumulative bulk composition of OTHER
B). Cumulative bulk composition of Mixed_Oxide_Rich
C). Cumulative bulk composition of Mixed_Sulfur_Rich
D). Cumulative bulk composition of Mixed_Carbon_Rich
E). Cumulative bulk composition of Mixed_Metal_Rich
F). Cumulative bulk composition of Mixed_Silicon_Rich
G). Cumulative bulk composition of the entire sample
H). S₀₃, Cl₂O₇, Cr₂O₃, BaO Free composition of the entire sample
### Pressurized Fluidized Bed - Bottom Ash

#### SEM Point Counts

| Mineral Name       | Frequency Percent | Silicon Rich          | User Defined List   |
|--------------------|-------------------|-----------------------|--------------------|
| Oxide Rich         |                   |                       |                    |
| MagnesiumOxide     | 0.4               | Quartz                |                    |
| AluminumOxide      | 0.0               | Albite                |                    |
| CalciumOxide       | 0.0               | Anorthite             |                    |
| TitaniumOxide      | 0.0               | PotassiumFeldspar     |                    |
| ChromiumOxide      | 0.0               | Nepheline             |                    |
| IronOxide          | 0.0               | Haayne                |                    |
| Spinel             | 0.0               | Leucite               |                    |
| CaTiOxide          | 0.0               | Kaolinite             |                    |
| CaAlOxide          | 0.0               | AlteredKaolinite      |                    |
| Mixed_Oxide_Rich   | 8.0               | Illite                |                    |
| Total for group    | 8.4               | Montmorillonite       |                    |
| Sulfur Rich        |                   | Pyroxene              |                    |
| Pyrite             | 0.0               | Wollastonite          |                    |
| Pyrrhotite         | 0.0               | CaSilicate            |                    |
| IronSulfate        | 0.0               | DiCalciumSilicate     |                    |
| SodiumSulfate      | 0.0               | NaCaSiO3              |                    |
| CalciumSulfate     | 2.8               | Gehlenite             |                    |
| NaCaSulfate        | 0.0               | Akermanite            |                    |
| Barite             | 0.0               | Merwinte              |                    |
| Mixed_Sulfur_Rich  | 58.4              | Spurrite              |                    |
| Total for group    | 61.2              | Mullite               |                    |
| Phosphorous Rich   |                   | Mixed_Silicon_Rich    |                    |
| Apatite            | 0.0               | Ettringite            |                    |
| Mixed_Phosporous_Rich | 0.0            | CalciumAluminate      |                    |
| Total for group    | 0.0               | Total for group       |                    |
| Carbon Rich        |                   | OTHER = 7.2           |                    |
| Calcite            | 3.2               |                       |                    |
| AlteredCalcite     | 0.0               |                       |                    |
| Dolomite           | 0.8               |                       |                    |
| SulfatedDolomite   | 0.0               |                       |                    |
| Ankerite           | 0.0               |                       |                    |
| SulphatedAnkerite  | 0.0               |                       |                    |
| Mixed_Carbon_Rich  | 1.6               |                       |                    |
| Total for group    | 5.6               |                       |                    |
| Metal Rich         |                   |                       |                    |
| Aluminum           | 0.0               |                       |                    |
| Titanium           | 0.0               |                       |                    |
| Iron               | 0.0               |                       |                    |
| Nickel             | 0.0               |                       |                    |
| Copper             | 0.0               |                       |                    |
| Chromium           | 0.0               |                       |                    |
| Mixed_Metal_Rich   | 0.0               |                       |                    |
| Total for group    | 0.0               |                       |                    |

TOTAL NUMBER OF POINTS ANALYSED = 250
Carbon threshold for analysis = 250
Oxygen threshold for analysis = 100
### Pressurized Fluidized Bed - Bottom Ash SEM Point Counts

#### Bulk Chemical Composition

|     | A  | B  | C  | D  | E  | F  | G  |
|-----|----|----|----|----|----|----|----|
| $\text{SiO}_2$ | 2.8 | 1.2 | 3.1 | 35.3 | 28.9 | 9.0 | 10.2 |
| $\text{Al}_2\text{O}_3$ | 0.4 | 0.0 | 0.5 | 10.5 | 9.5 | 2.4 | 2.7 |
| $\text{Fe}_2\text{O}_3$ | 6.4 | 0.9 | 1.6 | 12.0 | 15.9 | 4.2 | 4.8 |
| $\text{TiO}_2$ | 0.2 | 0.1 | 0.1 | 0.5 | 0.5 | 0.2 | 0.2 |
| $\text{P}_2\text{O}_5$ | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 |
| $\text{CaO}$ | 50.0 | 56.5 | 33.7 | 20.3 | 26.4 | 35.5 | 47.6 |
| $\text{MgO}$ | 32.1 | 38.6 | 26.7 | 12.6 | 14.9 | 25.3 | 33.7 |
| $\text{Na}_2\text{O}$ | 0.0 | 0.0 | 0.1 | 0.4 | 0.3 | 0.1 | 0.1 |
| $\text{K}_2\text{O}$ | 0.1 | 0.2 | 0.1 | 1.0 | 0.5 | 0.3 | 0.3 |
| $\text{SO}_3$ | 7.5 | 1.9 | 32.9 | 5.4 | 2.6 | 22.0 | 0.3 |
| $\text{Cl}_2\text{O}_7$ | 0.2 | 0.3 | 0.9 | 1.9 | 0.3 | 0.7 | 0.0 |
| $\text{Cr}_2\text{O}_3$ | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 0.0 |
| $\text{BaO}$ | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 | 0.0 |

- **A)** Cumulative bulk composition of Other
- **B)** Cumulative bulk composition of Mixed_Oxide_Rich
- **C)** Cumulative bulk composition of Mixed_Sulfur_Rich
- **D)** Cumulative bulk composition of Mixed_Carbon_Rich
- **E)** Cumulative bulk composition of Mixed_Silicon_Rich
- **F)** Cumulative bulk composition of the entire sample
- **G)** $\text{SO}_3$, $\text{Cl}_2\text{O}_7$, $\text{Cr}_2\text{O}_3$, $\text{BaO}$ Free composition of the entire sample
### SEM Point Counts

| Mineral Name                  | Frequency | Percent |
|-------------------------------|-----------|---------|
| Oxide Rich                    |           |         |
| Magnesium Oxide               | 0.0       |         |
| Aluminum Oxide                | 0.0       |         |
| Calcium Oxide                 | 0.0       |         |
| Titanium Oxide                | 0.0       |         |
| Chromium Oxide                | 0.0       |         |
| Iron Oxide                    | 0.0       |         |
| Spinel                        | 0.0       |         |
| CaTiOxide                     | 0.0       |         |
| CaAlOxide                     | 0.0       |         |
| Mixed Oxide Rich              | 0.0       |         |
| Total for group =             | 0.0       |         |
| Sulfur Rich                   |           |         |
| Pyrite                        | 0.0       |         |
| Pyrrhotite                    | 0.0       |         |
| Iron Sulfate                  | 0.0       |         |
| Sodium Sulfate                | 0.0       |         |
| Calcium Sulfate               | 0.8       | 65.6    |
| NaCa Sulfate                  | 0.0       |         |
| Barite                        | 0.0       |         |
| Mixed Sulfur Rich             | 65.6      | 66.4    |
| Total for group =             | 66.4      |         |
| Phosphorous Rich              |           |         |
| Apatite                       | 0.0       |         |
| Mixed Phosphorous Rich        | 0.0       |         |
| Total for group =             | 0.0       |         |
| Carbon Rich                   |           |         |
| Calcite                       | 0.0       |         |
| Altered Calcite               | 0.0       |         |
| Dolomite                      | 0.0       |         |
| Sulfated Dolomite             | 0.0       |         |
| Ankerite                      | 0.0       |         |
| Sulphated Ankerite            | 0.0       |         |
| Mixed Carbon Rich             | 32.0      | 32.0    |
| Total for group =             | 32.0      |         |
| Metal Rich                    |           |         |
| Aluminum                      | 0.0       |         |
| Titanium                      | 0.0       |         |
| Iron                          | 0.0       |         |
| Nickel                        | 0.0       |         |
| Copper                        | 0.0       |         |
| Chromium                      | 0.0       |         |
| Mixed Metal Rich              | 0.0       |         |
| Total for group =             | 0.0       |         |

**TOTAL NUMBER OF POINTS ANALYSED = 250**

Carbon threshold for analysis = 250

Oxygen threshold for analysis = 100
PRESSURIZED FLUIDIZED BED - ESP FLY ASH  
SEM POINT COUNTS  

BULK CHEMICAL COMPOSITION

|       | A    | B    | C    | D    | E    |
|-------|------|------|------|------|------|
| SiO2  | 18.3 | 39.1 | 41.4 | 25.4 | 35.1 |
| Al2O3 | 9.6  | 20.7 | 30.2 | 13.4 | 18.5 |
| Fe2O3 | 4.0  | 7.2  | 2.8  | 5.0  | 7.0  |
| TiO2  | 0.3  | 0.7  | 1.4  | 0.5  | 0.6  |
| P2O5  | 0.1  | 0.1  | 0.2  | 0.1  | 0.2  |
| CaO   | 15.5 | 4.8  | 6.2  | 12.1 | 20.5 |
| MgO   | 9.9  | 4.8  | 2.3  | 8.1  | 13.3 |
| Na2O  | 0.9  | 1.1  | 0.7  | 1.0  | 1.5  |
| K2O   | 1.7  | 2.9  | 3.8  | 2.1  | 3.0  |
| SO3   | 30.8 | 8.2  | 8.9  | 23.3 | 0.3  |
| Cl2O7 | 8.6  | 9.9  | 2.5  | 8.9  | 0.0  |
| Cr2O3 | 0.1  | 0.2  | 0.2  | 0.1  | 0.0  |
| BaO   | 0.2  | 0.1  | 0.0  | 0.2  | 0.0  |

A). Cumulative bulk composition of Mixed_Sulfur_Rich  
B). Cumulative bulk composition of Mixed_Carbon_Rich  
C). Cumulative bulk composition of Mixed_Silicon_Rich  
D). Cumulative bulk composition of the entire sample  
E). SO3, Cl2O7, Cr2O3, BaO Free composition of the entire samp
### PRESSURIZED FLUIDIZED BED - CYCLONE ASH
### SEM POINT COUNTS

| MINERAL NAME | FREQUENCY PERCENT |
|--------------|-------------------|
| Oxide_Rich   | Silicon_Rich      |
| MagnesiumOxide | 0.4          | Quartz                 | 7.2 |
| AluminumOxide | 0.0          | Albite                  | 0.0 |
| CalciumOxide  | 0.4          | Anorthite               | 0.0 |
| TitaniumOxide | 0.0          | PotassiumFeldspar       | 0.0 |
| ChromiumOxide | 0.0          | Nepehline               | 0.0 |
| IronOxide     | 2.0          | Haunye                  | 0.0 |
| Spinel        | 0.0          | Leucite                 | 0.0 |
| CaTiOxide     | 0.0          | Kaolinite               | 4.0 |
| CaAlOxide     | 0.0          | AlteredKaolinite        | 0.4 |
| Mixed_Oxide_Rich | 9.2    | Illite                  | 0.8 |
| Total for group = | 12.0      | Montmorillonite         | 3.6 |
| Sulfur_Rich   |                  |
| Pyrite        | 0.0          | Pyroxene                | 0.0 |
| Pyrrhotite    | 0.0          | Wollastonite            | 0.0 |
| IronSulfate   | 0.0          | CaSilicate              | 0.0 |
| SodiumSulfate | 0.0          | DiCalciumSilicate       | 0.0 |
| CalciumSulfate| 2.4          | Gehlenite               | 0.0 |
| NaCaSulfate   | 0.0          | Akermanite              | 0.0 |
| Barite        | 0.0          | Merwinitte              | 0.0 |
| Mixed_Sulfur_Rich | 25.2 | Spurrite                | 0.0 |
| Total for group = | 27.6      | Mullite                 | 0.0 |
| Phosphorous_Rich |           | Mixed_Silicon_Rich     | 14.4 |
| Apatite       | 0.0          | Total for group =       | 30.4 |
| Mixed_Phasporous_Rich | 0.0 | User_defined_list      | 0.0 |
| Carbon_Rich   |                  |
| Calcite       | 4.0          | Ettringite              | 0.0 |
| AlteredCalcite| 0.0          | CalciumAluminate        | 0.0 |
| Dolomite      | 1.6          | Total for group =       | 0.0 |
| SulfatedDolomite | 0.0 | OTHER = 5.6             |
| Ankerite      | 0.4          |                          |
| SulphatedAnkerite | 0.0 |                          |
| Mixed_Carbon_Rich | 18.4 |                          |
| Total for group = | 24.4       |                          |
| Metal_Rich    |                  |
| Aluminun     | 0.0          |                          |
| Titanium      | 0.0          |                          |
| Iron          | 0.0          |                          |
| Nickel        | 0.0          |                          |
| Copper        | 0.0          |                          |
| Chromium      | 0.0          |                          |
| Mixed_Metal_Rich | 0.0 |                          |
| Total for group = | 0.0       |                          |

**TOTAL NUMBER OF POINTS ANALYSED = 250**
**Carbon threshold for analysis = 250**
**Oxygen threshold for analysis = 100**
### PRESSURIZED FLUIDIZED BED - CYCLONE ASH
#### SEM POINT COUNTS

#### BULK CHEMICAL COMPOSITION

|   | A    | B    | C    | D    | E    | F    | G    |
|---|------|------|------|------|------|------|------|
| SiO₂ | 2.9  | 1.1  | 9.7  | 38.2 | 48.0 | 28.4 | 30.5 |
| Al₂O₃ | 8.7  | 0.0  | 3.3  | 23.0 | 22.9 | 11.9 | 12.8 |
| Fe₂O₃ | 15.5 | 0.9  | 2.6  | 12.9 | 11.7 | 8.4  | 9.1  |
| TiO₂ | 0.1  | 0.1  | 0.2  | 0.5  | 0.8  | 0.3  | 0.4  |
| P₂O₅ | 0.0  | 0.1  | 0.1  | 0.0  | 0.0  | 0.1  | 0.1  |
| CaO | 40.5 | 55.4 | 27.6 | 7.2  | 7.6  | 21.5 | 27.1 |
| MgO | 22.3 | 39.3 | 21.0 | 5.2  | 3.7  | 14.2 | 17.8 |
| Na₂O | 0.5  | 0.1  | 0.3  | 0.7  | 0.5  | 0.4  | 0.5  |
| K₂O | 1.1  | 0.1  | 0.5  | 2.3  | 2.9  | 1.3  | 1.5  |
| SO₃ | 7.4  | 2.2  | 31.7 | 6.2  | 1.2  | 11.5 | 0.3  |
| Cl₂O₇ | 0.8  | 0.5  | 2.8  | 3.3  | 0.4  | 1.7  | 0.0  |
| Cr₂O₃ | 0.2  | 0.1  | 0.1  | 0.2  | 0.1  | 0.1  | 0.0  |
| BaO | 0.2  | 0.0  | 0.1  | 0.2  | 0.1  | 0.1  | 0.0  |

A). Cumulative bulk composition of OTHER
B). Cumulative bulk composition of Mixed_Oxide_Rich
C). Cumulative bulk composition of Mixed_Sulfur_Rich
D). Cumulative bulk composition of Mixed_Carbon_Rich
E). Cumulative bulk composition of Mixed_Silicon_Rich
F). Cumulative bulk composition of the entire sample
G). SO₃, Cl₂O₇, Cr₂O₃, BaO Free composition of the entire sample
## COAL REBURNING - BOTTOM ASH (SLAG)
### SEM POINT COUNTS

| MINERAL NAME          | FREQUENCY | PERCENT |
|-----------------------|-----------|---------|
| **Oxide Rich**        |           |         |
| MagnesiumOxide        | 0.0       |         |
| AluminumOxide         | 0.0       |         |
| CalciumOxide          | 0.0       |         |
| TitaniumOxide         | 0.0       |         |
| ChromiumOxide         | 0.0       |         |
| IronOxide             | 0.0       |         |
| Spinel                | 0.0       |         |
| CaTiOxide             | 0.0       |         |
| CaAlOxide             | 0.0       |         |
| Mixed_Oxide_Rich      | 0.0       |         |
| Total for group =     | 0.0       |         |
| **Silicon Rich**      |           |         |
| Quartz                | 0.0       |         |
| Albite                | 0.0       |         |
| Anorthite             | 0.0       |         |
| PotassiumFeldspar     | 0.0       |         |
| Nepheline             | 0.0       |         |
| Haayne                | 0.0       |         |
| Leucite               | 0.0       |         |
| Kaolinite             | 0.0       |         |
| AlteredKaolinite      | 0.0       |         |
| Illite                | 0.0       |         |
| Montmorillonite       | 94.8      |         |
| Pyroxene              | 0.0       |         |
| Wollastonite          | 0.0       |         |
| CaSilicate            | 0.0       |         |
| DiCalciumSilicate     | 0.0       |         |
| NaCaSiO3              | 0.0       |         |
| Gehlenite             | 0.0       |         |
| Akermanite            | 0.0       |         |
| Mervinite             | 0.0       |         |
| Spurrite              | 0.0       |         |
| Mullite               | 0.0       |         |
| Mixed_Silicon_Rich    | 3.2       |         |
| Total for group =     | 98.0      |         |
| **Phosphorous Rich**  |           |         |
| Apatite               | 0.0       |         |
| Mixed_Phosphorous_Rich| 0.0       |         |
| Total for group =     | 0.0       |         |
| **Carbon Rich**       |           |         |
| Calcite               | 0.0       |         |
| AlteredCalcite        | 0.0       |         |
| Dolomite              | 0.0       |         |
| SulfatedDolomite      | 0.0       |         |
| Ankerite              | 0.0       |         |
| SulphatedAnkerite     | 0.0       |         |
| Mixed_Carbon_Rich     | 0.4       |         |
| Total for group =     | 0.4       |         |
| **Metal Rich**        |           |         |
| Aluminum              | 0.0       |         |
| Titanium              | 0.0       |         |
| Iron                  | 0.0       |         |
| Nickel                | 0.0       |         |
| Copper                | 0.0       |         |
| Chromium              | 0.0       |         |
| Mixed_Metal_Rich      | 0.0       |         |
| Total for group =     | 0.0       |         |

**User_defined_list**

- Ettringite: 0.0
- CalciumAluminate: 0.0
- Total for group = 0.0

**OTHER = 1.6**

**TOTAL NUMBER OF POINTS ANALYSED = 250**

**Carbon threshold for analysis = 250**

**Oxygen threshold for analysis = 100**
### COAL REBURNING - BOTTOM ASH (SLAG)
#### SEM POINT COUNTS

**BULK CHEMICAL COMPOSITION**

|       | A      | B     | C      | D      | E      |
|-------|--------|-------|--------|--------|--------|
| SiO₂  | 0.0    | 99.4  | 49.3   | 42.8   | 43.0   |
| Al₂O₃ | 34.2   | 0.0   | 13.6   | 20.1   | 20.2   |
| Fe₂O₃ | 34.8   | 0.5   | 23.5   | 19.9   | 19.9   |
| TiO₂  | 1.4    | 0.0   | 1.0    | 0.7    | 0.7    |
| P₂O₅  | 0.3    | 0.0   | 0.0    | 0.1    | 0.1    |
| CaO   | 24.3   | 0.1   | 9.6    | 13.9   | 13.9   |
| MgO   | 1.5    | 0.0   | 0.8    | 0.8    | 0.8    |
| Na₂O  | 1.1    | 0.0   | 0.6    | 0.6    | 0.6    |
| K₂O   | 1.7    | 0.0   | 0.9    | 0.9    | 0.9    |
| S₀₃   | 0.2    | 0.0   | 0.0    | 0.1    | 0.0    |
| Cl₂O₇ | 0.1    | 0.0   | 0.2    | 0.1    | 0.0    |
| Cr₂O₃ | 0.2    | 0.0   | 0.3    | 0.1    | 0.0    |
| BaO   | 0.3    | 0.0   | 0.1    | 0.2    | 0.0    |

**Note:**
A). Cumulative bulk composition of OTHER
B). Cumulative bulk composition of Mixed_Carbon_Rich
C). Cumulative bulk composition of Mixed_Silicon_Rich
D). Cumulative bulk composition of the entire sample
E). S₀₃, Cl₂O₇, Cr₂O₃, BaO Free composition of the entire sample
**COAL REBURNING - ESP FLY ASH**

**SEM POINT COUNTS**

| MINERAL_NAME               | FREQUENCY | PERCENT |
|----------------------------|-----------|---------|
| **Oxide Rich**             |           |         |
| MagnesiumOxide             | 0.0       | 8.0     |
| AluminumOxide              | 0.0       | 0.0     |
| CalciumOxide               | 2.4       | 0.0     |
| TitaniumOxide              | 0.0       | 4.4     |
| ChromiumOxide              | 0.0       | 4.4     |
| IronOxide                  | 4.8       | 0.8     |
| Spinel                     | 0.0       | 0.0     |
| CaTiOxide                  | 0.0       | 0.0     |
| CaAlOxide                  | 0.0       | 0.8     |
| Mixed_Oxide_Rich           | 0.4       | 37.2    |
| **Total for group =**       | 7.6       | 48.0    |
| **Sulfur Rich**            |           |         |
| Pyrite                     | 0.0       | 0.0     |
| Pyrrhotite                 | 0.0       | 0.0     |
| IronSulfate                | 0.0       | 0.0     |
| SodiumSulfate              | 0.0       | 0.0     |
| CalciumSulfate             | 0.0       | 0.0     |
| NaCaSulfate                | 0.0       | 0.0     |
| Barite                     | 0.0       | 0.0     |
| Mixed_Sulfur_Rich          | 3.2       | 0.0     |
| **Total for group =**       | 4.0       | 0.0     |
| **Phosphorous Rich**       |           |         |
| Apatite                    | 0.0       | 0.0     |
| Mixed_Photorous_Rich       | 0.8       | 0.0     |
| **Total for group =**       | 0.8       | 0.0     |
| **Carbon Rich**            |           |         |
| Calcite                    | 1.6       | 27.2    |
| AlteredCalcite             | 0.0       | 0.0     |
| Dolomite                   | 0.0       | 0.0     |
| SulfatedDolomite           | 0.0       | 0.0     |
| Ankerite                   | 0.4       | 0.0     |
| SulphatedAnkerite          | 0.0       | 0.0     |
| Mixed_Carbon_Rich          | 36.0      | 30.0    |
| **Total for group =**       | 38.0      | 48.0    |
| **Metal Rich**             |           |         |
| Aluminun                   | 0.0       | 0.0     |
| Titanium                   | 0.0       | 0.0     |
| Iron                       | 0.0       | 0.0     |
| Nickel                     | 0.0       | 0.0     |
| Copper                     | 0.0       | 0.0     |
| Chromium                   | 0.0       | 0.0     |
| Mixed_Metal_Rich           | 0.4       | 0.0     |
| **Total for group =**       | 0.4       | 0.0     |

**TOTAL NUMBER OF POINTS ANALYSED =** **250**

**Carbon threshold for analysis =** **250**

**Oxygen threshold for analysis =** **100**
COAL REBURNING - ESP FLY ASH
SEM POINT COUNTS

BULK CHEMICAL COMPOSITION

|     | A   | B   | C   | D   | E   | F   | G   | H   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| SiO2| 3.5 | 0.0 | 9.0 | 53.4| 50.7| 99.4| 50.4| 47.4|
| Al2O3| 31.3| 2.5 | 4.3 | 1.3 | 24.5| 0.0 | 27.8| 21.4|
| Fe2O3| 22.4| 5.2 | 7.2 | 1.6 | 10.5| 0.3 | 10.1| 12.7|
| TiO2| 0.8 | 0.5 | 0.2 | 0.0 | 1.4 | 0.0 | 1.1 | 0.9 |
| P2O5| 0.1 | 0.4 | 1.4 | 42.2| 0.2 | 0.0 | 0.1 | 0.5 |
| CaO | 30.4| 40.5| 50.8| 0.4 | 2.6 | 0.0 | 3.0 | 8.7 |
| MgO | 2.8 | 50.8| 1.1 | 0.0 | 1.1 | 0.0 | 1.2 | 1.3 |
| Na2O| 1.5 | 0.0 | 0.8 | 0.2 | 1.6 | 0.0 | 1.5 | 1.2 |
| K2O | 1.7 | 0.0 | 0.5 | 0.0 | 2.3 | 0.0 | 3.1 | 2.0 |
| SO3 | 4.0 | 0.0 | 21.8| 0.0 | 1.9 | 0.0 | 0.8 | 2.3 |
| Cl2O7| 0.9 | 0.0 | 2.7 | 0.2 | 2.9 | 0.3 | 0.4 | 1.4 |
| Cr2O3| 0.0 | 0.0 | 0.0 | 0.7 | 0.1 | 0.0 | 0.1 | 0.1 |
| BaO | 0.6 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.2 | 0.1 |

A). Cumulative bulk composition of OTHER
B). Cumulative bulk composition of Mixed_Oxide_Rich
C). Cumulative bulk composition of Mixed_Sulfur_Rich
D). Cumulative bulk composition of Mixed_Phosporous_Rich
E). Cumulative bulk composition of Mixed_Carbon_Rich
F). Cumulative bulk composition of Mixed_Metal_Rich
G). Cumulative bulk composition of Mixed_Silicon_Rich
H). Cumulative bulk composition of the entire sample
I). SO3, Cl2O7, Cr2O3, BaO Free composition of the entire sample
### SOx, NOx, ROx, BOX – BAGHOUSE FLY ASH
#### SEM POINT COUNTS

| Mineral Name          | Frequency Percent | Silicon_Rich |
|-----------------------|-------------------|--------------|
| **Oxide_Rich**        |                   |              |
| MagnesiumOxide        | 0.0               | Quartz 0.0   |
| AluminumOxide         | 0.0               | Albite 0.0   |
| CalciumOxide          | 0.0               | Anorthite 0.0|
| TitaniumOxide         | 0.0               | PotassiumFeldspar 0.0 |
| ChromiumOxide         | 0.0               | Wepheine 0.0 |
| IronOxide             | 0.0               | Haune 0.0    |
| Spinel                | 0.0               | Leucite 0.0  |
| CaTiOxide             | 0.0               | Kaolinite 0.4|
| CaAl2Oxide            | 0.0               | AlteredKaolinite 0.0 |
| Mixed_Oxide_Rich      | 0.0               | Illite 0.8   |
| Total for group =     | 0.0               | Montmorillonite 0.0 |
|                       |                   | Pyroxene 0.0 |
| **Sulfur_Rich**       |                   |              |
| Pyrite                | 0.0               | Wollastonite 0.0 |
| Pyrrhotite            | 0.0               | CaSilicate 0.0 |
| IronSulfate           | 0.0               | DiCalciumSilicate 0.0 |
| SodiumSulfate         | 0.0               | NaCaSiO3 0.0 |
| CalciumSulfate        | 17.3              | Gehlenite 0.0 |
| NaCaSulfate           | 0.0               | Akermanite 0.0 |
| Barite                | 0.0               | Herwinite 0.0 |
| Mixed_Sulfur_Rich     | 63.1              | Spurrite 0.0 |
| Total for group =     | 80.3              | Mullite 0.0  |
|                       |                   | Mixed_Silicon_Rich 0.0 |
|                       |                   | Total for group = 1.2 |
| **Phosphorous_Rich**  |                   |              |
| Apatite               | 0.0               |              |
| Mixed_Phasphorous_Rich| 0.0               |              |
| Total for group =     | 0.0               | OTHER = 0.0  |
| **Carbon_Rich**       |                   |              |
| Calcite               | 2.4               |              |
| AlteredCalcite        | 2.0               |              |
| Dolomite              | 0.0               |              |
| SulphatedDolomite     | 0.0               |              |
| Ankerite              | 0.0               |              |
| SulphatedAnkerite     | 0.0               |              |
| Mixed_Carbon_Rich     | 14.1              |              |
| Total for group =     | 18.5              |              |
| **Metal_Rich**        |                   |              |
| Aluminum              | 0.0               |              |
| Titanium              | 0.0               |              |
| Iron                  | 0.0               |              |
| Nickel                | 0.0               |              |
| Copper                | 0.0               |              |
| Chromium              | 0.0               |              |
| Mixed_Metal_Rich      | 0.0               |              |
| Total for group =     | 0.0               |              |

TOTAL NUMBER OF POINTS ANALYSED = 249
Carbon threshold for analysis = 250
Oxygen threshold for analysis = 100
## Bulk Chemical Composition

|       | A  | B  | C  | D  |
|-------|----|----|----|----|
| S\(_2\)O | 2.2 | 50.5 | 9.8 | 11.2 |
| A\(_2\)O | 1.3 | 22.9 | 4.4 | 4.9 |
| Fe\(_2\)O | 1.1 | 11.5 | 2.5 | 3.3 |
| TiO | 0.1 | 0.7 | 0.2 | 0.2 |
| P\(_2\)O | 0.2 | 0.2 | 0.2 | 0.3 |
| CaO | 55.1 | 3.9 | 47.2 | 75.2 |
| MgO | 1.4 | 4.7 | 1.9 | 3.0 |
| Na\(_2\)O | 0.2 | 0.4 | 0.2 | 0.5 |
| K\(_2\)O | 0.4 | 2.1 | 0.6 | 1.1 |
| SO \(_3\) | 35.6 | 2.1 | 30.8 | 0.2 |
| Cl\(_2\)O | 2.2 | 0.6 | 1.9 | 0.0 |
| Cr\(_2\)O | 0.3 | 0.1 | 0.2 | 0.0 |
| BaO | 0.1 | 0.3 | 0.1 | 0.0 |

A). Cumulative bulk composition of Mixed_Sulfur_Rich  
B). Cumulative bulk composition of Mixed_Carbon_Rich  
C). Cumulative bulk composition of the entire sample  
D). SO\(_3\), Cl\(_2\)O, Cr\(_2\)O, BaO Free composition of the entire sample
### SEM Point Counts

#### Mineral Name | FREQUENCY PERCENT | Silicon_Rich | Quartz | 0.0 |
|----------------|------------------|--------------|--------|-----|
| Oxide_Rich | MagnesiumOxide | 0.0 | Albite | 0.0 |
| | AluminumOxide | 0.0 | Anorthite | 0.0 |
| | CalciumOxide | 0.0 | PotassiumFeldspar | 0.0 |
| | TitaniumOxide | 0.0 | Nepheline | 0.0 |
| | ChromiumOxide | 0.0 | Hauny | 0.0 |
| | IronOxide | 0.0 | Leucite | 0.0 |
| | Spinel | 0.0 | Kaolinite | 0.0 |
| | CaTiOxide | 0.0 | AlteredKaolinite | 0.0 |
| | CaAlOxide | 0.0 | Illite | 0.0 |
| | Mixed_Oxide_Rich | 0.0 | Montmorillonite | 0.0 |
| | Total for group | 0.0 | Pyroxene | 0.0 |
| Sulfur_Rich | Pyrite | 0.0 | Wollastonite | 0.0 |
| | Pyrrhotite | 0.0 | CaSilicate | 0.0 |
| | IronSulfate | 0.0 | DiCalciumSilicate | 0.4 |
| | SodiumSulfate | 0.0 | NaCaSiO3 | 0.0 |
| | CalciumSulfate | 0.0 | Gehlenite | 0.0 |
| | NaCaSulfate | 0.0 | Akermanite | 0.0 |
| | Barite | 0.0 | Merwinit | 0.0 |
| | Mixed_Sulfur_Rich | 0.0 | Spurrrite | 0.0 |
| | Total for group | 0.0 | Mullite | 0.0 |
| | Total for group | 0.0 | Mixed_Silicon_Rich | 0.0 |
| | OTHER | 0.4 | Total for group | 0.4 |
| Phosphorous_Rich | Apatite | 0.0 | | |
| | Mixed_Phasorous_Rich | 0.0 | | |
| | Total for group | 0.0 | OTHER | 0.4 |
| Carbon_Rich | Calcite | 87.4 | | |
| | AlteredCalcite | 0.8 | | |
| | Dolomite | 10.3 | | |
| | SulfatedDolomite | 0.0 | | |
| | Ankerite | 0.0 | | |
| | SulphatedAnkerite | 0.0 | | |
| | Mixed_Carbon_Rich | 0.8 | | |
| | Total for group | 99.2 | | |
| Metal_Rich | Aluminum | 0.0 | | |
| | Titanium | 0.0 | | |
| | Iron | 0.0 | | |
| | Nickel | 0.0 | | |
| | Copper | 0.0 | | |
| | Chromium | 0.0 | | |
| | Mixed_Metal_Rich | 0.0 | | |
| | Total for group | 0.0 | | |

TOTAL NUMBER OF POINTS ANALYSED = 253
Carbon threshold for analysis = 250
Oxygen threshold for analysis = 100
SOX, NOX, ROX, BOX - SORBENT
SEM POINT COUNTS

BULK CHEMICAL COMPOSITION

|     | A   | B   | C   | D   |
|-----|-----|-----|-----|-----|
| SiO2| 7.7 | 18.1| 1.9 | 1.9 |
| Al2O3| 31.5| 0.1 | 0.8 | 0.8 |
| Fe2O3| 0.0 | 8.1 | 0.5 | 0.5 |
| TiO2| 0.0 | 0.0 | 0.1 | 0.1 |
| P2O5| 0.2 | 0.0 | 0.1 | 0.1 |
| CaO | 59.4| 3.3 | 90.9| 92.4|
| MgO | 0.3 | 53.5| 3.4 | 3.5 |
| Na2O| 0.0 | 4.5 | 0.2 | 0.3 |
| K2O | 0.3 | 4.0 | 0.4 | 0.5 |
| SO3 | 0.4 | 0.0 | 0.2 | 0.0 |
| Cl2O7| 0.0 | 8.5 | 1.1 | 0.0 |
| Cr2O3| 0.0 | 0.0 | 0.1 | 0.0 |
| BaO | 0.3 | 0.0 | 0.2 | 0.0 |

A). Cumulative bulk composition of OTHER
B). Cumulative bulk composition of Mixed_Carbon_Rich
C). Cumulative bulk composition of the entire sample
D). SO3, Cl2O7, Cr2O3, BaO Free composition of the entire sample
## LNB/AOFA - ESP FLY ASH

### Mineral Classification

| Mineral Name          | Frequency Percent |
|-----------------------|-------------------|
| **Oxide Rich**        |                   |
| MagnesiumOxide        | 0.0               |
| AluminumOxide         | 0.0               |
| CalciumOxide          | 0.0               |
| TitaniumOxide         | 0.0               |
| ChromiumOxide         | 0.0               |
| IronOxide             | 4.4               |
| Spinel                | 0.0               |
| CaTiOxide             | 0.0               |
| CaAlOxide             | 0.0               |
| Mixed_Oxide_Rich      | 0.0               |
| **Total for group**   | **4.4**           |
| **Silicon Rich**      |                   |
| Quartz                | 3.6               |
| Albite                | 0.0               |
| Anorthite             | 0.0               |
| PotassiumFeldspar     | 0.0               |
| Nepheline             | 0.0               |
| Haune                 | 0.0               |
| Leucite               | 0.0               |
| Kaolinite             | 8.0               |
| AlteredKaolinite      | 5.2               |
| Illite                | 23.2              |
| Montmorillonite       | 2.4               |
| Pyroxene              | 0.0               |
| Wollastonite          | 0.0               |
| CaSilicate            | 0.0               |
| DiCalciumSilicate     | 0.0               |
| NaCaSiO3              | 0.0               |
| Gehlenite             | 0.0               |
| Akermanite            | 0.0               |
| Merwinite             | 0.0               |
| Spurrite              | 0.0               |
| Mixed_Sulfur_Rich     | 0.0               |
| **Total for group**   | **52.4**          |
| **Mixed Silicon Rich**|                   |
| Mixed_Silicon_Rich    | 0.0               |
| **Total for group**   | **94.8**          |
| **Other**             | 0.0               |

**TOTAL NUMBER OF POINTS ANALYSED = 250**

**Carbon threshold for analysis = 2000**

**Oxygen threshold for analysis = 300**
# LNB/AOFA - ESP FLY ASH

## BULK CHEMICAL COMPOSITION

|     | A     | B     | C     | D     | E     |
|-----|-------|-------|-------|-------|-------|
| SiO2| 1.0   | 12.9  | 55.1  | 53.7  | 54.4  |
| A12O3| 0.2   | 7.9   | 27.9  | 28.1  | 28.4  |
| Fe2O3| 19.0  | 67.7  | 8.1   | 10.0  | 10.1  |
| TiO2| 0.0   | 0.0   | 1.8   | 1.5   | 1.5   |
| P2O5| 0.0   | 0.0   | 0.2   | 0.2   | 0.2   |
| CaO | 61.5  | 0.0   | 0.7   | 1.0   | 1.1   |
| MgO | 17.7  | 0.4   | 1.1   | 1.0   | 1.0   |
| Na2O| 0.5   | 0.0   | 0.5   | 0.4   | 0.4   |
| K2O | 0.1   | 0.4   | 3.3   | 2.9   | 2.9   |
| S03 | 0.0   | 10.4  | 0.9   | 0.7   | 0.0   |
| ClO | 0.0   | 0.0   | 0.2   | 0.1   | 0.0   |
| Cr2O3| 0.0  | 0.3   | 0.1   | 0.1   | 0.0   |
| BaO | 0.0   | 0.0   | 0.2   | 0.2   | 0.0   |

Points | 1 | 1 | 131 | 250 | 250 |

A). Cumulative bulk composition of OTHER
B). Cumulative bulk composition of Mixed_Carbon_Rich
C). Cumulative bulk composition of Mixed_Silicon_Rich
D). Cumulative bulk composition of the entire sample
E). S03, Cl2O7, Cr2O3, BaO Free composition of the entire sample
## LNB/AOFA - ECONOMIZER ASH

| MINERAL_NAME          | FREQUENCY | PERCENT |
|-----------------------|-----------|---------|
| **Oxide_Rich**        | Silicon_Rich |
| MagnesiumOxide        | 0.0       | 6.0     |
| AluminumOxide         | 0.0       | 0.0     |
| CalciumOxide          | 0.0       | 0.0     |
| TitaniumOxide         | 0.0       | 0.0     |
| ChromiumOxide         | 0.0       | 0.0     |
| IronOxide             | 1.2       | 2.0     |
| Spinel                | 0.4       | 4.8     |
| CaTiOxide             | 0.0       | 5.2     |
| CaAlOxide             | 0.0       | 0.0     |
| Mixed_Oxide_Rich      | 0.4       | 0.0     |
| Total for group =     | 2.0       | 0.0     |

| **Sulfur_Rich**       |            |
| Pyrite                | 0.0       |
| Pyrrhotite            | 0.0       |
| IronSulfate           | 0.0       |
| SodiumSulfate         | 0.0       |
| CalciumSulfate        | 0.0       |
| NaCaSulfate           | 0.0       |
| Barite                | 0.0       |
| Mixed_Sulfur_Rich     | 0.0       |
| Total for group =     | 0.0       |

| **Phosphorous_Rich**  |            |
| Apatite               | 0.0       |
| Mixed_Phosphorous_Rich| 0.0       |
| Total for group =     | 0.0       |

| **Carbon_Rich**       |            |
| Calcite               | 0.0       |
| AlteredCalcite        | 0.0       |
| Dolomite              | 0.0       |
| SulfatedDolomite      | 0.0       |
| Ankerite              | 0.0       |
| SulfatedAnkerite      | 0.0       |
| Mixed_Carbon_Rich     | 0.4       |
| Total for group =     | 0.4       |

| **Metal_Rich**        |            |
| Aluminum              | 0.0       |
| Titanium              | 0.0       |
| Iron                  | 0.0       |
| Nickel                | 0.0       |
| Copper                | 0.0       |
| Chromium              | 0.0       |
| Mixed_Metal_Rich      | 0.0       |
| Total for group =     | 0.0       |

TOTAL NUMBER OF POINTS ANALYSED = 250
Carbon threshold for analysis = 2000
Oxygen threshold for analysis = 300
**LNB/AOFA - ECONOMIZER ASH**

**BULK CHEMICAL COMPOSITION**

|   | A    | B    | C    | D    | E    |
|---|------|------|------|------|------|
| SiO2 | 0.0  | 0.0  | 52.5 | 53.9 | 54.2 |
| Al2O3 | 74.9 | 71.9 | 26.2 | 27.5 | 27.7 |
| Fe2O3 | 10.2 | 13.9 | 13.9 | 11.4 | 11.4 |
| TiO2 | 2.5  | 3.6  | 1.2  | 1.2  | 1.2  |
| P2O5 | 0.0  | 0.0  | 0.2  | 0.2  | 0.2  |
| CaO  | 1.2  | 2.3  | 1.0  | 1.2  | 1.2  |
| MgO  | 1.8  | 1.2  | 1.0  | 0.9  | 0.9  |
| Na2O | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  |
| K2O  | 8.6  | 5.7  | 3.1  | 2.9  | 2.9  |
| SO3  | 0.0  | 0.0  | 0.2  | 0.2  | 0.0  |
| ClO  | 0.0  | 1.0  | 0.1  | 0.1  | 0.0  |
| Cr2O3 | 0.6  | 0.0  | 0.1  | 0.1  | 0.0  |
| BaO  | 0.0  | 0.0  | 0.2  | 0.2  | 0.0  |
| Points | 1    | 1    | 155  | 250  | 250  |

A). Cumulative bulk composition of Mixed_Oxide_Rich
B). Cumulative bulk composition of Mixed_Carbon_Rich
C). Cumulative bulk composition of Mixed_Silicon_Rich
D). Cumulative bulk composition of the entire sample
E). SO3, Cl2O7, Cr2O3, BaO Free composition of the entire sample
### LNB/AOFA - BOTTOM ASH

| MINERAL NAME            | FREQUENCY | PERCENT |
|-------------------------|-----------|---------|
| **Oxide Rich**          |           |         |
| MagnesiumOxide          | 0.0       |         |
| AluminumOxide           | 0.4       |         |
| CalciumOxide            | 0.0       |         |
| TitaniumOxide           | 0.0       |         |
| ChromiumOxide           | 0.0       |         |
| IronOxide               | 0.8       |         |
| Spinel                  | 0.0       |         |
| CaTiOxide               | 0.0       |         |
| CaAlOxide               | 0.0       |         |
| Mixed Oxide_Rich        | 0.4       | 1.6     |
| **Total for group =**   |           | 4.4     |
| **Silicon Rich**        |           |         |
| Quartz                  | 4.4       |         |
| Albite                  | 0.0       |         |
| Anorthite               | 0.0       |         |
| PotassiumFeldspar       | 0.0       |         |
| Nepheline               | 0.0       |         |
| Haunyne                 | 0.0       |         |
| Leucite                 | 0.0       |         |
| Kaolinite               | 0.0       |         |
| AlteredKaolinite        | 2.4       |         |
| Illite                  | 4.8       |         |
| Montmorillonite         | 0.4       |         |
| Pyroxene                | 0.0       |         |
| Wollastonite            | 0.0       |         |
| CaSilicate              | 0.0       |         |
| DiCalciumSilicate       | 0.0       |         |
| NaCaSiO3                | 0.0       |         |
| Gehlenite               | 0.0       |         |
| Akermanite              | 0.0       |         |
| Merwinitie              | 0.0       |         |
| Spurrite                | 0.0       |         |
| Mullite                 | 0.0       |         |
| Mixed Silicon_Rich      | 80.0      | 97.2    |
| **Total for group =**   |           | 97.2    |
| **Sulfur_Rich**         |           |         |
| Pyrite                  | 0.0       |         |
| Pyrrhotite              | 0.0       |         |
| IronSulfate             | 0.0       |         |
| SodiumSulfate           | 0.0       |         |
| CalciumSulfate          | 0.0       |         |
| NaCaSulfate             | 0.0       |         |
| Barite                  | 0.0       |         |
| Mixed_Sulfur_Rich       | 0.0       |         |
| **Total for group =**   |           | 0.0     |
| **Phosphorous_Rich**    |           | 0.0     |
| Apatite                 | 0.0       |         |
| Mixed_Phosphorous_Rich  | 0.0       |         |
| **Total for group =**   |           | 0.0     |
| **OTHER = 0.8**         |           |         |
| **Carbon_Rich**         |           |         |
| Calcite                 | 0.0       |         |
| AlteredCalcite          | 0.0       |         |
| Dolomite                | 0.0       |         |
| SulfatedDolomite        | 0.0       |         |
| Ankerite                | 0.0       |         |
| SulfatedAnkerite        | 0.0       |         |
| Mixed_Carbon_Rich       | 0.0       |         |
| **Total for group =**   |           | 0.0     |
| **Metal_Rich**          |           |         |
| Aluminum                | 0.0       |         |
| Titanium                | 0.0       |         |
| Iron                    | 0.0       |         |
| Nickel                  | 0.0       |         |
| Copper                  | 0.0       |         |
| Chromium                | 0.0       |         |
| Mixed_Metal_Rich        | 0.4       |         |
| **Total for group =**   |           | 0.4     |

TOTAL NUMBER OF POINTS ANALYSED = 250
Carbon threshold for analysis = 2000
Oxygen threshold for analysis = 300
### BULK CHEMICAL COMPOSITION

|     | A     | B     | C     | D     | E     | F     |
|-----|-------|-------|-------|-------|-------|-------|
| SiO2| 0.0   | 14.0  | 96.2  | 54.4  | 54.9  | 55.1  |
| Al2O3| 52.8  | 35.0  | 0.6   | 25.6  | 25.7  | 25.8  |
| Fe2O3| 25.2  | 46.8  | 3.1   | 13.0  | 12.5  | 12.6  |
| TiO2 | 4.2   | 1.9   | 0.0   | 1.4   | 1.3   | 1.3   |
| P2O5 | 1.0   | 0.0   | 0.0   | 0.2   | 0.2   | 0.2   |
| CaO  | 4.1   | 0.5   | 0.0   | 0.9   | 0.9   | 0.9   |
| MgO  | 1.5   | 1.7   | 0.0   | 1.0   | 0.9   | 0.9   |
| Na2O | 1.4   | 0.0   | 0.0   | 0.4   | 0.3   | 0.4   |
| K2O  | 9.9   | 0.0   | 0.0   | 2.8   | 2.7   | 2.8   |
| SO3  | 0.0   | 0.0   | 0.0   | 0.1   | 0.1   | 0.0   |
| ClO  | 0.0   | 0.0   | 0.0   | 0.1   | 0.1   | 0.0   |
| Cr2O3| 0.0   | 0.0   | 0.0   | 0.1   | 0.1   | 0.0   |
| BaO  | 0.0   | 0.0   | 0.0   | 0.2   | 0.2   | 0.0   |
| Points | 2     | 1     | 1     | 200   | 250   | 250   |

A). Cumulative bulk composition of OTHER
B). Cumulative bulk composition of Mixed_Oxide_Rich
C). Cumulative bulk composition of Mixed_Metal_Rich
D). Cumulative bulk composition of Mixed_Silicon_Rich
E). Cumulative bulk composition of the entire sample
F). SO3, Cl2O7, Cr2O3, BaO Free composition of the entire sample
| Mineral Name               | Frequency | Percent |
|---------------------------|-----------|---------|
| Silicon Rich              |           |         |
| MagnesiumOxide            | 0.0       | 0.0     |
| AluminumOxide             | 0.0       | 0.0     |
| CalciumOxide              | 1.2       | 0.0     |
| TitaniumOxide             | 0.0       | 0.0     |
| ChromiumOxide             | 0.0       | 0.0     |
| IronOxide                 | 0.0       | 0.0     |
| Spinel                    | 0.0       | 0.0     |
| CaTiOxide                 | 0.0       | 0.0     |
| CaAlOxide                 | 0.0       | 0.0     |
| Mixed_Oxide_Rich          | 0.0       | 0.0     |
| Total for group =          | 1.2       | 0.0     |

| Sulfur Rich               |           |         |
| Pyrite                    | 0.0       | 0.0     |
| Pyrrhotite                | 0.0       | 0.0     |
| IronSulfate               | 0.0       | 0.0     |
| SodiumSulfate             | 0.0       | 0.0     |
| CalciumSulfate            | 98.4      | 0.0     |
| NaCaSulfate               | 0.0       | 0.0     |
| Barite                    | 0.0       | 0.0     |
| Mixed_Sulfur_Rich         | 0.4       | 0.0     |
| Total for group =          | 98.8      | 0.0     |

| Phosphorous Rich          |           |         |
| Apatite                   | 0.0       | 0.0     |
| Mixed_Phosphorous_Rich    | 0.0       | 0.0     |
| Total for group =          | 0.0       | 0.0     |

| Carbon Rich               |           |         |
| Calcite                   | 0.0       | 0.0     |
| AlteredCalcite            | 0.0       | 0.0     |
| Dolomite                  | 0.0       | 0.0     |
| SulfatedDolomite          | 0.0       | 0.0     |
| Ankerite                  | 0.0       | 0.0     |
| SulfatedAnkerite          | 0.0       | 0.0     |
| Mixed_Carbon_Rich         | 0.0       | 0.0     |
| Total for group =          | 0.0       | 0.0     |

| Metal Rich                |           |         |
| Aluminum                  | 0.0       | 0.0     |
| Titanium                  | 0.0       | 0.0     |
| Iron                      | 0.0       | 0.0     |
| Nickel                    | 0.0       | 0.0     |
| Copper                    | 0.0       | 0.0     |
| Chromium                  | 0.0       | 0.0     |
| Mixed_Metal_Rich          | 0.0       | 0.0     |
| Total for group =          | 0.0       | 0.0     |

Total number of points analysed = 250
Carbon threshold for analysis = 2000
Oxygen threshold for analysis = 300
### BULK CHEMICAL COMPOSITION

|   | A  | B  | C  |
|---|----|----|----|
| O2 | 0.0 | 0.2 | 0.4 |
| 203 | 0.0 | 0.1 | 0.3 |
| 203 | 1.0 | 0.1 | 0.3 |
| O2 | 0.0 | 0.0 | 0.1 |
| O5 | 0.0 | 0.1 | 0.3 |
| 0  | 0.0 | 40.4 | 98.1 |
| 0  | 0.4 | 0.1 | 0.1 |
| 20 | 0.6 | 0.1 | 0.2 |
| 0  | 0.0 | 0.0 | 0.1 |
| 203 | 96.9 | 58.5 | 0.0 |
| 0  | 1.0 | 0.2 | 0.0 |
| 203 | 0.0 | 0.1 | 0.0 |
| 0  | 0.0 | 0.1 | 0.0 |
| ints | 1  | 250 | 250 |

A). Cumulative bulk composition of Mixed_Sulfur_Rich

B). Cumulative bulk composition of the entire sample

C). SO3, Cl207, Cr203, BaO Free composition of the entire sample
## Advanced Coal Cleaning Process - Combustion Fly Ash

### Mineral Classification

| Mineral Name          | Frequency | Percent |
|-----------------------|-----------|---------|
| **Oxide_Rich**        |           |         |
| MagnesiumOxide        | 0.0       | 1.6     |
| AluminumOxide         | 0.4       | 0.8     |
| CalciumOxide          | 0.0       | 0.0     |
| TitaniumOxide         | 0.0       | 0.0     |
| ChromiumOxide         | 0.0       | 0.0     |
| IronOxide             | 3.6       | 40.0    |
| Spinel                | 0.0       | 19.6    |
| CaTiOxide             | 0.0       | 15.6    |
| CaAlOxide             | 0.0       | 14.8    |
| Mixed_Oxide_Rich      | 0.0       | 1.6     |
| Total for group =     | 4.0       | 93.6    |
| **Sulfur_Rich**       |           |         |
| Pyrite                | 0.0       | 0.0     |
| Pyrrhotite            | 0.0       | 0.0     |
| IronSulfate           | 0.0       | 0.0     |
| SodiumSulfate         | 0.0       | 0.0     |
| CalciumSulfate        | 0.0       | 0.0     |
| NaCaSulfate           | 0.0       | 0.0     |
| Barite                | 0.0       | 0.0     |
| Mixed_Sulfur_Rich     | 0.0       | 0.0     |
| Total for group =     | 0.0       | 0.0     |
| **Phosphorous_Rich**  | 1.6       | 0.4     |
| Apatite               | 0.0       |         |
| Mixed_Phosphorous_Rich| 1.6       |         |
| Total for group =     | 1.6       |         |
| **Carbon_Rich**       |           |         |
| Calcite               | 0.0       |         |
| AlteredCalcite        | 0.0       |         |
| Dolomite              | 0.0       |         |
| SulfatedDolomite      | 0.0       |         |
| Ankerite              | 0.0       |         |
| SulfatedAnkerite      | 0.0       |         |
| Mixed_Carbon_Rich     | 0.4       |         |
| Total for group =     | 0.4       |         |
| **Metal_Rich**        |           |         |
| Aluminum              | 0.0       |         |
| Titanium              | 0.0       |         |
| Iron                  | 0.0       |         |
| Nickel                | 0.0       |         |
| Copper                | 0.0       |         |
| Chromium              | 0.0       |         |
| Mixed_Metal_Rich      | 0.0       |         |
| Total for group =     | 0.0       |         |

**TOTAL NUMBER OF POINTS ANALYSED = 250**

**Carbon threshold for analysis = 2000**

**Oxygen threshold for analysis = 300**
|       | A   | B   | C   | D   | E   | F   |
|-------|-----|-----|-----|-----|-----|-----|
| SiO2  | 14.9| 10.9| 11.5| 48.5| 46.3| 46.8|
| AI2O3 | 13.3| 12.1| 12.9| 32.5| 37.4| 37.8|
| Fe2O3 | 68.3| 1.3 | 32.4| 8.9 | 7.4 | 7.5 |
| TiO2  | 0.0 | 0.3 | 38.6| 2.3 | 1.6 | 1.6 |
| P2O5  | 2.4 | 31.3| 1.4 | 1.7 | 1.7 | 1.7 |
| CaO   | 4.0 | 42.9| 1.3 | 2.6 | 2.7 | 2.7 |
| MgO   | 0.3 | 0.2 | 0.6 | 1.0 | 0.6 | 0.7 |
| Na2O  | 0.4 | 0.1 | 0.3 | 0.3 | 0.2 | 0.2 |
| K2O   | 0.0 | 0.0 | 0.1 | 1.5 | 1.1 | 1.1 |
| SO3   | 0.2 | 0.6 | 0.0 | 0.5 | 0.6 | 0.0 |
| ClO   | 0.1 | 0.1 | 0.0 | 0.0 | 0.1 | 0.0 |
| Cr2O3 | 0.0 | 0.0 | 0.7 | 0.1 | 0.1 | 0.0 |
| BaO   | 0.0 | 0.2 | 0.0 | 0.1 | 0.1 | 0.0 |

Points: 1 4 1 37 250 250

A). Cumulative bulk composition of OTHER
B). Cumulative bulk composition of Mixed_Phosphorous_Rich
C). Cumulative bulk composition of Mixed_Carbon_Rich
D). Cumulative bulk composition of Mixed_Silicon_Rich
E). Cumulative bulk composition of the entire sample
F). SO3, Cl2O7, Cr2O3, BaO Free composition of the entire sample
APPENDIX I

WASTE X-RAY DIFFRACTION ANALYSES
ENERGY & ENVIRONMENTAL RESEARCH CENTER
UNIVERSITY OF NORTH DAKOTA
X-RAY POWDER DIFFRACTION REPORT

P.I.: Moretti DATE: 1/14/93 I CC#: 54205241.XRD

SAMPLE DESCRIPTION: GAS REBURNING SORBENT INJECTION - ESP FLY ASH

MAJOR PHASE(S):
- Anhydrite
- Lime

NOMINAL COMPOSITION(S):
- CaSO₄
- CaO

MINOR PHASE(S):
- Quartz
- Calcite
- Hematite

NOMINAL COMPOSITION(S):
- SiO₂
- CaCO₃
- Fe₂O₃

COMMENTS:

Analyzed by
### Scan Parameters:

- **Radiation:** CU_1.540598
- **Scan Range:** 5 - 70
- **Step Size:** 0.02
- **Count Time:** 1 sec.

### Search Parameters:

- **Filter length(pts):** 11
- **Noise level(sigmas):** 3.5
- **Intensity cutoff(%):** 0.5 - 100
- **2-Theta Zero (degs):** 0

### Peak-Position

| # | 2Theta | d  | 2Theta | d  | Bkgrd | Peak | I%  | Area | I%  | FWHM* |
|---|--------|----|--------|----|-------|------|-----|------|-----|-------|
| 1 | 20.822 | 4.2627 | 20.823 | 4.2625 | 202 | 72 | 4.2 | 551 | 2.6 | 0.138 |
| 2 | 22.979 | 3.8671 | 22.979 | 3.8671 | 214 | 55 | 3.2 | 153 | 0.7 | 0.050 |
| 3 | 25.500 | 3.4903 | 25.499 | 3.4904 | 217 | 710 | 41.0 | 7969 | 37.0 | 0.202 |
| 4 | 25.960 | 3.4295 | 25.961 | 3.4294 | 219 | 80 | 4.6 | 588 | 2.7 | 0.132 |
| 5 | 26.600 | 3.3484 | 26.600 | 3.3484 | 218 | 445 | 25.7 | 5253 | 24.4 | 0.212 |
| 6 | 29.342 | 3.0415 | 29.352 | 3.0404 | 215 | 206 | 11.9 | 2984 | 13.9 | 0.261 |
| 7 | 31.321 | 2.8536 | 31.325 | 2.8533 | 217 | 150 | 8.7 | 2528 | 11.7 | 0.303 |
| 8 | 31.397 | 2.8469 | 31.381 | 2.8483 | 218 | 164 | 9.5 | 1652 | 7.7 | 0.181 |
| 9 | 32.260 | 2.7727 | 32.260 | 2.7726 | 215 | 582 | 33.6 | 7216 | 33.5 | 0.223 |
|10 | 33.200 | 2.6963 | 33.201 | 2.6963 | 218 | 60 | 3.5 | 389 | 1.8 | 0.117 |
|11 | 35.320 | 2.5391 | 35.321 | 2.5391 | 201 | 70 | 4.0 | 513 | 2.4 | 0.132 |
|12 | 35.581 | 2.5211 | 35.587 | 2.5207 | 204 | 137 | 7.9 | 2325 | 10.8 | 0.305 |
|13 | 35.639 | 2.5172 | 35.627 | 2.5180 | 204 | 137 | 7.9 | 1985 | 9.2 | 0.261 |
|14 | 36.359 | 2.4689 | 36.358 | 2.4690 | 200 | 80 | 4.6 | 1086 | 5.0 | 0.244 |
|15 | 37.401 | 2.4025 | 37.409 | 2.4020 | 210 | 1732 | 100.0 | 21529 | 100.0 | 0.224 |
|16 | 38.621 | 2.3294 | 38.630 | 2.3289 | 198 | 119 | 6.9 | 1348 | 6.3 | 0.204 |
|17 | 39.362 | 2.2872 | 39.365 | 2.2871 | 192 | 66 | 3.8 | 516 | 2.4 | 0.141 |
|18 | 40.560 | 2.2224 | 40.561 | 2.2223 | 186 | 59 | 3.4 | 364 | 1.7 | 0.111 |
|19 | 40.840 | 2.2078 | 40.841 | 2.2077 | 186 | 181 | 10.5 | 2503 | 11.6 | 0.249 |
|20 | 41.302 | 2.1842 | 41.303 | 2.1841 | 186 | 65 | 3.8 | 501 | 2.3 | 0.139 |
|21 | 42.922 | 2.1054 | 42.924 | 2.1053 | 188 | 80 | 4.6 | 468 | 2.2 | 0.105 |
|22 | 43.340 | 2.0861 | 43.338 | 2.0862 | 188 | 99 | 5.7 | 1852 | 8.6 | 0.337 |
|23 | 46.902 | 1.9356 | 46.902 | 1.9356 | 189 | 53 | 3.1 | 246 | 1.1 | 0.084 |
|24 | 47.239 | 1.9226 | 47.240 | 1.9225 | 192 | 73 | 4.2 | 798 | 3.7 | 0.197 |
|25 | 48.681 | 1.8689 | 48.681 | 1.8689 | 198 | 125 | 7.2 | 1720 | 8.0 | 0.248 |
|26 | 50.021 | 1.8220 | 50.024 | 1.8219 | 187 | 72 | 4.2 | 548 | 2.5 | 0.137 |
|27 | 52.321 | 1.7472 | 52.323 | 1.7471 | 187 | 77 | 4.4 | 803 | 3.7 | 0.188 |
|28 | 53.901 | 1.6996 | 53.910 | 1.6993 | 195 | 840 | 48.5 | 14566 | 67.7 | 0.312 |
|29 | 55.720 | 1.6484 | 55.721 | 1.6483 | 194 | 72 | 4.2 | 780 | 3.6 | 0.195 |
|30 | 57.141 | 1.6107 | 57.141 | 1.6107 | 187 | 56 | 3.2 | 252 | 1.2 | 0.081 |
|31 | 57.639 | 1.5980 | 57.639 | 1.5980 | 187 | 54 | 3.1 | 239 | 1.1 | 0.080 |
|32 | 60.620 | 1.5263 | 60.620 | 1.5263 | 192 | 53 | 3.1 | 146 | 0.7 | 0.050 |
|33 | 62.320 | 1.4887 | 62.320 | 1.4887 | 198 | 53 | 3.1 | 150 | 0.7 | 0.051 |
|34 | 64.220 | 1.4492 | 64.219 | 1.4492 | 199 | 199 | 11.5 | 3587 | 16.7 | 0.324 |
|35 | 67.181 | 1.3923 | 67.181 | 1.3923 | 183 | 52 | 3.0 | 151 | 0.7 | 0.052 |
|36 | 67.401 | 1.3883 | 67.414 | 1.3881 | 183 | 212 | 12.2 | 3647 | 16.9 | 0.310 |
|37 | 67.519 | 1.3862 | 67.508 | 1.3864 | 183 | 187 | 10.8 | 4598 | 21.4 | 0.443 |

* Intensity values are based on counts per second.
ENERGY & ENVIRONMENTAL RESEARCH CENTER
UNIVERSITY OF NORTH DAKOTA
X-RAY POWDER DIFFRACTION REPORT

P.I.: Moretti  DATE: 1/14/93  ICC#: 54205242.XRD

SAMPLE DESCRIPTION: GAS REBURNING SORBENT INJECTION - BOTTOM ASH

MAJOR PHASE(S):

NOMINAL COMPOSITION(S):

MINOR PHASE(S):

NOMINAL COMPOSITION(S):

Quartz
SiO₂

Plagioclase
(Ca,Na)(Al,Si)₄O₈

Hematite
Fe₂O₃

Ferrite Spinel
(Mg,Fe)(Fe,Al)₂O₄

COMMENTS: Large amorphous component.

Analyzed by
C. [Signature]
GAS REBURNING SORBENT INJECTION - BOTTOM ASH

![Graph showing data with 2-Theta and CPS axes, labeled with numerical values.]
GAS REBURNING SORBENT INJECTION - BOTTOM ASH

Scan Parameters:
- Radiation: CU_1.540598
- Scan Range: 5 - 70
- Step Size: 0.02
- Count Time: 1 sec.

Search Parameters:
- Filter length (pts): 11
- Noise level (sigmas): 3.5
- Intensity cutoff (%): 0.5 - 100
- 2-Theta Zero (degs): 0

| # | 2Theta| d  | 2Theta| d  | Bkgrd | Peak | I%  | Area | I%  | FWHM* |
|---|-------|----|-------|----|-------|------|-----|------|-----|-------|
| 1 | 24.259| 3.6659 | 24.258| 3.6660 | 298 | 81  | 24.9 | 479 | 9.2  | 0.106 |
| 2 | 26.679| 3.3386 | 26.670| 3.3398 | 314 | 199 | 61.2 | 1879| 36.0 | 0.170 |
| 3 | 27.861| 3.1996 | 27.872| 3.1985 | 315 | 113 | 34.8 | 1572| 30.1 | 0.250 |
| 4 | 27.920| 3.1930 | 27.919| 3.1931 | 315 | 123 | 37.8 | 2076| 39.8 | 0.304 |
| 5 | 29.460| 3.0295 | 29.460| 3.0296 | 312 | 73  | 22.5 | 458 | 8.8  | 0.113 |
| 6 | 30.320| 2.9455 | 30.320| 2.9455 | 303 | 69  | 21.2 | 438 | 8.4  | 0.114 |
| 7 | 33.281| 2.6899 | 33.284| 2.6897 | 276 | 243 | 74.8 | 2584| 49.5 | 0.191 |
| 8 | 35.161| 2.5503 | 35.162| 2.5502 | 264 | 72  | 22.2 | 439 | 8.4  | 0.110 |
| 9 | 35.720| 2.5116 | 35.719| 2.5117 | 258 | 325 | 100.0| 5217| 100.0| 0.289 |
|10 | 40.921| 2.2036 | 40.923| 2.2035 | 242 | 74  | 22.8 | 601 | 11.5 | 0.146 |
|11 | 41.020| 2.1985 | 41.015| 2.1988 | 242 | 69  | 21.2 | 727 | 13.9 | 0.190 |
|12 | 43.299| 2.0879 | 43.298| 2.0880 | 241 | 64  | 19.7 | 417 | 8.0  | 0.117 |
|13 | 49.599| 1.8365 | 49.596| 1.8366 | 238 | 143 | 44.0 | 2144| 41.1 | 0.270 |
|14 | 54.141| 1.6926 | 54.153| 1.6923 | 242 | 119 | 36.6 | 1249| 23.9 | 0.189 |
|15 | 54.259| 1.6892 | 54.251| 1.6895 | 243 | 106 | 32.6 | 1792| 34.3 | 0.304 |
|16 | 57.579| 1.5995 | 57.578| 1.5995 | 239 | 65  | 20.0 | 411 | 7.9  | 0.114 |
|17 | 62.660| 1.4814 | 62.656| 1.4815 | 251 | 146 | 44.9 | 2725| 52.2 | 0.336 |
|18 | 63.160| 1.4709 | 63.160| 1.4709 | 244 | 56  | 17.2 | 159 | 3.0  | 0.051 |
|19 | 64.100| 1.4516 | 64.104| 1.4515 | 256 | 83  | 25.5 | 805 | 15.4 | 0.175 |

* Intensity values are based on counts per second.
ID: 54205242 Bottom Ash 92-72
File: 54205242.MDI  Scan: 5-70/02/1/#3251, Anode:CU  Zero=0.0

GAS REBURNING SOREBENT INJECTION - BOTTOM ASH

1> 20-0020: Anorthite, ordered
ID: 54205242 Bottom Ash 92-72
File: 54205242.MDI Scan: 5-70.02/1/#3251, Anode:CU Zero=0.0

1> 39-1346: Maghemite\#ITC\#RG, syn
| Sample Description: | Pressurized Fluidized Bed - ESP Fly Ash |
|-------------------|----------------------------------------|

| Major Phase(s):   | Nominal Composition(s):                |
|-------------------|----------------------------------------|
| Anhydrite         | CaSO₄                                  |

| Minor Phase(s):   | Nominal Composition(s):                |
|-------------------|----------------------------------------|
| Quartz            | SiO₂                                   |
| Hematite          | Fe₂O₃                                  |
| Periclase         | MgO                                    |
| Calcium Magnesium Sulfate | CaMg₃(SO₄)₄    |

Comments:

Analyzed by [Signature]
**Scan Parameters:**

- Radiation = CU 1.540598
- Scan Range = 5 - 70
- Step Size = .02
- Count Time = 1 sec.
- Filter length(pts) = 11
- Noise level(sigmas) = 5.0
- Intensity cutoff(%) = .5 - 100
- 2-Theta Zero (degs) = 0

---

| #  | 2Theta  | d   | 2Theta  | d   | Bkgrd | Peak  | I%  | Area  | I%  | FWHM* |
|----|----------|-----|----------|-----|-------|-------|-----|-------|-----|-------|
| 1  | 20.860   | 4.2550 | 20.860   | 4.2550 | 212   | 79    | 4.0 | 217   | 1.0 | 0.049 |
| 2  | 22.960   | 3.8703 | 22.960   | 3.8704 | 215   | 98    | 4.9 | 589   | 2.7 | 0.108 |
| 3  | 24.581   | 3.6187 | 24.583   | 3.6184 | 241   | 197   | 9.9 | 1956  | 8.9 | 0.179 |
| 4  | 25.500   | 3.4903 | 25.501   | 3.4902 | 224   | 1983  | 100.0 | 21984 | 200.0 | 0.200 |
| 5  | 26.659   | 3.3412 | 26.651   | 3.3421 | 227   | 539   | 27.2 | 4768  | 21.7 | 0.159 |
| 6  | 28.540   | 3.1250 | 28.540   | 3.1250 | 215   | 79    | 4.0 | 219   | 1.0 | 0.050 |
| 7  | 31.380   | 2.8484 | 31.380   | 2.8484 | 240   | 574   | 28.9 | 6576  | 29.9 | 0.206 |
| 8  | 32.501   | 2.7527 | 32.501   | 2.7527 | 220   | 77    | 3.9 | 221   | 1.0 | 0.052 |
| 9  | 33.220   | 2.6947 | 33.218   | 2.6949 | 222   | 198   | 10.0 | 1984  | 9.0 | 0.180 |
| 10 | 35.661   | 2.5157 | 35.667   | 2.5152 | 205   | 240   | 12.1 | 3777  | 17.2 | 0.283 |
| 11 | 36.360   | 2.4689 | 36.367   | 2.4684 | 205   | 159   | 8.0 | 2676  | 12.2 | 0.303 |
| 12 | 38.680   | 2.3260 | 38.678   | 2.3261 | 200   | 379   | 19.1 | 4771  | 21.7 | 0.227 |
| 13 | 39.460   | 2.2817 | 39.460   | 2.2817 | 198   | 74    | 3.7 | 208   | 0.9 | 0.051 |
| 14 | 40.860   | 2.2068 | 40.862   | 2.2067 | 198   | 419   | 21.1 | 6306  | 28.7 | 0.271 |
| 15 | 41.360   | 2.1812 | 41.361   | 2.1812 | 199   | 157   | 7.9 | 1932  | 8.8 | 0.222 |
| 16 | 42.941   | 2.1045 | 42.947   | 2.1043 | 199   | 173   | 8.7 | 2181  | 9.9 | 0.227 |
| 17 | 43.380   | 2.0842 | 43.383   | 2.0841 | 197   | 151   | 7.6 | 1946  | 8.9 | 0.232 |
| 18 | 45.460   | 1.9936 | 45.459   | 1.9936 | 190   | 113   | 5.7 | 1141  | 5.2 | 0.182 |
| 19 | 48.702   | 1.8682 | 48.714   | 1.8678 | 188   | 294   | 14.8 | 3726  | 16.9 | 0.228 |
| 20 | 49.460   | 1.8413 | 49.462   | 1.8412 | 186   | 95    | 4.8 | 1170  | 5.3 | 0.222 |
| 21 | 50.180   | 1.8166 | 50.179   | 1.8166 | 188   | 81    | 4.1 | 650   | 3.0 | 0.144 |
| 22 | 52.320   | 1.7167 | 52.328   | 1.7169 | 186   | 202   | 10.2 | 2921  | 13.3 | 0.260 |
| 23 | 54.160   | 1.6921 | 54.159   | 1.6921 | 194   | 79    | 4.0 | 506   | 2.3 | 0.115 |
| 24 | 55.800   | 1.6462 | 55.800   | 1.6462 | 197   | 182   | 9.2 | 3310  | 15.1 | 0.327 |
| 25 | 62.301   | 1.4891 | 62.315   | 1.4888 | 201   | 143   | 7.2 | 1865  | 8.5 | 0.235 |
| 26 | 62.439   | 1.4862 | 62.428   | 1.4864 | 201   | 149   | 7.5 | 3174  | 14.4 | 0.383 |

* Intensity values are based on counts per second.
**Sample Description:**

**Pressurized Fluidized Bed - Bottom Ash**

| Major Phase(s):            | Nominal Composition(s): |
|----------------------------|-------------------------|
| Anhydrite                  | CaSO₄                   |
| Calcite                    | CaCO₃                   |
| Periclase                  | MgO                     |

| Minor Phase(s):            | Nominal Composition(s): |
|----------------------------|-------------------------|
| Quartz                     | SiO₂                    |
| Ferrite Spinel             | (Mg,Fe)(Fe,Al)₂O₄       |
| Lime                       | CaO                     |

**Comments:**

Analyzed by [Signature]
ID: 54205243 Bed Material 92-74
File: 54205243.MDI Scan: 5-70/02/1/#3251, Anode: CU
Zero=0.0

PRESSURIZED FLUIDIZED BED - BOTTOM ASH
--- Scan Parameters: ---

Radiation = CU_1.540598
Scan Range = 5 - 70
Step Size = .02
Count Time = 1 sec.

--- Search Parameters: ---

Filter length (pts) = 11
Noise level (sigmas) = 5.0
Intensity cutoff (%) = .5-100
2-Theta Zero (degs) = 0

| #  | 2Theta | d   | 2Theta | d   | Bkgd | Peak | I%  | Area | I%  | FWHM |
|----|--------|-----|--------|-----|------|------|-----|------|-----|------|
| 1  | 22.982 | 3.8667 | 22.994 | 3.8646 | 164  | 110 | 4.8 | 1584 | 4.7 | 0.259 |
| 2  | 23.040 | 3.8570 | 23.043 | 3.8566 | 164  | 131 | 5.7 | 2157 | 6.4 | 0.296 |
| 3  | 25.519 | 3.4877 | 25.515 | 3.4883 | 165  | 2305 | 100 | 24440 | 72.5 | 0.191 |
| 4  | 26.659 | 3.3411 | 26.655 | 3.3416 | 162  | 115 | 5.0 | 947  | 2.8  | 0.148 |
| 5  | 29.381 | 3.0375 | 29.386 | 3.0370 | 184  | 1584 | 68.7 | 20630 | 61.2 | 0.234 |
| 6  | 31.400 | 2.8467 | 31.395 | 2.8471 | 195  | 818 | 35.5 | 12759 | 37.9 | 0.281 |
| 7  | 31.981 | 2.7962 | 31.986 | 2.7958 | 198  | 159 | 6.9 | 1540 | 4.6  | 0.174 |
| 8  | 32.740 | 2.7331 | 32.740 | 2.7331 | 196  | 87  | 3.8 | 721  | 2.1  | 0.149 |
| 9  | 33.840 | 2.6468 | 33.840 | 2.6468 | 188  | 69  | 3.0 | 192  | 0.6  | 0.050 |
| 10 | 35.700 | 2.5130 | 35.699 | 2.5131 | 178  | 149 | 6.5 | 3693 | 11.0 | 0.446 |
| 11 | 36.140 | 2.4834 | 36.147 | 2.4829 | 172  | 224 | 9.7 | 8166 | 24.2 | 0.656 |
| 12 | 36.320 | 2.4715 | 36.315 | 2.4719 | 171  | 238 | 10.3 | 5856 | 17.4 | 0.443 |
| 13 | 36.981 | 2.4289 | 36.981 | 2.4289 | 178  | 176 | 7.6 | 2026 | 6.0  | 0.207 |
| 14 | 38.680 | 2.3259 | 38.681 | 2.3259 | 168  | 511 | 22.2 | 6845 | 20.3 | 0.241 |
| 15 | 39.520 | 2.2784 | 39.522 | 2.2783 | 171  | 279 | 12.1 | 4524 | 13.4 | 0.292 |
| 16 | 40.860 | 2.2068 | 40.861 | 2.2067 | 176  | 515 | 22.3 | 7934 | 23.6 | 0.277 |
| 17 | 41.361 | 2.1812 | 41.368 | 2.1808 | 177  | 219 | 9.5 | 3102 | 9.2  | 0.255 |
| 18 | 42.941 | 2.1045 | 42.953 | 2.1039 | 181  | 2137 | 92.7 | 33689 | 100.0 | 0.284 |
| 19 | 43.340 | 2.0861 | 43.335 | 2.0863 | 181  | 501 | 21.7 | 9291 | 27.6 | 0.334 |
| 20 | 45.479 | 1.9928 | 45.479 | 1.9928 | 181  | 139 | 6.0 | 1469 | 4.4  | 0.190 |
| 21 | 47.240 | 1.9225 | 47.246 | 1.9223 | 203  | 360 | 15.6 | 9526 | 28.3 | 0.476 |
| 22 | 47.739 | 1.9036 | 47.739 | 1.9036 | 188  | 75  | 3.3 | 366  | 1.1  | 0.088 |
| 23 | 48.501 | 1.8755 | 48.505 | 1.8753 | 210  | 353 | 15.3 | 6454 | 19.2 | 0.329 |
| 24 | 48.701 | 1.8682 | 48.699 | 1.8683 | 208  | 559 | 24.3 | 13117 | 38.9 | 0.422 |
| 25 | 49.101 | 1.8539 | 49.102 | 1.8539 | 203  | 137 | 5.9 | 2200 | 6.5  | 0.289 |
| 26 | 52.321 | 1.7472 | 52.331 | 1.7469 | 176  | 317 | 13.8 | 4851 | 14.4 | 0.275 |
| 27 | 55.760 | 1.6473 | 55.766 | 1.6471 | 188  | 315 | 13.7 | 5586 | 16.6 | 0.319 |
| 28 | 57.610 | 1.5989 | 57.605 | 1.5988 | 190  | 139 | 6.0 | 2792 | 8.3  | 0.362 |
| 29 | 59.060 | 1.5629 | 59.061 | 1.5628 | 186  | 83  | 3.6 | 509  | 1.5  | 0.110 |
| 30 | 60.701 | 1.5245 | 60.719 | 1.5241 | 196  | 151 | 6.6 | 1985 | 5.9  | 0.237 |
| 31 | 61.840 | 1.5213 | 60.838 | 1.5214 | 195  | 173 | 7.5 | 3861 | 11.5 | 0.402 |
| 32 | 62.320 | 1.4887 | 62.330 | 1.4885 | 198  | 1178 | 51.1 | 20434 | 60.7 | 0.312 |
| 33 | 62.420 | 1.4866 | 62.420 | 1.4866 | 198  | 917 | 39.8 | 15671 | 46.5 | 0.308 |
| 34 | 64.980 | 1.4340 | 64.985 | 1.4339 | 189  | 102 | 4.4 | 1154 | 3.4  | 0.204 |
| 35 | 65.659 | 1.4208 | 65.659 | 1.4208 | 186  | 69  | 3.0 | 197  | 0.6  | 0.051 |
| 36 | 67.000 | 1.3956 | 67.000 | 1.3956 | 179  | 84  | 3.6 | 506  | 1.5  | 0.108 |

* Intensity values are based on counts per second.
ID: 54205243 Bed Material 92-74
File: 54205243.MDI Scan: 5-70/02/1/#3251, Anode: CU

1> 37-1496: Anhydrite, syn
2> 05-0586: Calcite, syn
ENERGY & ENVIRONMENTAL RESEARCH CENTER
UNIVERSITY OF NORTH DAKOTA
X-RAY POWDER DIFFRACTION REPORT

P.I.: Moretii  DATE: 1/14/93  ICC#: 54205244. XRD

SAMPLE DESCRIPTION: PRESSURIZED FLUIDIZED BED - CYCLONE ASH

| MAJOR PHASE(S):       | NOMINAL COMPOSITION(S): |
|-----------------------|-------------------------|
| Anhydrite             | CaSO₄                   |
| Dolomite              | CaMg(CO₃)₂              |
| Periclase             | MgO                     |
| Quartz                | SiO₂                    |

| MINOR PHASE(S):       | NOMINAL COMPOSITION(S): |
|-----------------------|-------------------------|
| Lime                  | CaO                     |
| Sodium Calcium Sulfate| (Na₀.₈,Ca₀.₅)₂SO₄       |
| Calcite               | CaCO₃                   |

COMMENTS:

Analyzed by [Signature]
PRESSURIZED FLUIDIZED BED - CYCLONE ASH
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~de: Peak Listing
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PliESSURIZED FLUIDIZElii

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—-— -

ile: 54205244.MDI>

BED - CWL9NE
w

RSH

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Jan 13.1993 @6:31prfI
—-=mw===--x====

54205244 Fly Ash 92-75

Scan Parameters:. --------------------- Search Parameters: ---------Filter length(pts)
= CU_l.540598
= .11
Radiation
Noise level(sigmas) = 5.0
Scan Range = 5 - 70
Intensity cutoff(%) = .5-100
Step Size = .02
2-Theta Zero (degs) = O
Count Time = 1 sec.
--------------------- --------------------- ------------------------ ----------------------

Peak-Position

Centroid-Position

Peak

& Area

are

without

Bkgrd

2Theta
Bkgrd
Peak
1%
Area
1%
FWHM*
d
# 2Theta
d
--------------------- --------------------- --------------------- ---------------149
7.3
4.2515
193
4.2509
20.877
1187
5.5 0.143
1: 20.880
53
2.6
‘1092
5.1 0.371
206
3.8584
3.8568
23.032
2:
23.042
78
3.8
3.6927
3.6927
24.081
217
214
1.0 0.049
3: 24.081
48
2.4
223
3.6186
3.6190
24.582
277
1.3 0.104
4:
24.579
1110
54.4
3.4880
13184 61.1 0.214
211
3.4877
25.517
5: 25.519
93
4.6
3.4241
3.4242
26.002
591
215
2.7 0.114
6: 26.001
8136 37.7 0.180
812
39.8
3.3420
214
3.3411
26.652
26.659
7:
4884 22.6 0.275
320
15.7
3.0355
3.0356
29.400
229
8:
29.400
2.8825
31.000
21593 100.0 0.191
2039
100.0
234
2.8824
31.000
9:
360
17.7
2.8501
31.358
6451 29.9 0.323
233
2.8504
10: 31.360
70
3.4
2.7971
2.7980
31.970
221
1605
7.4 0.413
11: 31.960
2.6931
33.246
2421 11.2 0.208
210
10.3
2;6927
210
12: 33.241
2.6667
33.574
2754 12.8 0.222
223
10.9
2.6671
203
13: 33.579
2.5383
2.5390
35.332
147
7.2
203
1696
7.9 0.208
14: 35.322
239
11.7
2.5130
2.5130
35.699
7286 33.7 0.549
192
15: 35.700
176
8.6
2.4673
2.4676
36.383
4192 19.4 0.429
187
16: 36.380
149
7.3
2.4581
2.4572
36.525
2202 10.2 0.266
191
17: 36.540
89
4.4
2.4288
2.4289
36.981
539
2.5 0.109
196
18: 36.980
208
10.2
2.4020
2.4025
37.409
1945
9.0 0.168
205
19: 37.401
212
10.4
2.3268
2.3271
38.666
0.248
2925
13.5
195
38.661
20:
111
5.4
2.2796
1161
5.4 0.188
204
2.2796
39.499
21: 39.500
292
14.3
2.2072
4774 22.1 0.294
206
2.2077
40.852
22: 40.841
531
26.0
8941 41.4 0.303
2.1909
205
2.1913
41.169
41.161
23:
91
4.5
587
2.7 0.116
200
2.1271
2.1272
42.462
24: 42.461
651
31.9
13860 64.2 0.383
200
2.1042
2.1045
42.947
25: 42.940
181
8.9
4159 19..3 0.414
199
2.0862
2.0861
43.337
26: 43.340
89
4.4
684
3.2 0.138
199
2.0634
2.0634
43.840
27: 43.841
225
11.0
2146
9.9 0.172
199
2.0141
2.0146
44.971
28: 44.961
71
3.5
199
1.9919
195
0.9 0.049
1.9919
45.500
29: 45.500
186
9.1
2910 13.5 0.282”
228
1.8681
1.8682
48.703
30: 48.700
1320
6.1 0.193
123
6.0
1.8185
1.8186
50.122
213
31: 50.120
363
17.8
5160 23.9 0.256
227
1.8032
1.8032
50.578
32: 50.579
381
18.7
4814 22.3 0.227
1.7857
1.7860
51.109
223
33: 51.100
1795
8.3 0.241
134
6.6
1.7459
52.360
196
1.7459
34: 52.360
79
3.9
719
3.3 0.164
192
1.6977
1.6978
53.966
35: 53.962
94
4.6
420
1$9 0.080
194
1.6899
1.6899
54.238
36: 54.238
70
3.4
216
1.0 0.056
198
1.6505
1.6505
55.641
37: 55.641
1827
8.5 0.228
144
7.1
197
1.6467
55.786
1.6466
38: 55.780
872
4.0 0.141
111
5.4
197
1.6426
1.6424
55.934
39: 55.939
139
6.8
1867
8.6 0.242
210
1.5429
1.5429
59.900
40: 59.900
77
3.8
518
2.4 0.121
212
1.5241
1.5240
60.719
41: 60.720
0.360
6917
32.0
346
17.0
221
1.4885
1.4887
62.328
62.320
42:
0.051
222
1.0
79
3.9
226
1-4655
1.4655
63.420
63.420
43:


* Intensity values are based on counts per second.
ID: 54205244 Fly Ash 92-75
File: 54205244.MDI  Scan: 5-70/02/1/#3251, Anode: CU  Zero=0.0

1> 33-1161: Quartz, syn
2> 37-1496: Anhydrite, syn
PRESSURIZED FLUIDIZED BED - CYCLONE ASH

1. 36-0426: Dolomite
2. 291196: Sodium Carbonate Sulfate

ID: 54205244 Fly Ash 92-75
File: 54205244.MDI
Scan: 5-70/02/1#3251, Anode:CU

Zero=0.0

2-Theta

Cps
ENERGY & ENVIRONMENTAL RESEARCH CENTER
UNIVERSITY OF NORTH DAKOTA
X-RAY POWDER DIFFRACTION REPORT

P.I.: Moretti DATE: 1/14/93 ICC#: 54205239.XRD

SAMPLE DESCRIPTION: COAL REBURNING - BOTTOM ASH (SLAG)

MAJOR PHASE(S): 

NOMINAL COMPOSITION(S):

MINOR PHASE(S): 

NOMINAL COMPOSITION(S):

COMMENTS: No crystalline phases.

Analyzed by
ID: 54205239 Black Bottom Ash
File: 54205239.MDI Scan: 5-70/02/1/#3251. Anode:CU
Zero=0.0

COAL BURNING - BOTTOM ASH (SLAG)
P.I.: Moretti  DATE: 1/14/93  ICC#: 54205240.XRD

SAMPLE DESCRIPTION:  COAL REBURNING - ESP FLY ASH

MAJOR PHASE(S):  Quartz

NOMINAL COMPOSITION(S):  SiO₂

MINOR PHASE(S):  Mullite
                   Anhydrite
                   Lime
                   Ferrite Spinel
                   Hematite

NOMINAL COMPOSITION(S):  Al₆Si₂O₁₃
                           CaSO₄
                           CaO
                           (Mg,Fe)(Fe,Al)₂O₄
                           Fe₂O₃

COMMENTS:

Analyzed by  [Signature]
### Scan Parameters:
- **Radiation:** Cu 1.540598
- **Scan Range:** 5 - 70
- **Step Size:** .02
- **Count Time:** 1 sec.

### Search Parameters:
- **Filter length (pts):** 11
- **Noise level (sigmas):** 5.5
- **Intensity cutoff (%):** 0.5 - 100
- **2-Theta Zero (degs):** 0

### Peak-Position

| # | 2Theta | d  | 2Theta | d  | Bkgrd | Peak | I% | Area | I% | FWHM* |
|---|-------|----|-------|----|-------|------|----|------|----|-------|
| 1 | 16.421 | 5.3939 | 16.415 | 5.3957 | 207 | 74 | 8.3 | 853 | 9.3 | 0.207 |
| 2 | 20.859 | 4.2553 | 20.857 | 4.2556 | 256 | 126 | 14.2 | 757 | 8.3 | 0.108 |
| 3 | 24.242 | 3.6685 | 24.241 | 3.6687 | 294 | 40 | 4.5 | 627 | 6.9 | 0.282 |
| 4 | 25.480 | 3.4930 | 25.481 | 3.4929 | 291 | 108 | 12.2 | 680 | 7.4 | 0.113 |
| 5 | 26.020 | 3.4218 | 26.021 | 3.4216 | 290 | 136 | 15.3 | 1274 | 13.9 | 0.169 |
| 6 | 26.220 | 3.3960 | 26.221 | 3.3959 | 289 | 200 | 22.5 | 4178 | 45.7 | 0.376 |
| 7 | 26.660 | 3.3411 | 26.652 | 3.3420 | 288 | 887 | 100.0 | 9142 | 100.0 | 0.186 |
| 8 | 30.239 | 2.9532 | 30.238 | 2.9533 | 266 | 113 | 12.7 | 710 | 7.8 | 0.113 |
| 9 | 31.020 | 2.8806 | 31.020 | 2.8806 | 261 | 93 | 10.5 | 259 | 2.8 | 0.050 |
| 10 | 32.262 | 2.7726 | 32.262 | 2.7726 | 266 | 100 | 11.3 | 461 | 5.0 | 0.083 |
| 11 | 33.200 | 2.6963 | 33.202 | 2.6962 | 250 | 226 | 25.5 | 2606 | 28.5 | 0.208 |
| 12 | 35.280 | 2.5419 | 35.282 | 2.5418 | 252 | 137 | 15.4 | 1559 | 17.1 | 0.205 |
| 13 | 35.600 | 2.5198 | 35.598 | 2.5200 | 252 | 355 | 40.0 | 6879 | 75.2 | 0.349 |
| 14 | 36.560 | 2.4558 | 36.563 | 2.4556 | 226 | 127 | 14.3 | 1412 | 15.4 | 0.200 |
| 15 | 37.421 | 2.4013 | 37.426 | 2.4009 | 274 | 245 | 27.6 | 1936 | 21.2 | 0.142 |
| 16 | 39.440 | 2.2829 | 39.440 | 2.2829 | 217 | 95 | 10.7 | 416 | 4.6 | 0.079 |
| 17 | 40.261 | 2.2382 | 40.268 | 2.2379 | 215 | 45 | 5.1 | 615 | 6.7 | 0.246 |
| 18 | 40.841 | 2.2078 | 40.847 | 2.2074 | 219 | 161 | 18.2 | 1944 | 21.3 | 0.217 |
| 19 | 42.480 | 2.1263 | 42.490 | 2.1258 | 223 | 82 | 9.2 | 1588 | 17.4 | 0.349 |
| 20 | 43.040 | 2.0999 | 43.040 | 2.0999 | 224 | 85 | 9.6 | 239 | 2.6 | 0.051 |
| 21 | 45.760 | 1.9812 | 45.761 | 1.9811 | 221 | 45 | 5.1 | 756 | 8.3 | 0.302 |
| 22 | 49.339 | 1.8455 | 49.348 | 1.8452 | 212 | 67 | 7.6 | 906 | 9.9 | 0.243 |
| 23 | 50.120 | 1.8186 | 50.120 | 1.8186 | 216 | 160 | 18.0 | 1515 | 16.6 | 0.170 |
| 24 | 53.940 | 1.6985 | 53.949 | 1.6982 | 210 | 208 | 23.4 | 2865 | 31.3 | 0.248 |
| 25 | 57.121 | 1.6112 | 57.123 | 1.6111 | 217 | 101 | 11.4 | 1025 | 11.2 | 0.183 |
| 26 | 60.658 | 1.5254 | 60.658 | 1.5254 | 220 | 96 | 10.8 | 439 | 4.8 | 0.082 |
| 27 | 62.760 | 1.4793 | 62.757 | 1.4794 | 227 | 110 | 12.4 | 1297 | 14.2 | 0.212 |

* Intensity values are based on counts per second.
ID: 54205240 ESP Hopper Ash
File: 54205240.MDI Scan: 5-70/02/1/#3251, Anode: CU

Zero = 0.0

CPS

2-Theta

1 > 33-1161: Quartz, syn
2 > 19-0629: Magnetite, syn
1: 37-1496: Anhydrite, syn
2: 37-1497: Lime, syn
**MAJOR PHASE(S):**
- Anhydrite
- Calcite

**NOMINAL COMPOSITION(S):**
- CaSO$_4$
- CaCO$_3$

**MINOR PHASE(S):**
- Quartz
- Mullite
- Portlandite
- Hannebachite
- Periclase

**NOMINAL COMPOSITION(S):**
- SiO$_2$
- Al$_6$Si$_2$O$_{13}$
- Ca(OH)$_2$
- CaSO$_3$·5H$_2$O
- MgO

**COMMENTS:**

Analyzed by: Cathy O'Keefe
ENERGY & ENVIRONMENTAL RESEARCH CENTER
UNIVERSITY OF NORTH DAKOTA
X-RAY POWDER DIFFRACTION REPORT

P.I.: Moretti DATE: 6/23/93 ICC#: 54205711.XRD

SAMPLE DESCRIPTION: S0H, NOx, ROx, BOx - SORBENT

MAJOR PHASE(S):
Portlandite

NOMINAL COMPOSITION(S):
Ca(OH)₂

MINOR PHASE(S):
Periclase

NOMINAL COMPOSITION(S):
MgO

COMMENTS:

 Analyzed by: Cathy O'Keefe
ENERGY & ENVIRONMENTAL RESEARCH CENTER
UNIVERSITY OF NORTH DAKOTA
X-RAY POWDER DIFFRACTION REPORT

P.I.: Moretti  DATE: 6/7/94  ICC#: 54206734.XRD

SAMPLE DESCRIPTION:  LNB/AOFA - ESP FLY ASH

| MAJOR PHASE(S):       | NOMINAL COMPOSITION(S):      |
|-----------------------|------------------------------|
| Quartz                | SiO₂                         |
| Mullite               | Al₆Si₂O₁₃                    |

| MINOR PHASE(S):       | NOMINAL COMPOSITION(S):      |
|-----------------------|------------------------------|
| Maghemite             | Fe₂O₃                        |
| Ferrite Spinel        | (Mg,Fe)(Fe,Al)₂O₄           |

COMMENTS:  An amorphous component.

Analyzed by Cathy O'Keefe
--- Scan Parameters: ---

| Radiation      | 54.0598  |
|----------------|----------|
| Scan Range     | 5-70     |
| Step Size      | 0.2      |
| Count Time     | 1 sec    |

--- Search Parameters: ---

| Filter length(pts) | 15 |
|--------------------|----|
| Noise level(sigma) | 4.0|
| Intensity cutoff(%)| 0.5-100|
| 2-Theta Zero (deg) | 0.0|

--- Peak-Position Centroid-Position Peak & Area are without Bkgrd ---

| #  | 2Theta | 2Theta | Bkgrd | Peak  | I%   | Area  | I%   | FWHM* |
|----|--------|--------|-------|-------|------|-------|------|-------|
| 1  | 16.420 | 5.3940 | 120   | 111   | 24.7 | 1144  | 14.0 | 0.186 |
| 2  | 20.876 | 4.2517 | 190   | 96    | 21.3 | 558   | 6.8  | 0.105 |
| 3  | 25.280 | 3.5202 | 232   | 62    | 13.8 | 170   | 2.1  | 0.049 |
| 4  | 26.000 | 3.4243 | 228   | 198   | 44.0 | 3746  | 45.7 | 0.341 |
| 5  | 26.260 | 3.3910 | 229   | 256   | 56.9 | 8196  | 100.0| 0.576 |
| 6  | 26.581 | 3.3508 | 215   | 450   | 100.0| 7513  | 91.7 | 0.301 |
| 7  | 29.600 | 3.0155 | 165   | 19    | 4.2  | 259   | 3.2  | 0.245 |
| 8  | 30.261 | 2.9511 | 156   | 41    | 9.1  | 1076  | 13.1 | 0.472 |
| 9  | 31.000 | 2.8824 | 154   | 66    | 14.7 | 519   | 6.3  | 0.142 |
| 10 | 33.182 | 2.6977 | 139   | 153   | 34.0 | 2096  | 25.6 | 0.247 |
| 11 | 35.241 | 2.5447 | 133   | 152   | 33.8 | 1991  | 24.3 | 0.236 |
| 12 | 36.699 | 2.5130 | 127   | 96    | 21.3 | 1688  | 20.6 | 0.316 |
| 13 | 36.480 | 2.4610 | 121   | 52    | 11.6 | 330   | 4.0  | 0.114 |
| 14 | 39.319 | 2.2896 | 110   | 73    | 16.2 | 737   | 9.0  | 0.182 |
| 15 | 40.840 | 2.2078 | 115   | 151   | 33.6 | 2169  | 26.5 | 0.259 |
| 16 | 42.540 | 2.1234 | 117   | 80    | 17.8 | 907   | 11.1 | 0.204 |
| 17 | 49.400 | 1.8434 | 103   | 47    | 10.4 | 291   | 3.6  | 0.111 |
| 18 | 50.099 | 1.8193 | 101   | 53    | 11.8 | 320   | 3.9  | 0.109 |
| 19 | 53.959 | 1.6979 | 99    | 60    | 13.3 | 638   | 7.8  | 0.191 |
| 20 | 57.559 | 1.6000 | 99    | 77    | 17.1 | 1053  | 12.8 | 0.246 |
| 21 | 59.940 | 1.5420 | 104   | 42    | 9.3  | 119   | 1.5  | 0.051 |
| 22 | 60.602 | 1.5267 | 104   | 101   | 22.4 | 1148  | 14.0 | 0.205 |
| 23 | 62.580 | 1.4831 | 108   | 87    | 19.3 | 526   | 6.4  | 0.109 |
| 24 | 63.421 | 1.4655 | 105   | 42    | 9.3  | 115   | 1.4  | 0.049 |
| 25 | 64.540 | 1.4428 | 108   | 52    | 11.6 | 313   | 3.8  | 0.108 |
| 26 | 68.120 | 1.3754 | 96    | 40    | 8.9  | 116   | 1.4  | 0.052 |

* Intensity values are based on counts per second.
ID: 54206734 Unit #4 Hopper Ash
File: 54206734.MDI
Scan: 5-70/02/1/#3251, Anode: CU
Zero=0.0

1> 33-1161: Quartz, syn

2> 17-0464: Magnesioferrite, ordered, syn
ID: 54206734 Unit #4 Hopper Ash
File: 54206734.MDI Scan: 5-70/02/1/#3251, Anode: CU Zero=0.0

25-1402: Maghemite-ltQirG, syn
| MAJOR PHASE(S): | NOMINAL COMPOSITION(S): |
|----------------|------------------------|
| Quartz         | SiO₂                   |
| Mullite        | Al₆Si₂O₁₃              |

| MINOR PHASE(S): | NOMINAL COMPOSITION(S): |
|----------------|------------------------|
| Maghemite      | Fe₂O₃                  |
| Ferrite Spinel | (Mg,Fe)(Fe,Al)₂O₄      |

COMMENTS: An amorphous component.

Analyzed by Cathy O'Keefe
| #  | 2Theta | d   | 2Theta | d   | Bkgrd | Peak | I%   | Area | I%   | FWHM* |
|----|--------|-----|--------|-----|-------|------|------|------|------|-------|
| 1  | 7.360  | 12.0011| 7.360  | 12.0011| 80   | 37   | 7.2  | 104  | 1.0  | 0.051 |
| 2  | 16.497 | 5.3693| 16.480  | 5.3747| 110  | 115  | 22.3 | 1119 | 10.6 | 0.175 |
| 3  | 20.803 | 4.2665| 20.810  | 4.2652| 168  | 84   | 16.3 | 614  | 5.8  | 0.132 |
| 4  | 25.440 | 3.4984| 25.439  | 3.4985| 188  | 65   | 12.6 | 398  | 3.8  | 0.110 |
| 5  | 26.020 | 3.4218| 26.022  | 3.4214| 193  | 229  | 44.4 | 4241 | 40.2 | 0.333 |
| 6  | 26.279 | 3.3885| 26.278  | 3.3887| 190  | 342  | 66.3 | 10552| 100.0| 0.555 |
| 7  | 26.639 | 3.3435| 26.626  | 3.3451| 186  | 516  | 100.0| 6754 | 64.0 | 0.236 |
| 8  | 30.200 | 2.9569| 30.200  | 2.9569| 159  | 52   | 10.1 | 145  | 1.4  | 0.050 |
| 9  | 30.941 | 2.8878| 30.937  | 2.8882| 148  | 165  | 32.0 | 2289 | 21.7 | 0.250 |
| 10 | 33.240 | 2.6932| 33.235  | 2.6935| 132  | 226  | 43.8 | 3744 | 35.5 | 0.298 |
| 11 | 35.221 | 2.5461| 35.231  | 2.5453| 139  | 229  | 44.4 | 3863 | 36.6 | 0.304 |
| 12 | 35.699 | 2.5130| 35.688  | 2.5138| 128  | 169  | 32.8 | 8652 | 82.0 | 0.922 |
| 13 | 36.460 | 2.4623| 36.459  | 2.4624| 120  | 195  | 37.8 | 8441 | 80.0 | 0.779 |
| 14 | 36.959 | 2.4302| 36.958  | 2.4303| 139  | 75   | 14.5 | 927  | 8.8  | 0.222 |
| 15 | 39.240 | 2.2940| 39.244  | 2.2938| 104  | 104  | 20.2 | 1297 | 12.3 | 0.224 |
| 16 | 40.839 | 2.2078| 40.830  | 2.2083| 103  | 259  | 50.2 | 4212 | 39.9 | 0.293 |
| 17 | 42.540 | 2.1234| 42.537  | 2.1236| 105  | 107  | 20.7 | 1607 | 15.2 | 0.270 |
| 18 | 43.340 | 2.0861| 43.338  | 2.0862| 104  | 58   | 11.2 | 530  | 5.0  | 0.164 |
| 19 | 49.499 | 1.8400| 49.494  | 1.8401| 101  | 61   | 11.8 | 766  | 7.3  | 0.226 |
| 20 | 50.041 | 1.8213| 50.048  | 1.8211| 106  | 96   | 18.6 | 1157 | 11.0 | 0.217 |
| 21 | 53.420 | 1.7138| 53.420  | 1.7138| 106  | 46   | 8.9  | 118  | 1.1  | 0.046 |
| 22 | 54.060 | 1.6950| 54.056  | 1.6951| 100  | 96   | 18.6 | 2434 | 23.1 | 0.456 |
| 23 | 57.499 | 1.6015| 57.488  | 1.6018| 106  | 105  | 20.3 | 1850 | 17.5 | 0.317 |
| 24 | 58.620 | 1.5735| 58.618  | 1.5736| 114  | 58   | 11.2 | 424  | 4.0  | 0.132 |
| 25 | 59.881 | 1.5434| 59.881  | 1.5434| 114  | 52   | 10.1 | 234  | 2.2  | 0.081 |
| 26 | 60.601 | 1.5268| 60.614  | 1.5264| 115  | 150  | 29.1 | 2367 | 22.4 | 0.284 |
| 27 | 62.621 | 1.4823| 62.622  | 1.4822| 130  | 56   | 10.9 | 441  | 4.2  | 0.142 |
| 28 | 64.340 | 1.4467| 64.353  | 1.4465| 128  | 101  | 19.6 | 2212 | 21.0 | 0.394 |
| 29 | 64.480 | 1.4439| 64.473  | 1.4441| 135  | 112  | 21.7 | 2036 | 19.3 | 0.327 |
| 30 | 67.720 | 1.3825| 67.720  | 1.3825| 103  | 47   | 9.1  | 124  | 1.2  | 0.047 |
| 31 | 68.140 | 1.3750| 68.140  | 1.3750| 102  | 56   | 10.9 | 688  | 6.5  | 0.221 |

* Intensity values are based on counts per second.
ID: 54206733 Unit #4 Economizer Ash
File: 54206733.MDI Scan: 5-70/02/1/#3251, Anode: CU

Zero = 0.0

2\theta 33-1161: Quartz, syn

2\theta 17-0464: Magnesioferrite, ordered, syn
## Major Phase(s):
- Mullite

## Nominal Composition(s):
- $\text{Al}_6\text{Si}_2\text{O}_{13}$

## Minor Phase(s):
- Quartz
- Maghemite
- Ferrite Spinel

## Nominal Composition(s):
- $\text{Si}_2\text{O}$
- $\text{Fe}_2\text{O}_3$
- $(\text{Mg,Fe})(\text{Fe,Al})_2\text{O}_4$

## Comments:
- An amorphous component.

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**Analyzed by Cathy O'Keefe**
LNB/AOFA - BOTTOM ASH

ID: 54206735 Unit #4 Bottom Ash
Scan: 5-07/02/11 #3251, Anode: C4
### Scan Parameters:
- **Radiation**: Cu 1.540598
- **Scan Range**: 5 - 70
- **Step Size**: 0.02
- **Count Time**: 1 sec.

### Search Parameters:
- **Filter length (pts)**: 15
- **Noise level (sigmas)**: 4.0
- **Intensity cutoff (%)**: 0.5 - 100
- **2-Theta Zero (degs)**: 0

### Peak-Position Centroid-Position

| # | 2Theta | d   | 2Theta | d   | Bkgrd | Peak | I% | Area | I% | FWHM* |
|---|--------|-----|--------|-----|-------|------|----|------|----|-------|
| 1 | 16.420 | 5.3941 | 16.429 | 5.3912 | 107 | 252 | 66.5 | 2537 | 20.5 | 0.181 |
| 2 | 17.139 | 5.1694 | 17.139 | 5.1694 | 115 | 53  | 14.0 | 145  | 1.2  | 0.049 |
| 3 | 20.859 | 4.2552 | 20.859 | 4.2552 | 158 | 62  | 16.4 | 161  | 1.3  | 0.047 |
| 4 | 24.919 | 3.5703 | 24.919 | 3.5704 | 175 | 64  | 16.9 | 391  | 3.2  | 0.110 |
| 5 | 26.020 | 3.4217 | 26.025 | 3.4210 | 163 | 309 | 81.5 | 9051 | 73.2 | 0.527 |
| 6 | 26.279 | 3.3885 | 26.271 | 3.3896 | 169 | 379 | 100.0 | 12366 | 100.0 | 0.587 |
| 7 | 26.620 | 3.3459 | 26.608 | 3.3475 | 173 | 292 | 77.0 | 3949 | 31.9 | 0.243 |
| 8 | 30.301 | 2.9473 | 30.306 | 2.9468 | 132 | 62  | 16.4 | 955  | 7.7  | 0.277 |
| 9 | 30.417 | 2.9363 | 30.413 | 2.9367 | 132 | 72  | 19.0 | 513  | 4.1  | 0.128 |
| 10 | 30.901 | 2.8915 | 30.906 | 2.8910 | 128 | 141 | 37.2 | 1904 | 15.4 | 0.243 |
| 11 | 33.241 | 2.6931 | 33.243 | 2.6929 | 118 | 245 | 64.6 | 3800 | 30.7 | 0.279 |
| 12 | 35.259 | 2.5434 | 35.255 | 2.5437 | 121 | 202 | 53.3 | 3321 | 26.9 | 0.296 |
| 13 | 35.720 | 2.5116 | 35.718 | 2.5118 | 113 | 208 | 54.9 | 8465 | 68.5 | 0.733 |
| 14 | 36.400 | 2.4663 | 36.406 | 2.4659 | 106 | 150 | 39.6 | 7626 | 61.7 | 0.915 |
| 15 | 39.260 | 2.2929 | 39.259 | 2.2930 | 93  | 77  | 20.3 | 860  | 7.0  | 0.201 |
| 16 | 40.782 | 2.2108 | 40.797 | 2.2100 | 93  | 258 | 68.1 | 3801 | 30.7 | 0.265 |
| 17 | 42.558 | 2.1226 | 42.546 | 2.1231 | 94  | 101 | 26.6 | 1139 | 9.2  | 0.203 |
| 18 | 43.280 | 2.0888 | 43.280 | 2.0888 | 94  | 41  | 10.8 | 108  | 0.9  | 0.047 |
| 19 | 45.820 | 1.9787 | 45.821 | 1.9787 | 91  | 62  | 16.4 | 317  | 2.6  | 0.092 |
| 20 | 49.399 | 1.8434 | 49.403 | 1.8433 | 83  | 64  | 16.9 | 746  | 6.0  | 0.210 |
| 21 | 50.160 | 1.8173 | 50.160 | 1.8173 | 81  | 41  | 10.8 | 111  | 0.9  | 0.049 |
| 22 | 53.420 | 1.7138 | 53.421 | 1.7137 | 87  | 60  | 15.8 | 501  | 4.1  | 0.150 |
| 23 | 54.041 | 1.6955 | 54.043 | 1.6955 | 85  | 80  | 21.1 | 2529 | 20.5 | 0.569 |
| 24 | 54.300 | 1.6881 | 54.289 | 1.6884 | 85  | 71  | 18.7 | 948  | 7.7  | 0.240 |
| 25 | 57.440 | 1.6030 | 57.438 | 1.6031 | 97  | 84  | 22.2 | 1606 | 13.0 | 0.344 |
| 26 | 60.581 | 1.5272 | 60.594 | 1.5269 | 101 | 140 | 36.9 | 2245 | 18.2 | 0.289 |
| 27 | 62.741 | 1.4797 | 62.746 | 1.4796 | 109 | 61  | 16.1 | 641  | 5.2  | 0.189 |
| 28 | 63.599 | 1.4618 | 63.597 | 1.4619 | 101 | 57  | 15.0 | 522  | 4.2  | 0.165 |
| 29 | 64.221 | 1.4491 | 64.238 | 1.4488 | 105 | 94  | 24.8 | 1789 | 14.5 | 0.343 |
| 30 | 64.380 | 1.4459 | 64.377 | 1.4460 | 105 | 92  | 24.3 | 2016 | 16.3 | 0.394 |

*Intensity values are based on counts per second.*
Advanced FGD Process - Spent Scrubber Waste

MAJOR PHASE(S): Gypsum
NOMINAL COMPOSITION(S): CaSO₄·2H₂O

MINOR PHASE(S): Calcite
NOMINAL COMPOSITION(S): CaCO₃

Analyzed by John Kay
SAMPLE DESCRIPTION: Advanced Coal Cleaning Process - Combustion Fly Ash

MAJOR PHASE(S):  
Mullite

NOMINAL COMPOSITION(S):  
$\text{Al}_6\text{Si}_2\text{O}_{13}$

MINOR PHASE(S):  
Quartz
Hematite

NOMINAL COMPOSITION(S):  
$\text{Si}_2\text{O}$
$\text{Fe}_2\text{O}_3$

COMMENTS: amorphous component

Analyzed by Cathy O'Keefe
UNDEE ERC

File: 960590.MDI 960590 Ash From Combustion of Cleaned Coal (45kV, 40mA)

--- Scan Parameters: ---
Radiation = CU_1.54059
Scan Range = 5-70
Step Size = .02
Count Time = 2 sec.

--- Search Parameters: ---
Filter length(pts) = 11
Noise level(sigmas) = 7.0
Intensity cutoff(%) = 1.5-100
2-Theta Zero (degs) = 0

| Peak-Position | Centroid-Position | Peak & Area are without Bkgrd |
|---------------|-------------------|--------------------------------|
| # | 2Theta | d | 2Theta | d | Bkgrd | Peak | % | Area | % | FWHM* |
|---|--------|---|--------|---|-------|------|---|------|---|-------|
| 1 | 16.399 | 5.4009 | 16.400 | 5.4007 | 266 | 358 | 39.0 | 86 | 29.5 | 0.216 |
| 2 | 25.580 | 3.4795 | 25.578 | 3.4799 | 426 | 197 | 21.4 | 48 | 16.4 | 0.219 |
| 3 | 25.961 | 3.4293 | 25.976 | 3.4274 | 427 | 651 | 70.8 | 193 | 66.1 | 0.267 |
| 4 | 26.239 | 3.3936 | 26.232 | 3.3945 | 438 | 919 | 100.0 | 292 | 100.0 | 0.286 |
| 5 | 26.560 | 3.3533 | 26.559 | 3.3535 | 429 | 250 | 27.2 | 52 | 17.8 | 0.187 |
| 6 | 30.921 | 2.8896 | 30.928 | 2.8890 | 335 | 184 | 20.0 | 38 | 13.0 | 0.186 |
| 7 | 31.020 | 2.8806 | 31.020 | 2.8806 | 335 | 185 | 20.1 | 21 | 7.2 | 0.102 |
| 8 | 33.199 | 2.6963 | 33.197 | 2.6965 | 310 | 515 | 56.0 | 127 | 43.5 | 0.222 |
| 9 | 35.219 | 2.5462 | 35.219 | 2.5462 | 288 | 597 | 65.0 | 149 | 51.0 | 0.225 |
| 10 | 35.560 | 2.5226 | 35.560 | 2.5226 | 276 | 138 | 15.0 | 12 | 4.1 | 0.078 |
| 11 | 36.960 | 2.4302 | 36.959 | 2.4302 | 278 | 156 | 17.0 | 23 | 7.9 | 0.133 |
| 12 | 39.220 | 2.2952 | 39.223 | 2.2950 | 260 | 198 | 21.5 | 40 | 13.7 | 0.182 |
| 13 | 40.820 | 2.2088 | 40.825 | 2.2086 | 250 | 662 | 72.0 | 177 | 60.6 | 0.241 |
| 14 | 42.522 | 2.1243 | 42.531 | 2.1239 | 257 | 230 | 25.0 | 44 | 15.1 | 0.172 |
| 15 | 42.599 | 2.1206 | 42.590 | 2.1211 | 257 | 244 | 26.6 | 67 | 22.9 | 0.247 |
| 16 | 49.280 | 1.8476 | 49.280 | 1.8476 | 251 | 127 | 13.8 | 7 | 2.4 | 0.050 |
| 17 | 49.419 | 1.8428 | 49.419 | 1.8427 | 246 | 158 | 17.2 | 39 | 13.4 | 0.222 |
| 18 | 53.459 | 1.7126 | 53.459 | 1.7126 | 243 | 115 | 12.5 | 6 | 2.1 | 0.047 |
| 19 | 53.940 | 1.6985 | 53.943 | 1.6984 | 241 | 166 | 18.1 | 53 | 18.2 | 0.287 |
| 20 | 54.059 | 1.6950 | 54.059 | 1.6950 | 246 | 144 | 15.7 | 17 | 5.8 | 0.106 |
| 21 | 54.220 | 1.6904 | 54.220 | 1.6904 | 237 | 115 | 12.5 | 6 | 2.1 | 0.047 |
| 22 | 56.699 | 1.6222 | 56.699 | 1.6222 | 217 | 107 | 11.6 | 6 | 2.1 | 0.050 |
| 23 | 57.121 | 1.6112 | 57.121 | 1.6112 | 219 | 121 | 13.2 | 7 | 2.4 | 0.052 |
| 24 | 57.501 | 1.6015 | 57.506 | 1.6013 | 221 | 261 | 28.4 | 88 | 30.1 | 0.303 |
| 25 | 57.720 | 1.5959 | 57.720 | 1.5959 | 222 | 159 | 17.3 | 22 | 7.5 | 0.125 |
| 26 | 60.620 | 1.5263 | 60.622 | 1.5263 | 239 | 393 | 42.8 | 129 | 44.2 | 0.295 |
| 27 | 60.777 | 1.5228 | 60.778 | 1.5227 | 246 | 251 | 27.3 | 38 | 13.0 | 0.136 |
| 28 | 63.559 | 1.4626 | 63.559 | 1.4626 | 241 | 121 | 13.2 | 11 | 3.8 | 0.082 |
| 29 | 64.440 | 1.4447 | 64.440 | 1.4447 | 245 | 168 | 18.3 | 31 | 10.6 | 0.166 |
| 30 | 64.502 | 1.4435 | 64.501 | 1.4435 | 244 | 200 | 21.8 | 53 | 18.2 | 0.238 |
| 31 | 64.698 | 1.4396 | 64.698 | 1.4396 | 242 | 135 | 14.7 | 7 | 2.4 | 0.047 |
| 32 | 66.399 | 1.4068 | 66.399 | 1.4068 | 247 | 116 | 12.6 | 7 | 2.4 | 0.054 |

* Intensity values are based on total raw counts.
ID: 960590 Ash From Combustion of Cleaned Coal (45kV, 40mA)
File: 960590.MDI  Scan: 5-70/02/2/#3251, Anode: CU  2T(0) = .02

Counts

1250-
1000-
750-
500-
250-
0-

2-Theta

1> 15-0776: Mullite, syn - Al6 Si2 O13
Advanced Coal Cleaning Process - Coal

UND ENERGY RESEARCH CENTER
COAL ANALYSIS REPORT

GF NUMBER: 96-0678
LAB NUMBER: 2847

DATE SAMPLED: 11/27/96
DATE RECEIVED: 12/02/96
DATE OF REPORT: 12/04/96

SAMPLE DESCRIPTION: CLEANED COAL

SUBMITTER: C. MORETTI

AIR DRY LOSS: 6.88%

|                | AS DET. (%) | AS REC'D (%) | MOIST FREE (%) | MOIST/ASH FREE (%) |
|----------------|-------------|--------------|----------------|--------------------|
| PROXIMATE ANALYSIS |             |              |                |                    |
| MOISTURE        | 0.65        | 7.50         | N/A            | N/A                |
| VOLATILE MATTER | 19.43       | 18.10        | 19.56          | 21.41              |
| FIXED CARBON (IND) | 71.35   | 66.43        | 71.82          | 78.59              |
| ASH             | 8.56        | 7.97         | 8.62           | N/A                |

ULTIMATE ANALYSIS

|                | AS DET. (%) | AS REC'D (%) | MOIST FREE (%) | MOIST/ASH FREE (%) |
|----------------|-------------|--------------|----------------|--------------------|
| HYDROGEN       | 4.44        | 4.90         | 4.40           | 4.81               |
| CARBON         | 82.61       | 76.93        | 83.15          | 90.99              |
| NITROGEN       | 1.31        | 1.22         | 1.32           | 1.44               |
| SULFUR         | 1.12        | 1.04         | 1.13           | 1.24               |
| OXYGEN (IND)   | 1.96        | 7.94         | 1.38           | 1.52               |
| ASH            | 8.56        | 7.97         | 8.62           | N/A                |

HEATING VALUE (BTU/LB)

|                | BTU          | CALC. CALORIFIC VALUE |
|----------------|--------------|-----------------------|
|                | 0            | 14443                 |

AS RECEIVED HYDROGEN NOT INCLUDING HYDROGEN FROM MOISTURE: 4.07%
AS RECEIVED OXYGEN NOT INCLUDING OXYGEN FROM MOISTURE: 1.28%

SULFUR FORMS

| SULFATE | ASH FUSION (DEGREES F) |
|---------|------------------------|
| N/A     | INIT. DEFORM. TEMP.    |
| PYTHON  | SOFTENING TEMP.        |
| ORGANIC | HEMISPHER. TEMP.       |
| N/A     | FLUID TEMP.            |

COMMENTS: Ash sample 2.36% SO3
Advanced Coal Cleaning Process - Coal

Final Results

| Sample     | 49308-01 cleaned coal       |
|------------|-----------------------------|
|            |                             |
| Aluminum   | 14500 µg/g                  |
| Arsenic    | 4.36 µg/g                   |
| Barium     | 70 µg/g                     |
| Cadmium    | 0.13 µg/g                   |
| Calcium    | 1820 µg/g                   |
| Chromium   | 22 µg/g                     |
| Iron       | 4780 µg/g                   |
| Lead       | 5.20 µg/g                   |
| Mercury    | 0.117 µg/g                  |
| Phosphorus | 707 µg/g                    |
| Potassium  | 740 µg/g                    |
| Selenium   | 3.0 µg/g                    |
| Silicon    | 16400 µg/g                  |
| Silver     | < 0.1 µg/g                  |
| Sodium     | 134 µg/g                    |
| Titanium   | 814 µg/g                    |

Set Number: 49308
Request Date: Wednesday, November 27, 1996
Fund#: 5420
Due Date: Wednesday, December 18, 1996
PI: Chuck Moretti
Set Description: Geochemical/Geotechnical Characterization of Advanced Coal Utilization Wastes
Contact Person: Chuck Moretti

December 16, 1996
APPENDIX J

WASTE THERMOGRAVIMETRIC ANALYSIS
GAS REBURNING SORBENT INJECTION - BOTTOM ASH
THERMOGRAVIMETRIC ANALYSIS

0.7550 % MOISTURE
(0.3279 mg)

13.97 % WEIGHT LOSS #1
(0.067 mg)

276.54°C

589.77°C

12.26 % WEIGHT LOSS #2
(5.526 mg)

0.6186 % COMBUST & OXID.
(0.2891 mg)

Residue: 72.40 %
(31.45 mg)

0 - 100
Time (min)

0 - 110
Weight (g)

0 - 40
Temperature (°C)

0 - 1000
Deriv. Weight (%/min)

TGA V4.0D DuPont 2100
GAS REBURNING SORBENT INJECTION - ESP FLY ASH
THERMOGRAVIMETRIC ANALYSIS

0.09447 % MOISTURE
(0.03627 mg)

0.6145 % WEIGHT LOSS#1
259.67 °C

2.336 % WEIGHT LOSS#2
580.42 °C

5.782 % WEIGHT LOSS#3
(2.220 mg)

5.334 % WEIGHT LOSS#4
(0.648 mg)

-0.1823 % OXIDATION
(-0.06231 mg)

Residue: 88.05 %
(33.04 mg)

TGA V4.0D DuPont 2100
PRESSURIZED FLUIDIZED BED - BOTTOM ASH THERMOGRAVIMETRIC ANALYSIS

Comment: HEAT #92-74 TO 100°C, 700°C, 1200°C IN ARGON THEN OXIDIZE; #5420

- 0.002625 % MOISTURE (0.00101 mg)
- 7.726 % WEIGHT LOSS #1 (3.240 mg)
- 2.512 % WEIGHT LOSS #2 (1.054 mg)
- 0.5124 % OXIDATION (0.2149 mg)
- Residue: 88.68 % (37.44 mg)

Weight (%) vs. Time (min) and Temperature (°C) graph.
PRESSURIZED FLUIDIZED BED - ESP FLY ASH
THERMOGRAVIMETRIC ANALYSIS

Comment: HEAT #82-78 TO 100°C, 700°C, 1200°C IN ARSON THEN OXIDIZE; #5420

1.921% MOISTURE (0.5913 mg)

40°C-105°C

229.84°C 1.260% WEIGHT LOSS #1
(0.3578 mg)

23.94% WEIGHT LOSS #2
(7.367 mg)

-0.1550% OXIDATION
(-0.04771 mg)

Residue:
73.077% (22.48 mg)

TGA V4.00 DuPont 100

Weight (%)

Temperature (°C)

Time (min)

Deriv. Weight (mg/min)

110

100

90

80

70

60

50

40

30

20

10

0

2.0

1.5

1.0

0.5

0.0

-0.5
COAL REBURNING - ESP FLY ASH
THERMOGRAVIMETRIC ANALYSIS

Comment: HEAT ESP HOPPER ASH TO 100°C, 700°C, 1200°C IN ARGON THEN OXIDIZE

- 0.04645 % MOISTURE (0.01908 mg)
- 16.33 % DECOMPOSITION (6.710 mg)
- -4.474 % OXIDATION (-1.838 mg)
- Residue: 68.11 % (36.20 mg)

Weight (%) vs. Time (min) vs. Temperature (°C)

TGA V4.0D DuPont 2100
COAL REBURNING - BOTTOM ASH (SLAG)
THERMOGRAVIMETRIC ANALYSIS

Comment: HEAT BOTTOM ASH TO 100°C, 700°C, 1150°C IN ARGON; THEN OXIDIZE; A95420

- 0.01727 % MOISTURE (0.007922 mg)
- 0.4996 % NET TRACE OXID. (-0.2294 mg) 994.93°C
- 0.3351 % OXIDATION (0.1537 mg)

Residue 100.0 % (46.26 mg)

TSA V4.0D DuPont 2100
SOx, NOx, ROx, BOx - SORBENT THERMOGRAVIMETRIC ANALYSIS

Comment: HEAT SITE E SORBENT IN ARGON TO 1100C THEN ADD AIR; A#5420

- 0.9830% MOISTURE (0.2968 mg)
- 133.52°C 68.06%
- 358.85°C 97.62%
- 524.80°C 78.50%
- 704.15°C 46.32%
- 1090.80°C 18.11%
- 1104.87°C 175.08%

AIR @ 85MINS; NEGLIGIBLE EFFECT

TGA V4.0D DuPont 2100
SOX, NOX, ROX, BOX - BAGHOUSE FLY ASH
THERMOGRAMMETRIC ANALYSIS

Comment: HEAT SITE E HOPPER ASH IN ARSON TO 1100C THEN ADD AIR; A#5420

Temperature (°C)

Time (min)

Deriv. Weight (%/min)

Weight (%)
LNB/AOFA - ESP FLY ASH
THERMOGRAVIMETRIC ANALYSIS

Sample: MORETTI'S HOPPER ASH UNIT#4
Size: 57.1252 mg
Method: MORETTI
Comment: HEAT HOPPER ASH UNIT#4 TO 1100°C; A#5420; PC#940253

File: A:940253.001
Operator: KULAS
Run Date: 3-Jun-94 08:53

Weight Loss

110
100
90
80

0.9609 % WEIGHT LOSS#1
(0.5489 mg)
455.85°C

0.6177 % WEIGHT LOSS#2
(0.3528 mg)
762.95°C

2.648 % WEIGHT LOSS#3
(1.513 mg)
1090.38°C

7.077 % OXID/COMBUST.
(4.043 mg)

Residue:
88.63 %
(50.63 mg)

Deriv. Weight (%/min)

Time (min)

TGA V4.0D DuPont 2100
LNB/AOFA - ECONOMIZER ASH
THERMOGRAVIMETRIC ANALYSIS

Sample: MORETTI'S ECONOM. ASH: UNIT#4
Size: 66.0393 mg
Method: MORETTI
Operator: KULAS
Run Date: 3-Jun-94 06:18

Comment: HEAT ECONOM. ASH: UNIT#4 TO 1100C; A#5420; PC#940254

---

1.769% WEIGHT LOSS

867.25°C

3.102% OXID. COMBUST.

Residue: 95.13%

110 -> 100

80 -> 90 -> 100

80 20 40 60 80 100

Time (min)

TGA V4.0D DuPont 2100

Deriv. Weight (%/min)
Sample: MORETTI'S BOTTOM ASH UNIT#4
Size: 102.2610 mg
Method: MORETTI
Comment: HEAT BOTTOM ASH UNIT#4 TO 1100°C; A#5420; PC#940255

TGA

File: A: 940255.001
Operator: KULAS
Run Date: 3-Jun-94 04:27

29.04% MOISTURE
(29.70 mg)

32.20% DECOMP.#1
(33.01 mg)

537.0°C

1.408% DECOMP.#2
(1.440 mg)

1102.03°C

1087.86°C

0.6770% OXIDATION
(0.6923 mg)

Residue:
36.60%
(37.42 mg)

Deriv. Weight (%/min)

Time (min)

TGA V4.0D DuPont 2100

Weight (%)
Advanced FGD Process - Spent Scrubber Waste
Thermogravimetric analysis

Sample: MORETTI'S 951174
Size: 62.1690 mg
Method: MORETTI
Comment: DRIVE OFF H2O; HEAT TO 700°C; THEN SLOWLY TO 1100°C; THEN OXIDIZE

TGA File: A:950867.001
Operator: KULAS
Run Date: 11-Dec-95 09:31

3.050 % MOISTURE
(1.896 mg)

18.76 % DECOMP. #2
(11.66 mg)

131.29°C

2.097 % DECOMP. #3
(1.304 mg)

0.03342 % OXIDATION
(0.02077 mg)

1000.74°C 1032.35°C

Residue: 75.62 % RESIDUE
(47.01 mg)

TGA V5.1A DuPont 2100
Advanced Coal Cleaning Process - Combustion Fly Ash
Thermogravimetric Analysis

Sample: CLEAN COAL ASH
Size: 49.8080 mg
Method: MORETTI
Comment: HEAT ASH IN ARGON; DRIVE OFF MOISTURE & DECOMPOSE MINERAL MATTER

1.647 % MOISTURE
(0.8201 mg)

20.00min
599.84°C
98.29%

30.00min
755.77°C
97.81%

60.00min
1012.43°C
95.61%

11.00min
144.30°C
98.36%

3.925 % DECOMP. VOL.'S
(1.955 mg)

40.00min
843.24°C
97.24%

50.00min
931.25°C
96.46%

7.471 % COMBUSTION
(3.721 mg)

80.00min
1105.05°C
86.98%

Residue: 86.98 %
(43.31 mg)

Temperature (°C)

Weight (%)
APPENDIX K

COAL BULK CHEMICAL COMPOSITION DATA
**REQUESTOR**

- Ed Olson

**PROJ. #**

- 5420

**SAMPLE INFO**

- UFDA Coal Sample

**DATE SUBMITTED**

- 5-21-92

**SAMPLE ID.**

- 92-0544

**LAB #**

- 42153

**PARAMETER**

**PROXIMATE**

- Moisture %: 14.70
- Volatile Matter %: 32.61
- Fixed Carbon (IND) %: 41.56
- Ash %: 11.12

**ULTIMATE**

- Hydrogen %: 5.61
- Carbon %: 59.19
- Nitrogen %: 1.08
- Sulfur %: 2.85
- Oxygen (IND) %: 20.12

**HEATING VALUE**

- 10540 BTU/LB

**DATE REPORTED**

- 6-29-92

**REPORTED BY**

- [Signature]

**DISTRIBUTION**

- [Signature]
| SAMPLE ID. | Coal |
|-----------|------|
| LAB #     | 42153|

### Parameter

| Oxides     | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|------------|---|---|---|---|---|---|---|
| SiO₂ %     | 6.34 |  |  |  |  |  |  |
| Al₂O₃ %    | 2.38 |  |  |  |  |  |  |
| Fe₂O₃ %    | 1.68 |  |  |  |  |  |  |
| CaO %      | 0.66 |  |  |  |  |  |  |
| MgO %      | 0.15 |  |  |  |  |  |  |
| Na₂O %     | 0.14 |  |  |  |  |  |  |
| K₂O %      | 0.27 |  |  |  |  |  |  |
| P₂O₅ %     | 0.03 |  |  |  |  |  |  |
| TiO₂ %     | 0.10 |  |  |  |  |  |  |
| Silver μg/g | 0.12 |  |  |  |  |  |  |
| Arsenic μg/g | 2.1 |  |  |  |  |  |  |
| Barium μg/g | 43 |  |  |  |  |  |  |
| Cadmium μg/g | <0.50 |  |  |  |  |  |  |
| Chromium μg/g | 31 |  |  |  |  |  |  |
| Lead μg/g | 4.3 |  |  |  |  |  |  |
| Mercury μg/g | 0.08 |  |  |  |  |  |  |
| Selenium μg/g | 2.7 |  |  |  |  |  |  |

DATE REPORTED: 6-29-92

REPORTED BY: [Signature]

DISTRIBUTION: [Signatures]
| PARAMETER       | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|-----------------|----|----|----|----|----|----|----|
| PROXIMATE       |    |    |    |    |    |    |    |
| Moisture        |    |    |    |    |    |    |    |
| Volatile Matter |    |    |    |    |    |    |    |
| Fixed Carbon (IND) | 5.60 |    |    |    |    |    |    |
| Ash             |    |    |    |    |    |    |    |
| ULTIMATE        |    |    |    |    |    |    |    |
| Hydrogen        |    |    |    |    |    |    |    |
| Carbon          |    |    |    |    |    |    |    |
| Nitrogen        |    |    |    |    |    |    |    |
| Sulfur          |    |    |    |    |    |    |    |
| Oxygen (IND)    |    |    |    |    |    |    |    |
| HEATING VALUE   | 12040 |    |    |    |    |    |    |
| BTU/LB          |    |    |    |    |    |    |    |

DATE REPORTED: 9-9-92

REPORTED BY: [Signature]

DISTRIBUTION: 9/1/92 C. Lilliston
**ANALYSIS REPORT FWHM**

**REQUESTOR**
Ed Olson

**PROJ. #**
5420

**SAMPLE INFO**
UFDA Coal Sample

**DATE SUBMITTED**
6-23-92

**SAMPLE ID.**
Coal

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Lab # | 42264

**PARAMETER**

**OXIDES**

| Oxide | %  |
|---|---|
| SiO₂ | 6.04 |
| Al₂O₃ | 2.37 |
| Fe₂O₃ | 3.60 |
| CaO | 0.16 |
| MgO | 0.12 |
| Na₂O | 0.04 |
| K₂O | 0.27 |
| P₂O₅ | 0.02 |
| TiO₂ | 0.12 |

| Element | ug/g |
|---|---|
| Silver | <.10 |
| Arsenic | 2.5 |
| Barium | 38 |
| Cadmium | <.50 |
| Chromium | 10 |
| Lead | 2.7 |
| Mercury | <.20 |
| Selenium | 1.5 |

**DATE REPORTED**
9-9-92

**REPORTED BY**

**DISTRIBUTION**
Coal Reburning Process - Coal Sample

| REQUESTOR       | Ed Olson                       |
|-----------------|--------------------------------|
| PROJ. #         | 5420                           |
| SAMPLE INFO     | UFDA COAL SITE "D"              |
| DATE SUBMITTED  | 11-6-92 AS RECEIVED VALUES REPORTED |
| SAMPLE ID.      | 92-1158                        |
| LAB #           | 43025                          |
| PARAMETER       |                                 |
| PROXIMATE       |                                 |
| Moisture        | % 16.70                        |
| Volatile Matter | % 31.61                        |
| Fixed Carbon (IND) | % 44.89                  |
| Ash             | % 6.79                         |
| ULTIMATE        |                                 |
| Hydrogen        | % 5.68                         |
| Carbon          | % 61.63                        |
| Nitrogen        | % 1.07                         |
| Sulfur          | % 1.64                         |
| Oxygen (IND)    | % 23.17                        |
| HEATING VALUE   |                                 |
| BTU/LB          | 11045                          |

DATE REPORTED: 2-16-93
REPORTED BY: [Signature]
DISTRIBUTION: 2-16-93 [Signature]
ANALYSIS REPORT FORM

REQUESTOR: Ed Olson
PROJ. #: 5420
SAMPLE INFO: UFDA DOE Site "D" 11/4/92
DATE SUBMITTED: 11-06-92

SAMPLE ID: Coal Cyclone Feeder

| Lab # | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|-------|----|----|----|----|----|----|----|
|       |    |    |    |    |    |    |    |

PARAMETER

| OXIDES |     |     |     |     |     |     |     |
|--------|-----|-----|-----|-----|-----|-----|-----|
| SiO₂   | %   |     |     |     |     |     |     |
| Al₂O₃  | %   |     |     |     |     |     |     |
| Fe₂O₃  | %   |     |     |     |     |     |     |
| CaO    | %   |     |     |     |     |     |     |
| MgO    | %   |     |     |     |     |     |     |
| Na₂O   | %   |     |     |     |     |     |     |
| K₂O    | %   |     |     |     |     |     |     |
| P₂O₅   | %   |     |     |     |     |     |     |
| TiO₂   | %   |     |     |     |     |     |     |

| Trace Elements | ug/g |     |     |     |     |     |     |
|----------------|------|-----|-----|-----|-----|-----|-----|
| Silver         | 0.22 |     |     |     |     |     |     |
| Arsenic        | 11   |     |     |     |     |     |     |
| Barium         | 36   |     |     |     |     |     |     |
| Cadmium        | 1.4  |     |     |     |     |     |     |
| Chromium       | 9.9  |     |     |     |     |     |     |
| Lead           | 6.6  |     |     |     |     |     |     |
| Mercury        | 0.057|     |     |     |     |     |     |
| Selenium       | 2.5  |     |     |     |     |     |     |

DATE REPORTED: 2-11-93
REPORTED BY: (Signature)
DISTRIBUTION: 1-16-93
## ANALYSIS REPORT FORM

**REQUESTOR**
Ed Olson

**PROJ. #**
5420

**SAMPLE INFO**
UFDA COAL SITE "E"

**DATE SUBMITTED**
1-14-93 AS RECEIVED VALUES REPORTED

**SAMPLE ID.**
93-0031

**LAB #**
43620

### PROXIMATE

| PARAMETER         | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|-------------------|----|----|----|----|----|----|----|
| Moisture          | %  |    |    |    |    |    |    |
| %                 | 1.60|    |    |    |    |    |    |
| Volatile Matter   | %  |    |    |    |    |    |    |
| %                 | 36.96|    |    |    |    |    |    |
| Fixed Carbon (IND)| %  |    |    |    |    |    |    |
| %                 | 49.53|    |    |    |    |    |    |
| Ash               | %  |    |    |    |    |    |    |
| %                 | 11.90|    |    |    |    |    |    |

### ULTIMATE

| PARAMETER         | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|-------------------|----|----|----|----|----|----|----|
| Hydrogen          | %  |    |    |    |    |    |    |
| %                 | 4.62|    |    |    |    |    |    |
| Carbon            | %  |    |    |    |    |    |    |
| %                 | 68.95|    |    |    |    |    |    |
| Nitrogen          | %  |    |    |    |    |    |    |
| %                 | 1.18|    |    |    |    |    |    |
| Sulfur            | %  |    |    |    |    |    |    |
| %                 | 4.03|    |    |    |    |    |    |
| Oxygen (IND)      | %  |    |    |    |    |    |    |
| %                 | 9.29|    |    |    |    |    |    |

### HEATING VALUE

| PARAMETER         | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|-------------------|----|----|----|----|----|----|----|
| BTU/LB            |    |    |    |    |    |    |    |
|                   | 12652|    |    |    |    |    |    |

**DATE REPORTED**
5-13-93

**REPORTED BY**

**DISTRIBUTION**
5-13-93
## ANALYSIS REPORT FORM

**REQUESTOR:** Ed Olson  
**PROJ. #:** 5420  
**SAMPLE INFO:** UFDA DOE SITE "E"  
**DATE SUBMITTED:** 1-14-93

**SAMPLE ID:**

|   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
|   | Coal |   |   |   |   |   |   |

**LAB #**

|   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
|   | 43620 |   |   |   |   |   |   |

**PARAMETER**

### OXIDES

| Oxide | %   |
|---|---|
| SiO₂ | 5.73 |
| Al₂O₃ | 2.29 |
| Fe₂O₃ | 3.37 |
| CaO | 0.29 |
| MgO | 0.10 |
| Na₂O | 0.04 |
| K₂O | 0.22 |
| P₂O₅ | 0.02 |
| TiO₂ | 0.11 |

### Metal Concentrations (ug/g)

| Element |  |
|---|---|
| Silver | <0.1 |
| Arsenic | 16 |
| Barium | 47 |
| Cadmium | 0.18 |
| Chromium | 16 |
| Lead | 8.9 |
| Mercury | 0.25 |
| Selenium | 2.4 |

**ANALYSIS ON DRY BASIS**

**DATE REPORTED:** 5-13-93

**REPORTED BY:** [Signature]  
**DISTRIBUTION:** 5-13-93
| REQUESTOR     | Ed Olson          |
|--------------|-------------------|
| PROJ. #      | 5420              |
| SAMPLE INFO  | UFDA COAL SITE "F"|
| DATE SUBMITTED | 8-5-93 (AS RECEIVED VALUES REPORTED) |

| SAMPLE ID. | COAL |
|------------|------|
| 93-0568    |      |

| LAB # | 44631 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-------|-------|---|---|---|---|---|---|---|

| PARAMETER          | PROXIMATE |         |         |         |         |         |         |         |
|--------------------|-----------|---------|---------|---------|---------|---------|---------|---------|
| Moisture           | %         | 6.10    |         |         |         |         |         |         |
| Volatile Matter    | %         | 29.12   |         |         |         |         |         |         |
| Fixed Carbon (IND)| %         | 54.66   |         |         |         |         |         |         |
| Ash                | %         | 10.12   |         |         |         |         |         |         |

| ULTIMATE          |         |         |         |         |         |         |         |         |
| Hydrogen          | %         | 4.77    |         |         |         |         |         |         |
| Carbon            | %         | 70.53   |         |         |         |         |         |         |
| Nitrogen          | %         | 1.22    |         |         |         |         |         |         |
| Sulfur            | %         | 1.68    |         |         |         |         |         |         |
| Oxygen (IND)      | %         | 11.69   |         |         |         |         |         |         |

| HEATING VALUE     |         |         |         |         |         |         |         |         |
| BTU/LB            |         | 12598   |         |         |         |         |         |         |

| DATE REPORTED     | 10-6-93 |
| REPORTED BY       | G. H.   |
| DISTRIBUTION      | 10-6-93  |

Signature: [Signature]
ANALYSIS REPORT FORM

REQUESTOR: Ed Olson
PROJ. #: 5420
SAMPLE INFO: UFDA DOE SITE "F"
DATE SUBMITTED: 8-5-93

SAMPLE ID.
EER #: 155460
LAB #: 44631

PARAMETER
OXIDES

| Parameter | Value |
|-----------|-------|
| SiO2 %    | 5.32  |
| Al2O3 %   | 2.69  |
| Fe2O3 %   | 1.31  |
| CaO %     | 0.12  |
| MgO %     | 0.11  |
| Na2O %    | 0.04  |
| K2O %     | 0.30  |
| P2O5 %    | 0.02  |
| TiO2 %    | 0.14  |
| BaO %     | 0.01  |
| Silver ug/g | <0.1 |
| Arsenic ug/g | 20 |
| Cadmium ug/g | <0.1 |
| Chromium ug/g | 19 |
| Lead ug/g   | 1.2   |
| Mercury ug/g | 0.08 |
| Selenium ug/g | 2.9 |

ANALYSES ON DRY BASIS

DATE REPORTED: 10-6-93

REPORTED BY: [Signature]
DISTRIBUTION: 10-6-93 [Signature]
**Advanced Coal Cleaning Process - Coal**

**UNI Energy Research Center**

**Coal Analysis Report**

**GF Number:** 96-0678  
**LAB Number:** 2847

**Date Sampled:** 11/27/96  
**Date Received:** 12/02/96  
**Date of Report:** 12/04/96

**Sample Description:** Cleaned Coal

**Submitter:** C. Moretti

**Air Dry Loss:** 6.88%

|        | As Det. (%) | As Recd. (%) | Moist Free (%) | Moist/Ash (%) |
|--------|-------------|--------------|----------------|---------------|
| Moisture                     | 0.65         | 7.50         | N/A            | N/A           |
| Volatile Matter              | 19.43        | 18.10        | 19.56          | 21.41         |
| Fixed Carbon (Ind)           | 71.35        | 66.43        | 71.82          | 78.59         |
| Ash                           | 8.56         | 7.97         | 8.62           | N/A           |

**Ultimate Analysis**

|        | As Det. (%) | As Recd. (%) | Moist Free (%) | Moist/Ash (%) |
|--------|-------------|--------------|----------------|---------------|
| Hydrogen                     | 4.44         | 4.90         | 4.40           | 4.81          |
| Carbon                        | 82.61        | 76.93        | 83.15          | 90.99         |
| Nitrogen                      | 1.12         | 1.04         | 1.13           | 1.24          |
| Sulfur                        | 1.96         | 7.94         | 1.38           | 1.52          |
| Oxygen (Ind)                  | 8.56         | 7.97         | 8.62           | N/A           |

**Heating Value (BTU/LB)**

|        | BTU          | Calc. Calorific Value |
|--------|--------------|-----------------------|
|        | 0            | 14443                 |

**As Received Hydrogen not Including Hydrogen from Moisture:** 4.07%

**As Received Oxygen not Including Oxygen from Moisture:** 1.28%

**Sulfur Forms**

|        | Ash Fusion (Degrees F) |
|--------|-------------------------|
| Sulfate| N/A                    |
| Pyritic| N/A                    |
| Organic| N/A                    |

**Comments:** Ash sample 2.36% S03
Advanced Coal Cleaning Process - Coal

Final Results

Set Number: 49308
Fund#: 5420
PI: Chuck Moretti

Request Date: Wednesday, November 27, 1996
Due Date: Wednesday, December 18, 1996
Set Description: Geochemical/Geotechnical Characterization of Advanced Coal Utilization Wastes
Contact Person: Chuck Moretti

Sample 49308-01 cleaned coal

| Element   | Concentration (µg/g) |
|-----------|----------------------|
| Aluminum  | 14500                |
| Arsenic   | 4.36                 |
| Barium    | 70                   |
| Cadmium   | 0.13                 |
| Calcium   | 1820                 |
| Chromium  | 22                   |
| Iron      | 4780                 |
| Lead      | 5.20                 |
| Mercury   | 0.117                |
| Phosphorus| 707                  |
| Potassium | 740                  |
| Selenium | 3.0                  |
| Silicon   | 16400                |
| Silver    | < 0.1                |
| Sodium    | 134                  |
| Titanium  | 814                  |

Geochemical/Geotechnical Characterization of Advanced Coal Utilization Wastes

Chuck Moretti

December 16, 1996