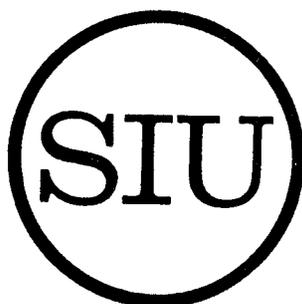


Proceedings of

**COAL COMBUSTION BY-PRODUCTS  
ASSOCIATED WITH COAL MINING -  
INTERACTIVE FORUM**

Southern Illinois University  
at Carbondale  
October 29-31, 1996



*Edited by:*  
Yoginder P. Chugh  
Brandi M. Sangunett  
Kimery C. Vories

*Sponsored by:*  
U.S. Department of the Interior, Office of Surface Mining, Alton, Illinois  
Coal Combustion Residues Management Program, and  
Mining Engineering Department, Southern Illinois University at Carbondale

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# Coal Combustion By-Products Associated with Coal Mining Interactive Forum

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## Foreword

Over the last decade, management of coal combustion by-products (CCBs) in mining areas has assumed significant importance as landfilling costs have increased at an accelerated pace. Mined-out areas provide a natural habitat for coal combustion by-products, provided their engineering and environmental characteristics can be utilized in areas such as structural fill, road construction, soil modification, and acid mine drainage and subsidence control.

Coal Combustion By-Products Associated with Coal Mining- Interactive Forum was organized to share experts and experience from throughout the U.S. and to compile an authoritative technical reference on the subject. The forum successfully achieved both these goals based on attendance, quality of presentations, and quality of proceedings.

Southern Illinois University at Carbondale, was pleased to host the forum. The co-sponsorship of the forum is truly impressive and I extend my sincere thanks to all the organizations for their efforts in making this forum a success. I would also like to take this opportunity to thank the members of the steering committee, chairs and co-chairs of the sessions, authors and co-authors of technical presentations, discussion panelists, and exhibitors for their interest and involvement in the forum. Without their support, the forum would not have been a success.

The papers were reviewed technically and editorially to develop a high quality proceedings. The proceedings also include a discussion for each session and the outcomes of Workgroup deliberations.

Once again, thanks to each and every one of you for participating in the forum and making it a tremendous success.

Yoginder P. Chugh  
December 28, 1996

## List of Acronyms

AMD	Acid mine drainage
ARS	Agricultural Research Service
ASTM	American Society for Testing and Materials
CCB	Coal combustion by-product
CCBs	Coal combustion by-products
CCW	Coal combustion waste
CLSM	Controlled low strength material
DNR	Department of Natural Resources
DOE	Department of Energy
DTPA	Diethylamine-triamine-penta-acetic acid
EERC	Energy and Environmental Research Center
EPRI	Electric Power Research Institute
FBC	Fluidized bed combustion
FGD	Flue gas desulfurization
ICCI	Illinois Clean Coal Institute
OSM	Office of Surface Mining
PFBC	Pulverized fluidized bed combustion
ppm	parts per million
psi	pounds per square inch
RCRA	Resource Conservaton and Recovery Act
SGLP	Synthetic groundwater leaching procedure
SIUC	Southern Illinois University at Carbondale
SMCRA	Surface Mining Control Reclamation Act
TCLP	Toxicity characteristic leaching procedure
TVA	Tennessee Valley Authority
U.S.	United States
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WRI	Western Research Institute

**Session I:**

**COAL COMBUSTION BY-PRODUCTS  
CHARACTERIZATION**

**Session Chairs:**

**Bill Joseph  
Office of Surface Mining  
Alton, Illinois**

**Kim Vories  
Office of Surface Mining  
Alton, Illinois**

**Panelist:**

**Dr. Rustu Kalyoncu  
USGS Minerals Information Team  
Reston, Virginia**

# LEACHING TESTS: COMMONLY USED METHODS, EXAMPLES OF APPLICATIONS TO COAL COMBUSTION BY-PRODUCTS, AND NEEDS FOR THE NEXT GENERATION

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## Abstract

There are a variety of tests available for characterizing the leaching behavior of waste materials. These vary in test type, leaching aspects that are addressed, and the particular use for which the test is designed. Types of leaching tests include agitated extraction tests, serial batch tests, flow-through tests, flow-around tests, etc. These tests address different aspects of leaching, such as the physical mechanisms involved, chemical interactions between the waste and the leaching fluid, the kinetics of leaching, leaching as a function of time, etc. Some of the uses of leaching tests include regulatory purposes, scientific research, and environmental assessment. This paper discusses some of the commonly used leaching methods, results of specific application of some of these to coal combustion by-products, and what is needed for the next generation of test methods to more accurately assess the release of contaminants into the environment.

## Introduction

There are a variety of leaching tests available for application to waste materials. A leaching test involves contacting the waste material with a liquid to determine which constituents will be leached by the liquid and released to the environment. Leaching methods vary in test type, leaching aspects addressed, and the particular use for which the test is designed. Types of leaching tests include agitated extraction tests, serial batch tests, flow-through tests, flow-around tests, etc. These tests address different aspects of leaching, such as the physical mechanisms involved, chemical interactions between the waste and the leaching fluid, the kinetics of leaching, leaching as a function of time, etc. Some of the uses of leaching tests include regulatory purposes, environmental impact assessment, scientific studies, and waste management. Commonly used leaching procedures in the United States include those developed by the U.S. Environmental Protection Agency (EPA) and the American Society for Testing and Materials (ASTM). In addition, there are a number of leaching methods commonly being used in Canada and the European countries.

The purpose of this paper is to discuss (1) some of the commonly used leaching methods, (2) results of specific application of some of these to coal combustion by-products, and (3) what is needed for the next generation of test methods to more accurately assess the release of contaminants into the environment.

## Commonly Used Leaching Procedures

A number of leaching procedures have been developed in the United States over the last two decades. The U.S. EPA and ASTM Committee D-34 on Waste Management have been primarily responsible for these method development activities. A brief summary of EPA and ASTM leaching methods is given below. State regulatory agencies have adopted variations of these methods; however, discussion of the state methods is beyond the scope of this paper.

### EPA Methods

*Toxicity Characteristic Leaching Procedure (TCLP) (U.S. EPA Method 1311):* The TCLP (U.S. EPA 1990c) is designed to simulate the leaching a waste will undergo if disposed in an unlined sanitary landfill. It is based on a co-disposal scenario of 95% municipal waste and 5% industrial waste. The method is an agitated extraction test using leaching fluid that is a function of the alkalinity of the solid

phase of the waste. Either a sodium acetate buffer solution having a pH of  $4.93 \pm 0.05$  or an acetic acid solution having a pH of  $2.88 \pm 0.05$  is used. The procedure requires particle size reduction to less than 9.5 mm. The TCLP is designed to determine the mobility of 40 Toxicity Characteristic (TC) constituents in liquid, solid, and multiphase wastes. The TC constituents include both inorganic and organic species. Leachability of volatile organic compounds is determined using a zero-headspace extractor and the sodium acetate buffer solution.

The TCLP was developed in 1984 under the Hazardous and Solid Waste Amendments to the Resource Conservation and Recovery Act (RCRA) (1984) and is the U.S. EPA regulatory method for classifying wastes as hazardous or nonhazardous based on toxicity. If the TCLP extract contains any one of the TC constituents in an amount equal to or greater than the concentrations specified in 40 CFR 261.24 (1992), the waste possesses the characteristic of toxicity and is a hazardous waste.

*Synthetic Precipitation Leaching Procedure (SPLP) (U.S. EPA Method 1312):* The SPLP (U.S. EPA 1990a), which is an agitated extraction method, was developed in 1988 by the U.S. EPA for use in evaluating the impact that contaminated soils may have on groundwater. The procedure calls for use of simulated acid rain or reagent water as the extraction fluid, depending on the constituents of interest. The extraction fluid used to determine the leachability of soil from a site that is east of the Mississippi River is a solution of sulfuric and nitric acids in reagent water having a pH of  $4.2 \pm 0.05$ . This extraction fluid is also used to extract waste or wastewater using the procedure. The extraction fluid used to determine the leachability of soil from a site that is west of the Mississippi River is a solution of sulfuric and nitric acids in reagent water having a pH of  $5.0 \pm 0.05$ . When the leachability of volatile organic compounds or cyanide is being evaluated, reagent water is used as the extraction fluid. The procedure requires particle size reduction to less than 9.5 mm, and as with the TCLP, extraction for volatile constituents is performed in a zero-headspace extractor.

*Multiple Extraction Procedure (MEP) (U.S. EPA Method 1320):* The MEP (U.S. EPA 1990b) is designed to simulate the leaching a waste will undergo from repeated precipitation of acid rain on an improperly designed sanitary landfill. The repetitive extractions are to reveal the highest concentration of each constituent that is likely to leach in a natural landfill (U.S. EPA 1990b).

The MEP is a serial batch test in which the first extraction is performed according to the Extraction Procedure (EP) Toxicity Test (U.S. EPA 1980). The EP is the U.S. EPA regulatory method that was replaced by the TCLP for determining the characteristic of toxicity. It is a leaching procedure that involves monitoring the pH of the waste in reagent water and using an acetic acid solution to maintain the pH of the slurry at  $5.0 \pm 0.2$ . After the first extraction in the MEP is completed, the remaining solid is re-extracted nine times (or more) using synthetic acid rain as the leaching fluid. If the concentration of any constituent of concern increases from the 7th or 8th extraction to the 9th extraction, the procedure is repeated until the concentrations decrease. The synthetic acid rain leaching fluid is prepared by adding the appropriate amount of a 60/40 weight percent sulfuric acid and nitric acid mixture to distilled, deionized water to give a pH of  $3.0 \pm 0.2$ . The method is applicable to liquid, solid, and multiphase materials.

#### ASTM Standard Methods

*ASTM Method D-3987, Standard Test Method for Shake Extraction of Solid Waste with Water (ASTM 1995a):* This method is a procedure for rapidly generating a leachate from solid waste that can be used to estimate the mobility of inorganic constituents from the waste under the specified test conditions (ASTM 1995a). The final pH of the leachate is to reflect the interaction of the leaching fluid with the buffering capacity of the waste. In the method, it is stated that the procedure is not intended to produce a leachate representative of leachate generated in the field, and the method does not simulate site-specific leaching conditions (ASTM 1995a).

ASTM Method D-3987 is an agitated extraction method that uses reagent water as the leaching fluid. The procedure involves an 18-hour contact time between a solid waste and reagent water with rotary agitation. The method calls for testing a representative sample of the waste, and as a result, it does not require particle size reduction. The method has been tested to determine its applicability to inorganic constituents, but it has not been tested for application to organic constituents.

*ASTM Method D-4793, Standard Test Method for Sequential Batch Extraction of Waste with Water (ASTM 1995b):* This method is a procedure for obtaining serial leachates of a waste that can be used to estimate the mobility of inorganic constituents from the waste under the specified test conditions (ASTM 1995b). The final pH of the leachate is intended to reflect the interaction of the leaching fluid with the buffering capacity of the waste (ASTM 1995b). Similar to ASTM Method D-3987, this method also contains statements that it is not intended to produce leachates representative of leachate generated in the field, and that it does not simulate site-specific conditions (ASTM 1995b).

ASTM Method D-4793 is a serial batch test that uses reagent water as the leaching fluid. The method has been tested for its applicability to inorganic constituents only and can be used to test any waste containing at least five percent solids. The leaching steps are repeated so that ten leachates are generated.

*ASTM Method D-5284, Standard Test Method for Sequential Batch Extraction of Waste with Acidic Extraction Fluid (ASTM 1995e):* This method is a modification of ASTM Method D-4793. It calls for use of a leaching fluid having a pH that reflects the pH of acidic precipitation in the geographic region in which the waste being tested is to be disposed (ASTM 1995e). The leaching fluid is prepared by mixing a 60/40 weight percent mixture of sulfuric acid/nitric acid with reagent water. This method has only been tested for its use in leaching inorganic constituents. The information given in the method concerning its intent and limitations is the same as described above for ASTM Method D-4793.

*ASTM Method D-5233, Standard Test Method for Single Batch Extraction Method for Wastes (ASTM 1995d):* This is an agitated extraction test that is very similar to TCLP. The major difference between the two procedures is that ASTM Method D-5233 does not require particle size reduction. The method states that it is applicable for leaching samples of treated or untreated solid wastes or sludges, or solidified waste samples, to provide an indication of the leaching potential (ASTM 1995d). This method is based on the same disposal scenario as TCLP, a sanitary landfill with co-disposal of 95% municipal waste and 5% industrial waste. According to the method, interpretation and use of the test results are limited by the assumption of a single co-disposal scenario and by differences between the extraction fluid used in the method and the real landfill leachate (ASTM 1995d).

*ASTM Method D-4874, Standard Test Method for Leaching Solid Waste in a Column Apparatus (ASTM 1995c):* This is a column method using reagent water in a continuous up-flow mode to generate aqueous leachate from waste materials. The current published version of the method (ASTM 1995c) is applicable for evaluating the leachability of inorganic constituents. However, a revised method will be published in 1996 (ASTM 1996) that can be used to evaluate the leachability of semivolatile and nonvolatile organic compounds, as well as inorganic constituents. The column method is intended to provide aqueous leaching in a dynamic partitioning manner (ASTM 1995c). It is written so that many of the specific column operating conditions can be selected by the user to meet their specific objectives (ASTM 1995c). The method states that analysis of the column effluent can provide information on the leaching characteristics of the waste under the testing conditions used (ASTM 1995c). It is also stated that the method is not intended to produce results to be used as the sole basis for (1) the engineering design of a landfill disposal site or (2) classification of wastes based on leaching characteristics (ASTM 1995c).

There are also a number of leaching methods that are being used in Canada and the European countries. Some of the commonly used international procedures are described below.

## Canadian Methods

*Leachate Extraction Procedure (LEP):* The LEP (Ministry of the Environment 1985) is an agitated extraction test that is the regulatory leaching test used in the province of Ontario, Canada. In addition, this method is identical to the regulatory leaching procedure used by the Canadian provinces of British Columbia, Alberta, and Manitoba (Environment Canada 1990). The test is very similar to the EP Toxicity Test. As previously mentioned, the EP involves monitoring the pH of the waste in reagent water and using acetic acid solution to maintain the pH of the slurry at  $5.0 \pm 0.2$ . The EP is based on a single co-disposal scenario of industrial waste in a municipal landfill (U.S. EPA 1980).

*Quebec R.s.Q. (Q.R.s.Q.):* The Q.R.s.Q. (Ministere de L'Environnement 1985) is an agitated extraction test that is the regulatory leaching method used in the province of Quebec, Canada. It is very similar to the TCLP, with some procedural differences (Environment Canada 1990).

## European Methods

*Availability Test (NEN 7341):* The availability test (Netherlands Normalization Institute 1993a) is an agitated extraction method that was developed in the Netherlands. It is based on leaching a finely ground sample under two controlled pH conditions, pH = 4 and pH = 7. The purpose of the test is to indicate the quantity of an element that may be leached from a material under environmentally extreme conditions, e.g. in the very long term, after disintegration of the material, when the material is fully oxidized, and with complete loss of acid neutralization capacity (de Groot and Hoede 1994).

*Column Test (NEN 7343):* The NEN 7343 column test (Netherlands Normalization Institute 1993b) is believed to simulate the leaching behavior of a waste material in the short, medium, and long term (van der Sloot 1995). This is done by relating contaminant release, expressed as mg/Kg leached, to the liquid-to-solid ratio (van der Sloot 1995). The time scale relation is obtained from the height of the column and rate of infiltration (van der Sloot 1995). The procedure involves passing demineralized water (pH = 4) upward through ground material (95% < 4 mm). Seven consecutive leachate fractions are collected, corresponding to a liquid-to-solid ratio range of 0.1 to 10 L/Kg (de Groot and Hoede 1994). van der Sloot (1995) states that very slow changes in mineral composition are not addressed by this test; and NEN 7343 test conditions do not correlate on a one-to-one basis with field conditions because several variables, such as temperature, channeling, aging, and degree and length of contact, must be considered.

*French Leach Test (Agence Francaise de Normulisation 1987):* This is an agitated extraction test that is a French Ministry of the Environment standard regulatory method for determining the soluble fraction of a solid waste in an aqueous solution (Environment Canada 1990). It requires particle size reduction and involves mechanical stirring of the sample with water in a 10:1 liquid-to-solid ratio for 16 hours. A second and third extraction are performed, and the cumulative extracted soluble fraction for each constituent can be determined.

*Germun Leach Test (DIN 38414 S4) (Institut fur Normung 1984):* This is the leaching test that is generally used in Germany (Rankers and Hohberg 1991). It is an agitated extraction test involving table shaking of the extraction slurry for 24 hours. The liquid-to-solid ratio is 10: 1. The method is applicable to solids, pastes, and sludges (van der Sloot 1995). Advantages of the method are its rapidity, extremely good reproducibility, and simplicity. However, the method is criticized for its use of a 10: 1 liquid-to-solid ratio, which is rarely reached under landfill conditions (Rankers and Hohberg 199 1).

*TVA (TVA 1988):* This agitated extraction test is the standard regulatory method used in Switzerland. The method calls for 100 to 200 grams of sample to be extracted using carbon dioxide-saturated water at a liquid-to-solid ratio of 10:1 for 24 hours. The continuous carbon dioxide injection is considered to represent a time-scale reduction (van der Sloot 1995).

## **Examples of Applications of Leaching Tests to Coal Combustion By-Products**

Several studies have been conducted in which coal combustion by-products have been tested by a variety of leaching methods. Listed below are just a few examples of studies involving leaching of coal combustion by-products using some of the specific leaching methods described above.

### TCLP Applied to Utility Wastes

Following proposal of the TCLP to replace the EP for hazardous-waste classification, the Electric Power Research Institute (EPRI) funded a study to evaluate application of the TCLP to utility wastes (Jackson and Sorini 1987). This study involved testing 41 electric utility wastes produced by conventional and advanced sulfur dioxide control technologies to obtain information on the results of testing these materials using TCLP test conditions and to compare TCLP and EP results. The study evaluated three aspects of the TCLP: (1) the effect of increasing the filter pore size from 0.45- $\mu\text{m}$  in the EP to 0.6-0.8- $\mu\text{m}$  in the TCLP; (2) the effect of changing the composition of the leaching fluid on the concentrations of the inorganic analytes in the leachates; and (3) the concentrations of organic compounds in the TCLP leachates of the coal combustion by-products. The results of the study show the following (Sorini and Jackson 1988): (1) the change in filter pore size does not affect the composition of the coal combustion waste leachates; (2) the TCLP is more aggressive than the EP towards leaching silver, arsenic, and chromium from the wastes tested, while the EP is more aggressive towards leaching barium, and selenium is equally well leached by both TCLP and EP; and (3) the concentrations of the TC organic compounds leached from the coal combustion by-products were very low, mostly in the low parts-per-billion range.

EPRI also sponsored a round-robin study to compare the results of the TCLP with those generated by the EP (Mason and Carlile 1986). In this study, three laboratories extracted seven utility wastes and determined the concentrations of 14 constituents in the resulting leachates. Data generated in the study show that the reproducibility of the TCLP and EP methods varied between constituent, type of utility waste, and method. The concentrations of the analytes of interest were generally higher in the TCLP leachates than in the EP leachates.

### Leachability of Lead from Fly Ash Using the TCLP Sodium Acetate Buffer Solution as the Leaching Fluid

A study was conducted to evaluate the effects of pH and extraction fluid composition on the leachability of lead and arsenic from fly ash (Sorini and Brown 1993). One of the testing conditions that was evaluated was TCLP extraction of the fly ash using the sodium acetate buffer solution. Results of this study definitely show that acetate complexation of lead species prevents precipitation of lead minerals, and as a result, increases extractable lead concentrations. This is an example of where the co-disposal scenario represented by TCLP, which does not represent a typical disposal scenario for fly ash, results in over estimation of the amount of lead that would be leached from the material.

### Development of ASTM Method D-3987, Standard Test Method for Shake Extraction of Solid Waste with Water, and Its Application to Fossil Energy Wastes

During the time of EPA's proposal to classify wastes as hazardous or nonhazardous based on the EP test method, a research team became involved with ASTM and worked on development of ASTM Method D-3987 (Jackson and Moore 1984). Since fossil energy wastes are normally disposed in sites where they are the only waste type, the co-disposal scenario represented by the EP (9.5% municipal waste co-disposed with 5% industrial waste in a sanitary landfill) did not seem appropriate for these types of materials. As a result, ASTM Method D-3987, which uses reagent water as the leaching fluid and is believed to be more representative of the leaching environment found at fossil energy waste disposal sites (Jackson and Moore 1984) was developed.

Jackson and Moore (1984) describe a study in which 18 fossil energy wastes were tested using the ASTM and EP methods. The results of the study showed that most of the wastes tested gave very low concentrations of the eight RCRA metals in their leachates, and that none of the concentrations of these metals in the ASTM or EP leachates exceeded the regulatory levels.

There are some differences between the original ASTM Method D-3987 (Jackson and Moore 1984) and the current version of the method (ASTM 1995a). However, both versions require use of reagent water as the leaching fluid, and both allow the final pH of the leachate to reflect the interaction of the leaching fluid with the waste.

#### Evaluation of NEN Methods 7341 and 7343 Applied to Fly Ash

According to Janssen-Jurkovicova et al. (1994), NEN 7341 (availability test) and NEN 7343 (column test) are laboratory leachability tests that were introduced by the Dutch Standardization Institute for evaluating the leaching behavior of granular materials and /or fly ash. A study they conducted evaluated the correlation between leaching behavior of fly ash simulated by the NEN 7343 column method and leaching of fly ash occurring in a field lysimeter. The results of the study show discrepancy between data generated by applying the column test to fly ash and data generated by analyzing the lysimeter leachate. The reason given in the paper for this discrepancy is that the test conditions (e.g. time, pH, Eh) under which the column method is performed vary considerably from natural conditions, and this results in different leaching behavior of the material. The study also showed that the concentration of an element leached by standard tests can be much higher than expected based on the results of the availability test (NEN 7341). As a result, it was concluded that the availability test does not accurately predict the maximum elemental concentrations available for leaching from fly ash. The findings of the study also indicate that results of the column method do not provide sufficient information to relate the liquid-to-solid ratio used in the method to a time scale under field conditions. The authors of the paper describing this study propose development of a model to predict field leaching based on column leachate data.

#### **Future Direction of Leachability/Mobility Methods Development**

The applications of leaching methods to coal combustion by-products described above provide data that are specific to the particular application. However, these data provide little information for accurately assessing the release of contaminants from the materials into the environment. As pointed out in the descriptions of the leaching methods and the examples of their application to coal combustion by-products, these methods have deficiencies, such as modeling a single disposal scenario, not being intended to produce leachate representative of leachate generated in the field, specifying test conditions that do not correlate with field conditions, etc. As a result, there is a need for a new generation of test methods that address the deficiencies listed above. The U.S. EPA Science Advisory Board (SAB) has recommended that development of a leaching method to characterize the leachability/mobility of wastes involve the following: (1) a better understanding of the mechanisms controlling leaching, (2) multiple tests to address different disposal scenarios, (3) improved models to complement the leaching tests, and (4) field validation of leaching tests and predictive models (U.S. EPA SAB 1991).

Recently, there has been a move towards developing leaching methods that involve multiple procedures. Because a single leaching test cannot address all leaching aspects, van der Sloot (1995) describes combining existing procedures to address the particular leaching parameters of concern. He refers to this as a "concise test."

ASTM Task Group D-34.02.01 on Waste Leaching Techniques has also been working on developing a draft method for determining the leachability/mobility of wastes. Proposed aspects of this method are use of multiple procedures, such as a serial batch test and column test, and design of the method for site-specific applications, so that test parameters, e.g. leaching fluid composition and pH, soil type, etc., can be adjusted to accommodate specific disposal/management scenarios. In addition, at a recent task group meeting, a method for characterizing leachability by evaluating fundamental parameters, such as

constituent solubility, availability, and diffusivity, was discussed (Garrabrants et al. 1995). The method involves applying a number of characterization procedures, including leaching tests and physical tests, to the material being evaluated.

With particular relation to coal combustion by-products, Kosson et al. (1996) describe an approach to estimate constituent release from disposal and utilization of municipal waste combustion residues. The approach described varies greatly from use of a single test to predict leaching behavior. It involves use of portions of the method described above (Garrabrants et al. 1995) to measure fundamental leaching parameters, mathematical modeling to extrapolate laboratory results to field scenarios, and field verification.

In addition, Hassett et al. (1992) describe a study in which a solid scrubber residue was characterized by (1) qualitative screening to identify the elements present, (2) quantitative determination of total concentrations of selected elements, (3) determination of mineral phases present, and (4) application of selected leaching procedures. The leaching methods that were used were TCLP, a synthetic groundwater leaching procedure (SGLP), and a long-term leaching procedure.

The SGLP is a generic agitated extraction procedure that was developed to (1) simulate natural groundwater conditions with respect to groundwater chemistry, (2) be flexible enough to be site specific, and (3) be directly comparable to the TCLP (Hassett 1987). The steps in the method are the same as those performed in the TCLP, except synthetic groundwater is used in place of the specified acetic acid solution or sodium acetate buffer solution. Since the test is generic, any composition of leaching fluid can be used to simulate the groundwater chemistry of any location (Hassett 1987).

The long-term leaching procedure was performed to evaluate mineralogical changes occurring in the waste during long-term contact with water. Samples were analyzed after 18 hours, 48 hours, 1 week, 4 weeks, and 12 weeks of contact.

In the study, results of the various characterizations performed were used in combination to make conclusions concerning environmental impact of the material. For example, solubility trends in the leachate were related to formation of soluble and insoluble mineral phases. One of the conclusions of the study concerning the material tested is that the leachability of most of the RCRA metals in the scrubber residue is very low. A more general overall conclusion of the study is that characterization of waste materials for disposal must include more than a single leaching procedure. Chemical, physical, and mineralogical characteristics of the material must be considered, as well as site characteristics and interactions of the leachate and disposal environment (Hassett et al. 1992).

Based on the above discussion, it appears that a new generation of test methods will involve multiple procedures to address the various aspects of leachability and that these will be more waste- and site-specific oriented. Ideally, what is needed for the next generation of test methods are research methods, which can be longer and more complicated, condensed into shorter, more simple methods that can be used as good predictive tools for regulatory purposes and management practices.

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## **BULK CHEMICAL AND MINERAL CHARACTERISTICS OF COAL COMBUSTION BY-PRODUCTS (CCB)**

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### **Introduction**

Coal ash is a versatile material that can be used as a construction material as well as in agricultural applications. It can be used successfully in mineland reclamation as a substitute for soil in structural fills, capping material, liming material, and topsoil. Although coal ash can be used like soil, its characteristics and properties are very different. There are very few standard tests for coal ash, most tests are modified versions of cement or soil tests. There is no broad classification system for coal ash that covers all of the materials available. The classification system established by ASTM C 618 (Class F and Class C) is very limited and does not describe the different types of CCB, their mineralogy, or its range of properties. Many of the applications mentioned above do not require the material specifications defined by ASTM C 618. When evaluating the types of CCB available for mineland reclamation, it is very important that the basic characteristics of the CCB be understood and related to the mechanical or physical property necessary to successfully utilize the material in an engineering or agricultural application.

### **Elements in Coal and Coal Ash**

Coal is a highly variable, heterogeneous, fossilized material that formed from ancient plant material exposed to elevated temperatures and pressures after burial. In addition to the major elements of carbon, oxygen, hydrogen, nitrogen, and sulfur, coal also contains varying levels of trace elements such as sodium, mercury, chlorine, etc. Coal occurs in association with various types of inorganic minerals such as aluminosilicates (clay minerals), carbonates (calcite and dolomite), sulfides (pyrite), chlorides, and silica (quartz). Some elements such as sulfur occur in both the organic and inorganic coal fractions. The inorganic minerals, deposited along with the plant material, are inherent and make up 5 to 10% of the coal. It is principally these incombustible materials that form the ash that remains after combustion of the coal.

The chemical composition of coal ash is typically made up of silicon, calcium, aluminum, iron, magnesium, and sulfur oxides, along with carbon and various trace elements. These elements are found in the ash because of their high melting points and the short time the ash particles actually remain in the furnace during combustion. The mineral quartz ( $\text{SiO}_2$ ) survives the combustion process and remains as quartz in the coal ash. Other minerals decompose, depending on the temperature, and form new minerals. The clay minerals lose water and may melt, forming aluminosilicate crystalline and noncrystalline (glassy) materials. Elements such as Fe, Ca, and Mg combine with oxygen in the air to form oxide minerals, such as magnetite ( $\text{Fe}_3\text{O}_4$ ), hematite ( $\text{Fe}_2\text{O}_3$ ), lime (CaO), and periclase (MgO).

### **Coal Combustion Technologies**

Conventional coal combustion involves pulverizing the raw coal into small particles and injecting it into a furnace ("boiler") where it is burned in a long luminous flame at temperatures of 1500°C or greater. Temperatures this high melt 70 to 90 percent of the mineral phases leaving fused mineral impurities we call coal ash or coal combustion by-products (CCB). Approximately one fifth of the ash particles fall to the bottom of the furnace and are collected as bottom ash. The rest of the fused matter is transported to a low temperature zone (200°C) in about 4 seconds. Here it solidifies into crystalline and non-crystalline glassy phases that are carried out of the furnace with the flue gas. We refer to this material as pulverized coal fly ash (PCFA) or simply "fly ash".

Coal combustion technologies are changing in order to burn coal more cleanly. The so called "Clean Coal Technologies" work at several stages of the combustion process; pre-combustion, combustion, and post-combustion. Pre-combustion involves cleaning the coal prior to combustion. Physical coal cleaning removes mineral particles, especially pyrite, to reduce ash content and SO<sub>2</sub> emissions. Combustion and post-combustion technologies remove the SO<sub>2</sub> and NO<sub>x</sub> gases, and/or particulate matter during combustion, or from the gases leaving the furnace. It is the combustion and post-combustion technologies that have a major influence on the chemical and mineralogical composition of the resulting CCB.

One new type of combustion technology is called Fluidized Bed Combustion (FBC). This technology involves mixing limestone with the crushed coal to act as a sorbent for SO<sub>2</sub> gas formed in the furnace. The mixture of coal and limestone are suspended on jets of air inside the furnace. The turbulent mixing of coal and sorbent causes the solids to behave as a pseudo-fluid allowing the coal to be burned at lower temperatures (800-900°C). As much as 90% of the SO<sub>2</sub> can be removed in this manner. The lower temperatures minimize melting resulting in CCB that do not contain the spherical glassy material typical of the fly ash formed during pulverized coal combustion. The amount of limestone used depends on the sulfur content of the coal, but generally it requires 1/3 to 1/2 ton of limestone for each ton of coal burned. This causes a significant increase in the volume of by-products formed from combustion.

Post-combustion cleaning technologies clean the down stream flue gases after they leave the boiler or combustion zone. They are used in conjunction with pulverized coal combustion furnaces and are often referred to as "scrubbers." There are two approaches to post-combustion cleaning technologies, Flue Gas Desulfurization (wet and spray dryer FGD) and Duct Injection. In wet FGD, the flue gases are bubbled through a tank containing hydrated lime slurry or some other alkaline sorbent, reacting with calcium and forming a wet sludge precipitate. In spray dryer FGD the hydrated lime slurry is sprayed directly into the hot flue gases, reacting with the SO<sub>2</sub> and forming a dry particulate material. Duct Injection is a similar process to spray dryer FGD except the sorbent is added directly into the existing furnace ductwork instead of a separate chamber.

### **Mineralogical Composition of CCB**

The bulk chemical and mineralogical characteristics of CCB and their hydration behavior depend mainly on the rank of coal burned, the calcium content of the coal, and the combustion process or scrubbing technology (if applied) (McCarthy, 1988; McCarthy et al., 1990; McCarthy et al., 1993). It has been shown (McCarthy et al., 1990) that the amount of silicon, aluminum, and iron in a coal ash varies proportionately with the amount of calcium in the coal ash and the calcium content of the ash is related to the source coal (Table 1). Bulk chemical analyses are routinely done for CCB that are sold for use in the concrete industry. Mineralogical characterization is not done routinely and the few laboratories that do this type of work are usually involved in research.

#### Pulverized Coal Fly Ash

The various minerals that have been identified with x-ray diffraction analysis of pulverized coal fly ash (and bottom ash) include: quartz (SiO<sub>2</sub>); mullite (Al<sub>6</sub>Si<sub>2</sub>O<sub>13</sub>); tricalcium aluminate (Ca<sub>3</sub>Al<sub>2</sub>O<sub>6</sub>); melilite (Ca<sub>2</sub>(Mg,Al)(Al,Si)<sub>2</sub>O<sub>7</sub>); merwinite (Ca<sub>3</sub>Mg(SiO<sub>4</sub>)<sub>2</sub>); C<sub>3</sub>S (Ca<sub>3</sub>SiO<sub>5</sub>); C<sub>2</sub>S (Ca<sub>2</sub>SiO<sub>3</sub>); ferrite spinel ((Mg,Fe)(Fe,Al)<sub>2</sub>O<sub>4</sub>); magnetite (Fe<sub>3</sub>O<sub>4</sub>); hematite (Fe<sub>2</sub>O<sub>3</sub>); lime (CaO); anhydrite (CaSO<sub>4</sub>); periclase (MgO); and alkali sulfates ((Na,K)<sub>2</sub>SO<sub>4</sub>). The predominant minerals in ash resulting from combustion of eastern and midwestern coals are quartz, mullite, hematite, and magnetite. This ash (as will be discussed later) is referred to as ASTM Class F fly ash. These minerals are also present in ash derived from western subbituminous coal along with the minerals periclase, lime, anhydrite, and tricalcium aluminate. This ash is referred to as ASTM Class C fly ash. It is these later minerals that give Class C fly ash its unique hydration behavior (Solem and McCarthy, 1992).

Quartz (SiO<sub>2</sub>) in the fly ash originates from silt and clay in the coal that is not fluxed by other inorganic materials. The amount of quartz does not correlate with chemical SiO<sub>2</sub> content. CCB from eastern and midwestern bituminous coal contain 40 to 50% chemical SiO<sub>2</sub> and 5-10% quartz. Quartz does not significantly react with water when the ash is hydrated.

Mullite (Al<sub>6</sub>Si<sub>2</sub>O<sub>13</sub>) is the principal aluminum containing phase in Class F fly ash. It crystallizes directly from the molten ash or by devitrification of the glass after cooling. Its formation requires temperatures above 1000 °C. Mullite is twice as abundant in low-calcium ashes as in high-calcium. This is due to differences in the composition of the clays found in the coal. The higher aluminum/silicon ratio in kaolinite (0.85) and mica-illite (0.61) produce an ash richer in mullite compared to ash from coals containing smectitic clays (0.35). Coals that contain more calcium also produce ashes having less mullite because some of the aluminum combines with the calcium forming tricalcium aluminate (C<sub>3</sub>A, Ca<sub>3</sub>Al<sub>2</sub>O<sub>6</sub>). Like quartz, mullite is nonreactive when the ash grains contact water.

Ferrite spinel ((Mg,Fe)(Fe,Al)<sub>2</sub>O<sub>4</sub>), magnetite (Fe<sub>3</sub>O<sub>4</sub>), and hematite (Fe<sub>2</sub>O<sub>3</sub>) are the principal iron containing phases in PCFA. These minerals, present in almost all fly ashes, form from the oxidation of iron sulfides and other iron bearing minerals associated with the coal. Approximately one-third to one-half of the iron present in PCFA is speciated as crystalline iron oxides. These minerals are largely inert during reactions with water. The rest of the chemical Fe<sub>2</sub>O<sub>3</sub> is contained in the glass and will be available under high pHs.

Calcite and dolomite in the coal provide most of the calcium and magnesium in the PCFAs, but the another source is from organic exchange sites and organic complexes in the coal. Crystalline lime (CaO) has been identified in all high-calcium, most intermediate-calcium and some low-calcium PCFAs. Even in high-calcium PCFAs, only a small percentage of the chemical CaO crystallizes to form lime. In high- and intermediate-calcium ashes, the calcium also speciates as C<sub>3</sub>A (Ca<sub>3</sub>Al<sub>2</sub>O<sub>6</sub>), melilite (Ca<sub>2</sub>(Mg,Al)(Al,Si)<sub>2</sub>O<sub>7</sub>), and anhydrite (CaSO<sub>4</sub>). The hydration of lime to portlandite in high-calcium PCFAs is one mechanism for providing a source of the high pH necessary to activate cementitious reactions.

Tricalcium aluminate (Ca<sub>3</sub>Al<sub>2</sub>O<sub>6</sub>) occurs in most intermediate- and all high-calcium PCFAs, along with what is speculated to be a calcium aluminate-rich glass. C<sub>3</sub>A is soluble and participates, along with the calcium aluminate-rich glass component, in the formation of the hydration product ettringite.

Periclase (MgO), the principal magnesian mineral in high- and intermediate-calcium PCFAs, contains about half of the MgO present. Magnesium also speciates as melilite (Ca<sub>2</sub>(Mg,Al)-(Al,Si)<sub>2</sub>O<sub>7</sub>) and merrillite (Ca<sub>3</sub>Mg(SiO<sub>4</sub>)<sub>2</sub>), neither of which participate in cementitious reactions. The high temperatures of conventional coal combustion form periclase that is dead-burned (i.e., does not react significantly with water).

In the presence of higher CaO, MgO, Na<sub>2</sub>O, and K<sub>2</sub>O content, some of the SO<sub>2</sub> that results from the oxidation of pyrite during combustion of the coal can be captured as water soluble alkali and alkaline earth sulfate salts. This partial "self-scrubbing" effect has made these more alkaline low-rank coals useful for reducing SO<sub>2</sub> emissions without installing scrubbers.

Anhydrite (CaSO<sub>4</sub>) results from the reaction of calcium, oxygen and SO<sub>2</sub> in the gases leaving the furnace. Anhydrite is characteristic of high calcium PCFAs, but has also been observed in intermediate- and low-calcium ashes. In the lower alkali ashes, anhydrite accounts for most of the chemical S<sub>03</sub>. but in high alkali ashes, SO<sub>3</sub> is also speciated as alkali sulfates, ((Na,K)<sub>2</sub>SO<sub>4</sub>). Anhydrite in PCFAs is soluble and will react with water to form gypsum, ettringite, or monosulfate (Solem and McCarthy, 1992).

The particle density of PCFA grains varies with the type of minerals present. Iron oxide-rich grains have a density of 4.5-5.1, quartz 2.65, mullite 3.03, carbon 1.2-2.0, and alumino-silicate glass 2.5-2.7 g/cm<sup>3</sup> (Hemmings and Berry, 1988). Therefore, the average bulk density of PCFA reflects the proportions of solid and hollow particles, their size, the mineralogy of the crystalline components, the nature of the glass, and the amount of unburned coal. These characteristics also affect the reactivity of the PCFA when hydrated.

These materials have been used successfully in the U.S. in a number of applications including structural fill and as a topsoil replacement in direct revegetation of coal ash landfills.

#### Flue Gas Desulfurization By-Products

Flue gas desulfurization (FGD) by-products consist of PCFA grains entrained with reacted and unreacted sorbent. The average particle size ranges from 20-40 micrometers. The fly ash in the FGD sludge is similar in particle size, particle density and morphology to those of conventional PCFAs, but the sorbent reaction products have lower bulk densities due to differences in their chemical and mineralogical characteristics. FGD by-products contain higher concentrations of calcium and sulfur, and lower concentrations silicon, aluminum, and iron than PCFAs. The principal sorbent reaction products are hannebachite (calcium sulfite hemihydrate) or gypsum (calcium sulfate dihydrate). Unused sorbent remains as hydrated lime (portlandite) in the by-products.

These materials have been used successfully in Indiana as both structural fill, low permeability caps, underground mine stabilization (injected as a slurry), as well as a replacement for agricultural lime.

#### Fluidized Bed Combustion Residues

The bottom ash collected from FBC technology is sometimes referred to as spent bed, however, the fine material captured in the baghouse is still referred to as “fly ash”. The chemical and physical characteristics of FBC by-products vary from one power plant to another depending on several factors including; the composition of the “bed” material used to fluidize the coal particles (originally limestone, sand or shale), the amount of sulfur in the coal, reactivity of the sorbent, and when the bed is removed. There are times when the load in the boiler becomes too high and portions of the bed are removed from the furnace. This influences the amount of char or partially burned coal present in the spent bed. By-products formed in plants using inert beds (such as sand and shale) also contain variable amounts of x-ray amorphous phases that are produced by the thermal decomposition of the clay minerals in the bed materials. These amorphous materials form a “hump” on the X-ray diffraction scan that resembles the glasses in PCFAs but is not composed of melted material.

The main crystalline phases in the FBC by-products are anhydrite (reacted sorbent), lime (unreacted sorbent), quartz, and iron oxides. Anhydrite forms from the calcination of limestone into lime followed by its reaction with SO<sub>2</sub> and oxygen. The amount of reacted and unreacted sorbent depends on the scrubbing efficiency and the amount of limestone added. Power plants that burn high-calcium, low-sulfur subbituminous coal have to use more sorbent to attain the high percent sulfur removal required by regulations. These ashes contain more lime (due to increased use of limestone) and less anhydrite (due to lower sulfur content of the coal). High sulfur coal also contains more iron resulting in higher concentrations of iron oxide (hematite and magnetite) in the ash. Other crystalline phases present include calcite, periclase, and feldspars.

FBC by-products, bottom ash and fly ash, contain the same type of minerals but often in different proportions. The bottom ash is often enriched in anhydrite and lime while the fly ash is richer in silicon and iron oxides. FBC fly ash is a fine grained homogeneous material that consists of angular particles smaller than 45 micrometers. It is generally irregularly shaped and does not have the fused, spherical characteristics of PCFAs, due to the lower combustion temperatures of FBC. The spent bed

residues are generally larger than 75 micrometers, with a narrower range of particle size than fly ash particles.

Most published studies that included characterization of FBC residuals looked at materials from only one or two different plants. According to a 1991 Electric Power Research Institute database, there were more than 115 plants in the United States operating more than 161 FBC boilers. This technology can be used for small-scale and large-scale power generation. FBC technology can utilize many different types of alternative fuels, such as petroleum coke, bituminous coal mine wastes (GOB), wood chips, agriculture waste, process wastes, refuse derived fuel, and municipal sewage sludge. There is as yet no literature that describes the effects that alternative fuels have on the nature of the FBC residues or their variability due to changing sources of coal. The use of these materials as a soil amendment has been described in a manual by Stout et al. (1988).

These materials have been used successfully at Purdue as structural fill and in the manufacture of synthetic topsoil.

### **Classification of Coal Combustion By-products**

There is currently only one commonly used classification system for CCB defined by ASTM C 618. It distinguishes two classes of pulverized coal fly ash, Class C and Class F (Helmuth, 1987). Materials are first tested according to ASTM C 311, "Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzoloans for use as a Mineral Admixture in Portland-Cement Concrete", and then classified according to ASTM C 618, "Standard specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete". ASTM C 311 describes the methods for bulk chemical analyses. The chemical and physical requirements specified in ASTM C618 are given in Table 2.

The distinction between Class F and Class C fly ash is based on the sum of the total silicon, aluminum, and iron ( $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ ) in the ash. When the sum is greater than 70% an ash is classified as Class F. When the sum is between 50% and 70% the ash is classified as Class C. A bituminous coal will always produce a Class F ash, but a subbituminous or lignite coal can form either a Class C ash or a Class F fly ash depending on the calcium content of the coal. Ash that results from blending of bituminous and subbituminous coal have not been studied in any detail.

In every state, where CCB specifications have been developed by the Department of Transportation, it is required that coal ash materials must pass C-618 specifications. There are several utilization practices, such as high-volume structural fills and control density fills (flowable fills), where ASTM C618 requirements are irrelevant. In these engineering applications, CCB can be used successfully even though they do not meet ASTM C618 specifications. ASTM C 618 specifications were developed for a specific application, the use of fly ash as a mineral admixture in Portland cement concrete. Their use as a generic material specification for all CCB used in any engineering applications has eliminated a significant volume of CCB from potential utilization.

ASTM C 618 does not adequately characterize the physicochemical properties of fly ash. It only requires a bulk chemical analysis that indicates the total amount of certain elements such as calcium, silicon, aluminum, iron present in the fly ash. It does not provide any indication of the minerals or compounds in which these elements are speciated. Minerals have varying solubility and they control the rate and amount of an ion available in solution, which controls the formation of various hydration products.

### **Physical Characterization of CCB**

Modified soil and cement or concrete testing procedures can be used to characterize the physical properties of CCB that relate to its use as a construction material. However, in many cases, the results of

the tests must be reevaluated in order to understand what the tests are actually measuring, since coal ash is a fundamentally different material than either soil or Portland cement.

The physical characteristics (such as particle size) depend mainly on where the residues are collected (baghouse or bottom ash). Both bottom ash and fly ash usually have a fairly uniform particle size gradation but when commingled can result in a somewhat wider particle size distribution. CCB do not contain clay and therefore exhibit no plasticity. Index tests which measure plasticity and are used to classify soil for engineered applications are not appropriate for CCB. The physical properties most relevant to engineering applications are the particle size, gradation, and hydration behavior. Hydration behavior will depend on whether the material is chemically reactive with water. The compaction behavior and water demands, strength, density, permeability, and leachability will depend very strongly on hydration behavior.

Eastern and midwestern bituminous coals (unscrubbed) produce low sulfur, low-calcium ashes that are unreactive when mixed with water. These materials can be easily compacted provided sufficient water is applied. A simple rule of thumb to follow is that if the ash is dusty, you don't have enough water. Most of this type of coal ash will drain freely and therefore if too much water is applied the situation remedies itself fairly quickly. These CCB will tolerate a relatively wide range of water contents and still produce a well compacted material. They can be placed in thicker lift sizes than most soils and will compact more densely using less compaction energy.

Western subbituminous coal produces ash that typically contains more than 20% CaO and exhibits a self-cementing behavior when mixed with water. Much of the fly ash produced is used by the cement industry and not usually available free of charge. CCB that result from FBC and FGD technology typically contain large amounts of calcium and sulfur in the mineral forms of lime and anhydrite (in FBC) and gypsum or hennrichite (in FGD). The engineering behavior of these CCB is largely controlled by the dominant type of mineral(s) present. Some have cementitious properties, and others do not. The strength gain in these materials will depend on the amount of lime present. The presence of anhydrite and lime causes considerable expansive behaviors due to the formation of ettringite and gypsum (Solem and McCarthy, 1992).

### **Summary**

Coal ash is a versatile material that can be used as a construction material as well as a liming agent or topsoil substitute. These applications are the most relevant to mineland reclamation. The only existing standard specification for coal ash is ASTM C 618. It defines the chemical and physical requirements for fly ash that permits its use as a mineral admixture in portland cement concrete. The bulk chemical and mineralogical characteristics of CCB and their hydration behavior depend mainly on the rank of coal burned, the calcium content of the coal, and the combustion process or scrubbing technology. Modified soil and cement or concrete testing procedures can be used to characterize the physical properties of CCB that relate to its use as a construction material; however, in many cases, the results of the tests must be reevaluated in order to understand what the tests are actually measuring. It is possible to mix various types of CCB, modify them by adding other materials, or use them to modify existing materials at a site in order to achieve successful results in almost any application.

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Table 1. Calcium Content in Coal Ash is Related to the Coal Source

Source Coal	CaO (in ash)
Eastern and Midwestern bituminous	1-6%
Colorado bituminous	4-8%
Utah and Alberta subbituminous	6-12%
Texas Lignite	7-15%
Saskatchewan lignite	10-15%
North Dakota lignite	18-25%
Montana and Wyoming subbituminous	22-32%

Table 2. Chemical and Physical Requirements Defined by ASTM C 618.

Chemical Requirements:	Class F	Class C
SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> , min. %	70.0	50.0
SO <sub>3</sub> , max. %	5.0	5.0
Moisture content, max. %	3.0	3.0
Loss on ignition (LOI), max. %	6.0	6.0
Available alkalies, as Na <sub>2</sub> O, max. %	1.5	1.5
Physical Requirements:	Class F	Class C
Fineness, max. %	34	34
<i>Strength Activity Index:</i>		
-with portland cement, 7 days, min. %	75	75
-with portland cement, 28 days, min. %	75	75
-with lime, 7 days, min. psi	800	800
Water Requirements, max. % of control	105	105
Soundness; autoclave expansion or contraction, max. %	0.8	0.8
<i>Uniformity Requirements:</i>		
Specific Gravity, max. % variation from average.	5.00	5.00
Percent retained on #325 sieve, max. % variation from average	5	5

## ENGINEERING AND REGULATORY ISSUES FOR COAL COMBUSTION BY-PRODUCT CHARACTERIZATION AND UTILIZATION

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### **Introduction**

The term coal combustion by-products (CCBs) generally refers to the typical high-volume residues that inevitably result from coal use in energy production. These high-volume residues are fly ash, bottom ash, boiler slag, and FGD (flue gas desulfurization) byproducts. Many of these CCBs have properties advantageous for engineering, construction, and manufacturing applications (Baker, 1984; Helmuth, 1987; University of North Dakota Mining and Mineral Resources Research Institute [UNDMMRI], 1988). The first university research study on coal fly ash was reported in the Proceedings of the American Concrete Institute (ACI) in 1937, where the term "fly ash" first appeared in the literature. In 1946, the Chicago Fly Ash Company was formed to market coal fly ash as a construction material for manufacturing concrete pipe (Faber and Babcock, 1987). The first large-scale use of coal fly ash was by the U.S. Bureau of Reclamation in the construction of the Hungry Horse Dam in Montana in 1949 (Faber and Babcock, 1987). Six other dams were constructed during the 1950s using coal fly ash concrete. Initial markets opened up by the Chicago Fly Ash Company were as a cement replacement and as an enhancer of the qualities of concrete to meet the new postwar demands. The technology used to establish these markets came from the U.S. Bureau of Reclamation and Army Corps of Engineers experience using natural pozzolans in concrete for dam construction. Pozzolanic technology dates back to Roman times, some 2000 years ago, in the building of the aqueducts and the coliseums.

Currently, CCBs are an underutilized industrial by-product in the United States. Approximately 20% of all U.S. by-products produced in 1991, including FGD material, were utilized (American Coal Ash Association [ACAA], 1991). Large potential markets for these byproducts have not yet been exploited. Many of the applications referred to above are in the initial stages of commercial development. Although extensive research, development, and promotional effort have been expended, much more work is needed to achieve full commercial potential. Research, development, and demonstration are continuing under the auspices of numerous institutions across the United States. The ACAA, Edison Electric Institute and the Utility Solid Waste Activities Group, the Electric Power Research Institute (EPRI), and many individual utilities and marketing organizations are devoting their best efforts to promote CCB use, especially in engineering and construction applications.

### **Engineering Applications for CCBs**

Historically, the principal use of coal by-products has been in concrete, and this still holds true today. However, many other utilization applications are discussed in the literature, including controlled low-strength materials, highway road base and subgrade, soil amendments for agricultural uses, waste stabilization, extenders in plastics and paints, and the manufacture of products such as cement, insulating materials, lightweight building block, brick, and other construction materials.

The use of CCBs in concrete and concrete products is primarily in the incorporation of fly ash as a partial replacement for portland cement in concrete. This use generally has the following beneficial effects:

- . Reduced water requirements
- . Increased ultimate strength
- . Improved workability
- . Extended setting time
- . Reduced heat release
- . Lower permeability
- . Improved durability
- . Increased resistance to chemical degradation

Mechanisms proposed to explain the improved microstructure and density obtained by using fly ash are 1) the packing of finer fly ash particles into interstices, 2) an increased binder-water ratio resulting from this packing, and 3) the pozzolanic reaction of calcium hydroxide and fly ash occurring over a period of weeks or months. Analytical characterization of fly ash cement during curing shows that a variety of calcium-silicon-hydrate gels are responsible for the gain in both strength and density notably occurring from about 28 days (Pietersen and others, 1991). These reactions are restricted by low alkalinity, low temperatures, or high water-solid ratios in pozzolanic systems. Reaction mechanisms overall are similar for either pozzolanic or cementitious fly ash, except that cementitious fly ash provides both cementitious calcium and silicon reactants, whereas pozzolanic fly ash supplies primarily silicon, which reacts more slowly with the calcium hydroxide released from the portland cement.

Fly ash used in this application generally must meet one of the commonly applied standard specifications developed by ASTM (American Society for Testing and Materials) or AASHTO (American Association of State Highway and Transportation Officials). These specifications contain both chemical and physical requirements for fly ash to be used as a mineral admixture in concrete. Cementitious fly ash generally falls into the ASTM and AASHTO specification for Class C, and pozzolanic fly ash generally falls into the ASTM and AASHTO specification for Class F. These are material specifications and not performance-based standards, so they do not always accurately predict performance.

There are varying reports of the effects of the use of fly ash in concrete relative to its performance in several situations. Freeze-thaw durability of fly ash concrete can be ensured by the use of practices that ensure good freeze-thaw performance for other concretes (Tyson, 1991; Dunstan, 1991). Freeze-thaw performance is reported to improve with the addition of Class C fly ash up to a 50% replacement level (von Fay and others, 1993). Overall, the resistance of fly ash concrete to salt scaling due to deicing in cold climates appears to be similar to that of conventional concrete, and improved resistance correlates with strength and reduced permeability (Soroushian and Hsu, 1991). Unwanted alkali-silica reactions are the cause of detrimental expansion in concrete both during and after curing. This problem occurs in various forms when free alkalies (usually reported in terms of  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ ) are introduced with any of the raw materials and is common when portland cement is used with high-silica aggregate. As commonly used, the term alkali-silica reaction appears to represent a class of related problems. These problems are variously reported to be remedied or aggravated by the addition of specification-grade fly ashes, suggesting that mineralogical properties not currently considered may be important. In general, the addition of fly ash, and particularly Class F ash, is considered to be beneficial because of the ability of finely divided silicious particles to tie up alkalies and free lime by pozzolanic reactions (Butler and Ellis, 1991; Smith, R. L., 1993). The concrete expansion encountered during curing when using certain Class C fly ashes has been reported to depend on the amount of free lime introduced with the ash, which has been correlated with reduced furnace temperatures and a less vitrified (fused) ash (Kruger and Kruger, 1993). High concentrations of sodium in certain western coals, occurring in an organically associated form, are an identifiable cause of alkali-silica reaction.

Manufacture of artificial aggregates from fly ash or other CCBs can be accomplished by either sintering processes (Puccio and Nuzzo, 1993) or hydrothermal and cold-bonding processes. Sintering processes are well-established technology and have operated successfully for decades, but lower-temperature processes under development have attracted more recent attention because of their lower

energy requirement and greater cost-effectiveness. Commercial production of lightweight aggregate for building block based on low-temperature processing has commenced recently in Florida using the Aardelite process (Smith, C.L., 1993; Hay and Dunstan, 1991) and in Virginia using the Agglite process (Courts, 1991).

Synthetic aggregate was experimentally produced from lime-based spray dryer FGD byproducts in the early 1980s by pelletizing at pressures of 5 to 20 tons per square inch followed by extended 10- to 60-day curing under controlled moisture conditions (Donnelly and others, 1986). Strength properties were adequate for confined applications such as road base. Pellets produced from Coolside, LIMB (limestone injection modified burner), and fluidized-bed combustion (FBC) by-products in the Ohio Coal Development Office demonstration project have passed the ASTM abrasion test for use as road base aggregate (Hopkins and others, 1993). Commercial production of lightweight aggregate suitable for use in lightweight building block commenced in Florida in 1992 using bituminous coal fly ash and FGD scrubber sludge as raw materials in the low-temperature Poz-0-Lite process (Smith, C.L., 1993).

A novel method for producing lightweight aggregate by agglomerating fly ash or sand in foamed cement has been developed in Germany (Gorsline, 1986). The properties of the aggregate can be controlled to meet a range of specifications on size, strength, density, and porosity. The cellular structure imparts high strength in relation to weight and reduces the amount of cement required.

Autoclaved cellular concrete used in building blocks, roof slabs, and other cast products represents an important market for fly ash in Europe. In this process (Pytlík and Saxena, 1991; Payne and Car-roll, 1991), fly ash is combined with cement, lime, sand, and aluminum powder and mixed with hot water. The reaction of aluminum and lime generates hydrogen gas which forms an aerated cellular structure. Curing in high-pressure steam autoclaves produces a physically chemically stable product.

The use of fly ash alone or together with lime or cement in self-hardening road base is an evolving technology which is receiving increased attention. New information in this area includes the results of laboratory testing and extended field monitoring, use of reclaimed pond ash, incorporation of FGD by-products, and use of the ash-based aggregates discussed previously.

Monitoring of a 1500-ft test section using cement-fly ash base for a Michigan 4-lane highway has indicated quite satisfactory performance since its construction in 1987 (Gray and others, 1991). Some heaving and cracking occurred in winter months due to frost effects. Laboratory leachate concentrations for heavy metals using ASTM and RCRA (Resource Conservation and Recovery Act) (U.S. Environmental Protection Agency [EPA]) procedures approached drinking water standards. Replacement of lime with Class C fly ash in the subbase for a Kansas racetrack reduced the cost by one-half; swelling potential was reduced compared to lime stabilization, but strength was reduced at soil temperatures below 40°F (Ferguson and Zey, 1991). Laboratory evaluation of fly ash stabilization of caliche, a red-brown calcareous material used for roadways in South Texas, indicated that both Class C and Class F ashes were more effective than lime for reducing plasticity and that Class C fly ash also significantly increased strength (Keshawar and others, 1991). Laboratory and field tests on the use of artificial aggregate produced from fly ash in asphalt paving, both as road base and in the asphalt mix, indicated that bitumen is absorbed in the pores of the aggregate, producing good bonding but a relatively dry and stiff mix; replacement of commonly used gravel with fly ash aggregate did not result in higher leaching of any of the heavy elements analyzed (Mulder and Houtepen, 1991).

Reclaimed pond ash containing fly ash and bottom ash from Canadian lignite has been used to stabilize road base for asphalt paving (Culley and Smail, 1986). The wet pond ash, when compacted in 1-in. layers using standard equipment and handling procedures, had good structural bearing, but the unconfined surface suffered rapid surface abrasion when dry. Adequate bonding between the ash subbase and asphalt paving was achieved by blade-mixing the first layer of asphalt into the underlying ash. Road surface condition was adequate over time where appropriate construction techniques were used. Recent laboratory testing on strength development for a reclaimed high-calcium fly ash used along with kiln dust

to stabilize road base materials indicated strengths in the range of 200 to 1000 psi (Bergeson and Overmohle, 1991).

Fly ash has been successfully used in combination with lime sludge to stabilize unstable sand in Florida road base projects (Jones, 1986). A base prepared by mixing lime and fly ash with in situ sand hardened sufficiently after several weeks to allow heavy truck traffic. By-products from coolside, LIMB, and FBC sulfur control technologies are currently being evaluated for use in road base. Laboratory tests on the compaction, swelling, shear strength, permeability, and leaching properties of the coolside FGD by-product indicate a good potential for use in road base applications, but final assessment awaits the performance of field trials and engineering analysis (Hopkins and others, 1993).

Controlled low-strength material (CLSM) is a fill formulated from a pozzolanic material such as fly ash along with small amounts of cement, a natural filler such as sand, and water. CLSM is also commonly called flowable fill, flowable mortar, or controlled-density fill (CDF). CLSMs have been investigated for numerous applications, including subbase for paving and foundations; backfills for trenches, culverts, and bridge abutments; and fillings for abandoned tanks, sewers, and mine shafts. Starting in the late 1960s, the Detroit Edison Company working with the Kuhlman Corporation pioneered the development of flowable fill formulations using fly ash, which they call K-Krete. Advantages of CLSM over compacted soil include delivery in ready-mix trucks, placement without tamping or compacting, strength development supporting equipment within 24 hours, and the opportunity to formulate mixes having an ultimate strength well in excess of that of compacted fill. Significant savings in time and related cost can be achieved in designing rapid turnaround projects for high-traffic road applications. For example, bridge replacement in the Mississippi Basin in the aftermath of the 1993 flood could be accomplished more quickly and economically by substituting large culverts imbedded in fly ash fill for damaged abutment-type bridges, where applicable. This type of bridge replacement has been reported to save as much as 75% of the cost of conventional construction (Buss, 1990).

The properties of CLSM vary widely depending on the class of fly ash used and the mixing proportions. Nonspecification fly ashes, relative to requirements established for fly ash as a mineral admixture in concrete, can be quite satisfactory for flowable mortar. Compressive strengths within a nominal range of 50 to 1500 psi can be tailored to fit the requirements of the application, including the possible requirement for reexcavating. In flowable tills, Class F fly ash serves primarily as aggregate, and large amounts can be used. Recent research on the mechanical properties of formulations using Class F fly ash (Maher and Balaguru, 1991) indicates that satisfactory 28-day strengths in the range of 198 to 1726 psi were obtained for mixes containing up to about 40% fly ash along with sand and 3% to 7% portland cement; strength development continued up to and possibly beyond 180 days, at which time a 7% cement mixture testing at 172 psi at 28 days had reached a strength of 3000 psi. Class C fly ash is itself a cementing agent, and 1500-psi 28-day strength is achieved using only about 3% portland cement and 5% high-calcium ash (Naik and others, 1991). The amount of Class C fly ash that can be used in CLSM is limited by the desired strength, where higher proportions of fly ash alone, without cement, will produce compressive strengths exceeding low-strength concrete.

The use of CLSM to correct acid mine drainage and subsidence in old underground coal mines is a well-demonstrated technology that could be more widely applied (Ryan, 1979). The bonding material in the grouting used is typically fly ash and cement in a 10:1 ratio, although ash alone can be used in less critical applications. Subsidence can be prevented either by backfilling the entire mine void with a low-strength grout or by establishing stronger grout/gravel columns at appropriate intervals to support the mine roof. Acid mine drainage and underground burning in spoil piles can be remediated by similar grouting methods engineered to isolate, fill, and/or extinguish affected areas in a mine. Advantages of using flowable mortars are minimum disturbance (no excavation), engineering flexibility, and low cost. Fly ash is returned to the in from whence it came, while at the same time remedying in related environmental problems,

## Manufacturing Applications for CCBs

A large number of potential uses for CCBs in industrial applications have been investigated. Commercial practice is limited in the United States, but is more common in some other countries. These applications include the following:

- Gypsum
- Brick
- Fillers in paint, plastics, and metal
- Mineral wool
- Ceramics

## Land Applications for CCBs

It is important to point out land application of CCBs as a special case of CCB utilization. Land application includes use as soil amendments and in mining applications. Soluble forms of calcium, magnesium, sulfur, and certain necessary trace metals such as boron, molybdenum, zinc, selenium, and copper that are present in CCBs can be used to provide needed plant nutrients. No significant amounts of the primary nutrient elements-nitrogen, phosphorus, and potassium-are found in CCBs, but wood ash is rich in potassium and phosphorus. By-product gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) can be used to improve the tilth of clayey soils and mitigate the toxicity of exchangeable aluminum in acid soils. Calcium contributes to soil aggregation by displacing sodium on clay minerals and providing microscopic cementation. Concerns relating to the agricultural use of CCBs involve the presence of soluble salts and trace concentrations of toxic metals which may be present in CCBs.

### Soil Amendment Applications

A review of past work on the effect of CCBs on plant growth (Clark and others, 1993) indicates that little agricultural utilization is occurring and that information is limited. Scrubber sludge impoundments have been successfully vegetated using wheat grass, tall fescue, sweet clover, millet, cottonwoods, and red cedars. Scrubber sludges have been successfully used as a source of boron and selenium trace nutrients. FBC bed residues are variously reported to increase maize and soybean yields and to provide a necessary source of calcium for apples. Research has been conducted by the Tennessee Valley Authority (TVA) on the inclusion of lime/limestone scrubbing waste into fertilizer formulations (Santhanam and others, 1981). Research is being conducted on the agricultural use of wood-fueled power plant ash from generating units in California (Wheelabrator Shasta Energy Company, 1991; Meyer and others, 1992).

In controlled greenhouse tests on several different CCBs (Clark and others, 1993) the addition of FBC residues to an acid soil of known severe aluminum toxicity served to double the yield of maize at an optimum add rate of 2% to 3% in the soil mix, but yields decreased at higher use rates. The effect of fly ash addition varied with coal type, with a bituminous Class F fly ash showing its highest growth enhancement at 3% addition, whereas lignitic Class C fly ash continued to increase yields at rates up to 25% of the soil mix. FGD by-products generally provided less growth enhancement, and optimum results were obtained at very low rates of 1% or less of the soil mix, possibly owing to detrimental effects of sulfite contained in these by-products. The use of an FGD sludge that had been processed to convert sulfate to gypsum enhanced growth rates at add rates up to 75% of the soil mix, consistent with the known beneficial effect of gypsum application to acid soil.

A major study on land application of FGD and pressurized fluidized-bed combustion (PFBC) by-products (Beeghly and others, 1993) is in progress in Ohio, sponsored by the Ohio Coal Development Office, the U.S. Department of Energy (DOE), EPRI, Ohio Edison, American Electric Power, Dravo Lime Company, and Ohio State University. By-products from fifteen sources are being investigated, representing four major clean coal technologies, including furnace injection FGD (LIMB), duct injection FGD, spray dryer FGD, and fluidized-bed combustion (atmospheric FBC and PFBC). These by-products

are characterized by high alkalinity expressed as calcium carbonate equivalents of 25%-70%; sulfur contents of 2.4%-10.3%; fly ash contents of 10%-32%; and, with the exception of FBC bed material, a high surface area and fineness. Selected by-products, alone or in combination with sewage sludge, were mixed with acid soils and mine spoils and tested in greenhouse growth studies. Interactions of different materials gave somewhat different results. For example, growth of tall fescue was enhanced in overburden spoil, but was suppressed in acid underclay. Sulfite-bearing material did not harm seed germination. LIMB by-product was successfully composted with sewage sludge. The conclusion reached from the greenhouse tests was that the by-products tested, when used appropriately, are suitable substitutes for traditional soil-liming materials for acid soils. Field tests are under way to demonstrate the practicality of this use.

The commercial N-Viro Soil Process (Burnham, 1993) combines agricultural use with waste stabilization by composting CCBs, or cement/lime kiln dust as originally used, with municipal wastewater treatment sludge. The soil conditioner produced has a low nutrient value (1 % N, P, K); a high lime equivalency of 25%-60%; good storage, handling, and spreading properties; and acceptable odor. The product is being produced from sludges produced in several municipalities and is used in agriculture and in cover for landfill. The key to the success of this process is that pathogenic microorganisms are destroyed by the alkalinity and heat associated with the addition of CCBs and possibly quicklime (CaO), followed by temperature-controlled composting and air drying. Leachability tests at various pH levels have indicated that the heavy metals are below EPA toxicity limits.

The efficacy of using CCBs in agricultural applications cannot be generalized since it is evident in comparing case studies that success is varied and depends on the suitability of the amendment to the soil and use conditions. For example, composting coal fly ash with field-collected waste vegetation was found to have no detrimental effect on bean germination in clayey and sandy soil, but reduced germination in a high-humus soil (Varallo, 1993). Alkaline treatment is appropriate for eastern acidic soil, but not for many midwestern soils that are already alkaline in nature. Novel applications in specialized areas may provide some of the more immediate commercial opportunities. FBC bed residues have been used at high rates of over 100 tons per acre as a mulching agent applied directly to cap the soil surface in orchards and raised-bed tomato rows (Korcak, 1993). Coal bottom ash has been demonstrated as an acceptable root medium for growing flowers in a hydroponic nutriculture system (Bearce and others, 1993). Widespread acceptance of CCBs in agriculture still has performance and economic barriers to overcome, but opportunities exist today where the properties of a utility's by-products meet the needs of a local market,

Some concerns still exist about the environmental safety of using CCBs in agriculture, despite findings that leachable concentrations of toxic metals are very low (Beeghly and others, 1993; Burnham, 1993; Bennett and others, 1981). While results vary somewhat for different by-products and soil types, the general finding reported is that leachates are nontoxic relative to the eight RCRA toxic metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) and often approach the more stringent primary standard for drinking water. The mobility of metals depends on the mineral matrix and on pH, and solubility is generally reduced at the high pH levels associated with alkaline CCBs. Certain beneficial trace plant nutrients present in coal fly ash, such as boron, selenium, and molybdenum, are assimilated in animal tissues (Lisk, 1981), and selenium deficiency in farm animals has been shown to be correctable by feeding the animals fly ash-grown crops. In coordinated tests on farm crops and animals (Bennett and others, 1981), there has been little evidence of detrimental effects on the food chain. One reason for caution is that standard tests for determining the leachability of trace metals, primarily the EPA toxicity characteristic leaching procedure (TCLP) tests for acid solubility, do not accurately represent all utilization environments, and they may either evidence problems that do not exist or miss worst-case problems that would occur in practice. At the current stage of understanding, states will tend to regulate ash reuse on farmland as solid waste management, requiring case-by-case permitting (e.g., California [Marshack, 1992]).

## Mining Applications

There are several scenarios in which CCBs may be utilized in a mined setting:

- The use of CCBs for abatement of acid mine drainage or for treatment of acid mine spoils (Schueck and others, 1993; Ackman and others, 1993; Stehouwer and others, 1993).
- The use of CCBs in reclamation activities or highwall mining (Bergeson and Lapke, 1993; Paul and others, 1993; Robl and Sartaine, 1993).

The placement of ash, as a low-strength structural material, in an underground mine for reclamation and prevention of subsidence (Chugh, 1993, Butler and others, 1995).

These three options represent most, but not all, scenarios under which CCBs would be returned to the environment in a mined setting. Mine applications have previously been considered disposal but, because of the relatively benign nature of CCBs, should more appropriately be considered reuse for reclamation of mined land because of the benefits derived in these applications.

Solid residues from the combustion of low-rank coals, which generates leachate at extremely high pH, tend to form the mineral ettringite. The alkaline nature of some CCBs (including duct injection residues/FBC residues and low-rank coal fly ash) can be capitalized on for abatement of acid mine drainage and spoils (Schueck and others, 1993; Ackman and others, 1993; Stehouwer and others, 1993). Ettringite has the capacity to chemically fix elements such as arsenic, boron, chromium, molybdenum, selenium, and vanadium that exist as oxyanions in aqueous solution. Thus ash that generally leaches low concentrations of most potentially problematic trace elements tends to form stable minerals of some of the most highly problematic of the trace elements known to concentrate in ash from coal combustion (Hassett and others, 1991). Although CCBs are generally benign with respect to leaching significant concentrations of potentially problematic elements, proper and environmentally sound testing should be conducted (Hassett, 1991; Hassett, 1994). This testing should be done using long-term as well as short-term leaching to determine the total mass of trace elements that may potentially be mobilized and the trends of analyte chemistry evolution (Hassett, 1987; Hassett and Pflughoeft-Hassett, 1993). Although leachate chemistry of most trace elements is accumulation of analyte to an equilibrium concentration that increases to a plateau, some of the oxyanionic trace elements can actually increase to a plateau quickly and then exhibit a trend of decreasing solution concentration. This is important to understand, since it is the long term that is usually important in assessment of potential for environmental impact.

A field demonstration at Center, North Dakota, where scrubber sludge was placed into a mined area was performed by the Energy & Environmental Research Center (EERC). The only observed impact was caused by the disturbance of the environment at the time of mining. An increase in total dissolved solids, mostly from sodium sulfate, was seen, but this rapidly returned to background levels (Beaver and others, 1987).

The primary conclusion that can be drawn is that return of ash to the mined settings is a sound high-volume use of this versatile engineering material. Not only can land be reclaimed, but in the case of underground mines, the setting can be stabilized to prevent future subsidence. Treatment of acid mine drainage and spoils has high potential, especially for high-volume alkaline residues from advanced coal processes. Impacts from trace elements, the primary concern, have been minimal or unmeasurable in almost all instances where monitoring has been carried out. There have been examples where groundwater quality has been shown to actually improve from the placement of CCBs in the environment (Ackman and others, 1993; Paul and others, 1993).

## Coal Combustion By-Product Classification

Alternative classification standards are needed for a growing list of CCBs to address engineering and environmental performance in a manner that will provide public assurance of safety and effectiveness, while not impeding utilization. It is widely believed, as evidenced by this and other

studies, that the present ASTM and EPA test protocols and specifications and related state standards do not adequately predict performance under actual use conditions. Important advances are being made in applicable analytical methods, but their application is hindered by misplaced reliance on existing empirical standards. For example, specifications developed for the use of fly ash in concrete are sometimes used by default in applications involving flowable fill or road base. New, automated analytical methods for statistically characterizing individual particles contained in bulk by-product samples by size, surface composition, and mineral type give a true indication of the chemical and mineralogical diversity in CCBs (Folke Dahl and others, 1993). Leaching tests for determining the mobility of RCRA elements under conditions simulating actual field conditions are being compared with the EPA TCLP acid-leaching procedures (Hassett and Pflughoeft-Hassett, 1993). These and other advanced characterization methods provide powerful tools for understanding the behavior of various by-products in diverse applications. Advanced analytical characterization can be systematically correlated with practical performance experience to provide an entirely new basis for classifying CCBs for optimum beneficial use. A scientifically based classification offering broad coverage of different by-product types and applications would assist greatly over time in providing the added assurance of safety and effectiveness needed to break down overly conservative practices currently prevailing under federal and state regulations.

### **Federal Regulations Applying to Coal Combustion By-Products**

The Resource Conservation and Recovery Act of 1976 and the 1980 Solid Waste Disposal Act Amendments provide for comprehensive cradle-to-grave regulation of solid waste generation, collection, transportation, separation, recovery, and disposal (Jagiella, 1993; Findley and Farber, 1992; Butler and Binion, 1993). Subtitle C of RCRA and its implementing regulations impose specific federal requirements on materials deemed to be "hazardous," either because of being listed by EPA as hazardous or by reason of having hazardous or toxic characteristics. Subtitle D of RCRA delegates regulation of nonhazardous solid wastes to the individual states. In its original form, RCRA did not specify whether CCBs fell under Subtitle C or D. The 1980 amendments temporarily excluded CCBs from Subtitle C regulation pending an EPA study report addressing appropriate classification. In the interim, CCBs were subject to regulation under state laws pertaining to solid wastes.

On August 2, 1993, EPA presented its final regulatory decision on fly ash, bottom ash, boiler slag, and flue gas emission control waste (40 CFR Part 261), stating that, effective September 2, 1993, these materials are not regulated as hazardous wastes under Subtitle C and officially placing them under Subtitle D as solid wastes under the jurisdiction of individual states. Further evaluation will be made by EPA of hazardous or toxic properties of industrial solid wastes, but at this time, CCBs are expected to remain under state regulation where little positive change is expected regarding beneficial use.

An important barrier issue originating in RCRA legislation is the indiscriminate designation of CCBs as solid wastes, whether they are recovered for use or disposed of in a landfill. In the absence of special state exemptions from solid waste regulations for beneficial use, which exist in only a few states, the "waste" designation can trigger case-by-case approval and permitting procedures that discourage CCB use because of unreasonable cost and delay. The remedies for this barrier problem include both the elimination of the "waste" designation and the creation of appropriate exemptions from regulation based on environmentally sound regulatory classifications for various classes of by-product use.

While RCRA is the principal federal law affecting the regulation of CCBs, a larger statutory framework of federal laws that are more or less integrated with state and local statutes may ultimately have to be considered. It is not within the scope of this study to unravel this potential regulatory maze. However, other federal statutes that potentially apply to CCB use or disposal in particular circumstances, as well as to virgin raw materials and derived products, include the Clean Water Act of 1972, the Safe Drinking Water Act of 1974, the Toxic Substances Control Act of 1976, and the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA, the Superfund Act). All of these statutes deal with the control of toxic substances and ultimately rely on environmental testing

and risk assessment to establish regulatory criteria. The final answer to regulatory questions constituting barriers to beneficial use, therefore, lies in obtaining adequate environmental data to demonstrate environmental safety, a process which is well advanced for CCBs but requires systematic compilation and refinement to provide the basis for regulatory classification.

### **State Regulation of Coal Combustion By-Products**

Limited information has been gathered and reported that defines and discusses state regulations pertaining to CCB utilization and barriers to utilization. State regulations have been summarized in a survey of use and disposal provisions (Jagiella, 1993). Hudson and others (1982) discussed barriers to CCB utilization in Maryland, Alabama, Illinois, New York, Pennsylvania, Ohio, Texas, Virginia, and West Virginia. Changes in regulations and practices relating to CCB utilization in these states have been noted in more recent works. The Texas Coal Ash Utilization Group (TCAUG) (1992) addressed regulatory issues in Texas in a recent report. The *Pennsylvania Bulletin* (1992) discussed current regulatory issues in Pennsylvania. These summaries point out that most state regulation of CCBs is designed to regulate disposal. Very few states have regulations regarding utilization of CCBs, either allowing or disallowing use. Common uses include concrete paving by state highway departments. A summary of state department of transportation CCB utilization specifications was prepared by the EERC (Docket, 1994) for the Coal Ash Resources Research Consortium. This report also summarizes the percentages of fly ash typically allowed as a mineral admixture and other utilization applications accepted by the state departments of transportation where specified, although these are not common.

### **Legal Barriers**

It is important to include a brief discussion of the key legal barrier to CCB utilization, which is the potential for environmental liability. Other issues involving commercial law and patents pose limited constraints of much less significance. The most serious environmental issue centers on the wide divergence in the legal and regulatory treatment of the beneficial use of CCBs under state laws. Whereas EPA confirmed in a ruling on August 2, 1993, that CCBs (fly ash, bottom ash, boiler slag, and FGD material) are not hazardous materials under RCRA Subtitle C; the delegation of regulatory authority under RCRA Subtitle D for solid waste allows various states to regulate the use and disposal of CCBs by very different standards (EPA, 1993). Some states restrictively control CCBs as a de facto hazardous material, while other states treat recycled ash as an unregulated construction material (Jagiella, 1993). Some states regulate CCBs on a case-by-case basis. In recent years, several states have adopted statutes prohibiting the importation of solid wastes. Although these statutes have been regularly overruled as restraint of trade, their temporary status has impeded ash sales in some instances.

The principal federal statute affecting the regulation of solid waste, and therefore related beneficial use, is RCRA. Other federal environmental statutes that may affect barriers to CCB utilization are the Clean Water Act and CERCLA. A 1988 summary of state statutes compiled by the Utility Solid Waste Activities Group (USWAG) identified 43 states that exempt CCBs from hazardous waste regulations; seven states-Kentucky, Tennessee, Oklahoma, Washington, New Jersey, Maine, and California-require testing to determine whether the ash would be regulated as a solid waste or a hazardous material and one state, Ohio, exempts CCBs from both solid and hazardous waste regulations (Wald and others, 1983).

Legal review is needed to clarify the grounds and remedies that apply to environmental liability. As a general consideration, statutory liability under environmental law is not based on fault and imposes strict responsibility without regard to negligence. Tort law, on the other hand, applies where a dangerous condition can be traced back to the point of manufacture of a product, which is not a condition that commonly applies to CCB utilization. The commonly held opinion, that semantic reclassification of CCBs as a product rather than a solid waste would by itself simplify regulatory liability, appears to have little legal validity since the intent of the statutes would not change and their wording could be readily adapted. Also, compliance with one statute would not remove jeopardy on others: therefore, compliance

with state regulations under delegated RCRA authority does not prevent liability under the Clean Water Act or CERCLA. The CERCLA statute appears to be the broadest statute covering hazardous materials that present "substantial danger to public health or welfare or the environment," and it incorporates by reference any substance designated as hazardous or toxic in the Clean Water Act or RCRA (Findley and Farber, 1992). CERCLA places strict liability for remediation and restitution on the party responsible for the hazardous material without regard to negligence. However, it is very significant to note that petroleum and natural gas are specifically exempted from liability under CERCLA. This type of exemption from liability establishes a precedent that could appropriately be considered in legislation for CCBs, owing to its importance as the largest- volume recyclable material in the United States and the record of environmental testing that indicates CCBs are not hazardous substances, pollutants, or contaminants.

Other legally recognized remedies for environmental liability, apart from statutory exemption, involve demonstration of compliance with a regulatory authority based on recognized technical specifications and environmental criteria. Improved regulatory classification of CCBs for use in various classes of applications would help to reduce environmental liability by providing background and specificity for legally defending particular utilization practices. By controlling the end use of CCBs, utilities and marketers can limit their liability by providing material only for those uses that are demonstrated to be environmentally safe (Hudson and others, 1982). More effectively, exemption from regulatory control as solid wastes under RCRA could be provided for pre-approved classes of by-product use. Although such federal deregulation of pre-approved products may be politically difficult, it would permit approved CCBs to move into unrestricted interstate commerce. Federal regulatory clarification and improved specifications would, at a minimum, provide leadership and direction for state regulators.

Some difficulties may exist in applying commercial or contract law to the sale of CCBs because of the current lack of both technical specifications and environmental criteria applying to some uses. Suggestions have been advanced for developing a uniform commercial code for by-product transactions that would incorporate specifications to assist buyers and sellers in writing clear and enforceable contracts. Legal research is needed to establish the usefulness of this approach. As better specifications are incorporated, quality control in the production of CCBs becomes a more significant factor in meeting legal responsibility (Hudson and others, 1982).

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## LUNCHEON REMARKS

Kathrine L. Henry, Acting Director  
Office Of Surface Mining  
U.S. Department Of The Interior

It is indeed a pleasure to be here today at Southern Illinois University for three **days** of discussion and information sharing on an important environmental topic. I am glad that so many people from so many parts of the country are participating, from all levels of government, and from industry, universities, and the general public. This is an excellent venue for communicating problems, solutions, and concerns related to coal combustion by-products associated with surface mining. I especially want to thank our colleagues from Southern Illinois University for hosting this forum, and I'd like to recognize the other sponsors, as well:

- . The Illinois Clean Coal Institute
- . Illinois Office of Mines and Minerals
- . Indiana Division of Reclamation
- . Texas Utilities, Inc.

Most of us think of what's left after burning coal as simply "ash." But as with so many environmental aspects of coal mining and coal use, it turns out there's much more to it than that. As a lawyer, I promise not to come before this audience as a technical expert, because my area of expertise is in the law, not chemistry, soil science, agronomy, hydrology, or any of the related fields we depend on for scientific solutions to environmental problems related to mining and using coal. But I would like to summarize where we are in dealing with issues related to coal combustion by-products, and how we got there.

In May of 1994, OSM solicited recommendations for technical studies and applied research topics from the states, industry, and public interest groups. A wide variety of them identified the field of coal combustion by-products as a priority topic for consideration. In September of 1995, OSM began assessing interest in a national interactive forum on coal combustion by-products associated with coal mining. Then in February of 1996, a steering committee was formed to organize and develop such a forum. That brings us to today. The meetings we are now participating in are the result of the combined efforts of numerous interested parties to make this timely and much needed discussion possible.

Back when the Surface Mining Control and Reclamation Act (SMCRA) was passed in 1977, planning for any significant utilization or disposal of coal combustion by-products at surface coal mines did not seem like much of a concern. OSM regulations provide guidance for protecting surface and ground water quality. They also require specific plans for the disposal of coal cleaning wastes and non-coal wastes normally associated with on-site repair shop facilities. Neither SMCRA nor the OSM regulations, however, specifically address the use or disposal of the by-products of electric power generation at surface coal mines, even though a truly systematic plan for producing and using coal would logically take into consideration what to do with the final waste products, things like ash, for instance. After all, according to the First Law of Ecology, *Everything Has To Go Somewhere*.

Since those early days of SMCRA, dramatic changes have taken place. More people are starting to take a more full-systems, full-circle look. U.S. coal consumption is now approximately one billion tons per year. It's increasing at a rate of 2 percent per year. Eighty percent of that coal is used as fuel for the generation of electrical power. Major environmental legislation passed during the 1970s and more recently in 1990, has led to significantly increased removal of contaminants associated with coal fired electric power generation. That is, power plants practically everywhere are requiring cleaner coal, and clean air regulations are requiring more emission control. It's working. Sulfur emissions produced by burning coal have *declined* by 11 percent for the entire U.S. over the period 1970 through 1992, while at the same time coal consumption *increased* by 70 percent.

Where did all that “stuff” go? Controls on particulates and acid forming chemicals from electric utility stack gases plus the addition of more stringent controls on water discharges and waste disposal have provided the nation with effective solutions for improving air and water quality at electrical power plants, no doubt about it. But those very solutions to the problem of air and water contaminants associated with coal fired power plants have generated new challenges for the coal mining industry and for the state and federal programs charged with environmental regulation of coal mining activities. A big part of the challenge comes from the production of large volumes of fly ash, bottom ash, boiler slag, spent bed material from fluidized bed combustion, and flue gas desulfurization residues, collectively referred to as coal combustion by-products. That’s why I no longer think of it simply as “ash.”

More important to the discussions at this forum is the idea of taking the system full-circle, that is, looking at the potential for coal mines to be disposal sites for excess solid residues, and a potential market for products derived partly or wholly from coal combustion by-products. Logically, it makes perfect sense.

To give an idea of the immense volume of coal combustion by-products being generated, our late lamented sister agency, the U.S. Bureau of Mines, provided an estimate. They calculated that a typical power plant burning 100 rail car loads of high sulfur coal (3.5 percent sulfur) will produce 30 car loads of coal combustion by-products. Total annual production of such residues in the U.S. has risen from approximately 68 million tons, at the time of the passage of SMCRA in 1977, to over 100 million tons today. The total could exceed 170 million tons by the year 2000. That’s a 240 percent increase over a period of just 23 years. As I said before, Everything Has To Go *Somewhere*.

Although a major emphasis of this administration and the electric utility industry has been to recycle coal combustion by-products into economically viable commodities, the recycling of coal combustion by-products has remained steady at around 25 percent over the last decade. Potential uses on the mine site have included:

- Injection as fill into old underground mines to combat or reduce subsidence.
- Use as a soil amendment to neutralize acidic spoil and thereby reduce acid mine drainage.
- And as a an ingredient in synthetic concrete substitutes for traditional underground mine timbers.

OSM supports those efforts to recycle coal combustion by-products into commercial items for use on or off the mine site. Despite everything that’s been done to create economically viable products for those residues, however, only about one-quarter of them are used in that way. The other 75 percent of the coal combustion by-products still has to be stockpiled or disposed of, *somewhere*. Interest in coal mines as potential disposal facilities or markets for new products produced from coal combustion by-products has gone up with the dramatic cost increases and mounting difficulties involved in handling those residues on site at coal fired power plants. Typical costs for disposal of solid residues produced by coal combustion in a new disposal facility are at least two to three times what it costs to dispose of them at existing sites, So why not keep on using the existing sites? Well, many existing disposal facilities are just about full. When they reach their design capacity, the next step is to replace them with new disposal facilities that, unfortunately, cost lots more.

In 1993, the Environmental Protection Agency issued its final regulatory determination that coal combustion by-products are deemed non-hazardous and are to be regulated by the individual states under Sub-title D of the Resource Conservation and Recovery Act, when disposed of as solid waste. As a result, the states have been challenged to develop appropriate strategies for integrating the concerns of state solid waste programs with SMCRA programs regarding disposal on permitted coal mine sites.

When the use or disposal of coal combustion by-products happens at surface coal mines, state coal mining regulators are involved to the extent that SMCRA requires:

- The mine operator to ensure that all toxic materials are treated, buried, and compacted, or otherwise disposed of, in a manner designed to prevent contamination of ground or surface water.
- Making sure the proposed land use does not present any actual or probable threat of water pollution.
- And ensuring the permit application contains a detailed description of the measures to be taken during mining and reclamation to assure the protection of the quality and quantity of surface and ground water systems, both on- and off-site, from adverse effects of the mining and reclamation process, also to assure the rights of present users of such water are protected.

Any disposal of coal combustion by-products at mine sites must be in accordance with those standards, and with applicable solid waste disposal requirements. The states differ in their regulatory requirements for disposal of coal combustion by-products as solid waste. Trace element concentrations in coal combustion by-products vary according to where the coal came from. Chemical and physical characteristics differ by region, as do mine site conditions. Accordingly, regulatory programs to allow use or disposal must be designed to handle those differences. At OSM, we are supportive of state efforts to develop appropriate methods and criteria. We will do what we can to help, on request.

Currently, the debate over use or disposal of coal combustion by-products at coal mines centers on the potential for the materials to release toxins back into the environment. We recognize that improved knowledge of the risks and benefits associated with disposal and use of coal combustion by-products, is badly needed, as is a greater acceptance of that knowledge by regulators and the public. The more we know, the more options we have. So I look forward to the discussions that will take place at this forum. I am optimistic that constructive dialogues such as those held here will lead to better understanding of the benefits and risks involved with using coal combustion by-products associated with coal mining.

Thank you for inviting me here today. I commend all the forum participants for being part of this valuable information exchange. The public and the coalfield residents can only benefit from the information that is shared and the knowledge that is gained at this event. I thank you for applying your minds to the task and I wish you success in your efforts on behalf of the coalfield environment.

**Session II:**

**SITE CHARACTERIZATION**

**Session Chairs:**

**Shawn Glacken**  
**Texas Utilities Services, Inc.**  
**Dallas, Texas**

**Richard Shockley**  
**Illinois Clean Coal Institute**  
**Carterville, Illinois**

## **COAL COMBUSTION BY-PRODUCTS THE WESTERN U.S. PERSPECTIVE**

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### **Abstract**

Coal Combustion By-Products (CCBP) production and the subsequent use both on-site and off-site are currently environmental and economic concerns throughout the Western U.S. for electric utilities. Texas Utilities presents the Western U.S. perspective by providing local information on CCBP production and uses on-site at lignite mining operations and electric generation facilities.

### **Introduction to Texas Utilities**

The Texas Utilities Company consists of six (6) principal subsidiary companies that include: TU Electric, TU Australia PTY. LTD., Southwestern Electric Service Company, TU Services, Texas Utilities Fuel Company and Texas Utilities Mining Company. The primary business of United States operations is to bring low cost and reliable electric service to approximately 2.4 million customers in 101 Texas counties with 89 billion kilowatt-hours of electricity. The customer base is composed of residential and large industrial facilities. Twenty-four generating facilities give the System 22 million kilowatts of power resources. Fuel sources range from fossil fuels such as natural gas, oil, lignite and western coal to nuclear fuels and renewable resources.

TU Electric provides, through various business units, generation, transmission, distribution, marketing and customer service to North Central, East and West Texas. Southwestern Electric Service Company, acquired in 1993, provides service to areas in North Central and East Texas.

Texas Utilities Fuel Company provides natural gas and fuel oil to TU Electric generating facilities through a 2,100-mile pipeline system and with 27 million cubic feet of underground storage. TU Electric, with this system and by direct connection to other suppliers, is the nation's largest consumer of natural gas, using about 15 percent of all natural gas consumed by electric utilities. Texas Utilities is also in the process of completing the acquisition of the ENSERCH Corporation which is the parent company to several natural gas related businesses including the Lone Star Gas Company, Texas' largest gas company.

Texas Utilities Mining Company (TUMCO) is the mining unit within the system and is the largest lignite producer in Texas. We are presently rated as the 5th largest mining company in the nation and the largest mining company in relation to overburden removed to obtain the mined product. Lignite is produced at mine-mouth operations for use in TU Electric generation facilities where 100% of the lignite produced is consumed.

TUMCO has three primary lignite mines with two of the mines containing satellite operations. Currently, more than 104,000 acres of land are regulated under permits issued by the Texas Railroad Commission. Mines range in size from 1,200 to more than 26,000 acres. Eleven mine permits are active plus other associated permits required for operation.

Mines operate as surface mines with a successive series of narrow, parallel pits. Equipment such as draglines, bucket wheel excavators and cross-pit spreaders provide overburden removal. Lignite transportation is accomplished by a combination of haul roads, service roads and rail transportation for movement of material from remote locations.

## Other Electric Utilities in Texas

Other regions within Texas receive electric service from various public and private utilities. These utilities include small local cooperatives and large corporations with residential, rural and industrial customers. Major utility companies include Central & Southwest, Houston Lighting & Power and Entergy.

### **Regional Perspective & Characteristics**

Texas Utilities Mining Company operates mines at locations within North Central and East Texas. The Big Brown Mine is in Freestone County approximately 90 miles south of Dallas. Directly east of Dallas in Titus County, is the Monticello Mine with a satellite operation in Hopkins County. Further to the southeast in Panola County, near the Louisiana border, are the Martin Lake Mine and the satellite Oak Hill Mine in Rusk County.

Terrestrial and aquatic wildlife, within the area surrounding these mines, is typical of species that inhabit the Texan and Austroriparian biotic provinces (Blair, 1950). The forested Austroriparian biotic province, as described by Blair (1950) is bordered on the west by the Texan province. It extends eastward from east Texas to the Atlantic coastal plain and as far north as the Dismal Swamp in southeast Virginia. Species range from forest dwellers to grassland inhabitants and transitional species between the two provinces. Many species are local inhabitants throughout much of East and North Central Texas.

## Typical Wildlife Species in the Area

### Mammals

white-tailed deer (*Odocoileus virginiana*)  
Virginia opossum (*Didelphis virginiana*)  
fox squirrel (*Sciurus niger*)  
cotton mouse (*Peromyscus gossypinus*)  
gray squirrel (*Sciurus carolinensis*)  
common raccoon (*Procyon lotor*)  
beaver (*Castor canadensis*)  
coyote (*Canis latrans*)  
fulvous harvest mouse (*Reithrodontomys fulvescens*)  
nine-banded armadillo (*Dasyus novemcinctus*)

### Birds

northern mockingbird (*Mimus polyglottos*)  
mourning dove (*Zenaida macroura*)  
red-winged blackbird (*Agelaius phoeniceus*)  
great blue heron (*Ardea herodias*)  
red-eyed vireo (*Vireo olivaceus*)  
Carolina wren (*Thryothorus ludovicianus*)  
northern cardinal (*Cardinalis cardinalis*)  
blue jay (*Cyanocitta cristata*)

### Reptiles

ornate box turtle (*Terrapene ornata ornata*)  
western cottonmouth (*Agkistrodon piscivorus leucostoma*)  
east Texas toad (*Bufo woodhousii*)  
bullfrog (*Rana catesbeiana*)  
common snapping turtle (*Chelydra serpentina serpentina*)  
red-eared slider (*Trachemys scripta elegans*)

Texas Utilities Mining Company operations are found within three distinct vegetational regions in Texas including the Post Oak Savannah, Blackland Prairies and Pineywoods (Gould, 1975). Historically, between regions, vegetation is variable and ranges from: 1) open prairies with tall grass climax communities of little bluestem, 2) savannahs of oak, oak-hickory and tall grasses, and 3) extensive pine and pine-hardwood forests.

Land uses include the full spectrum of uses typical of East and North Central Texas. These include cropland, pastureland, grazingland, forestry, fish & wildlife habitat, developed water resources, undeveloped land, recreation areas, residential and industrial/commercial. Most of the area is rural in nature with scattered pockets of urbanization near major transportation routes. Rural areas are predominately agricultural in nature with primary land uses dictated by vegetational region. East Texas is dominated by land uses such as forestry and undeveloped areas intermixed with pastureland. Areas to the north and west are dominated by pastureland and grazingland areas intermixed with remnant bottomland forests that are vestiges of past forestland.

Generally, much of East and North Central Texas was affected by farming and forestry activities that occurred from the mid to late 1800's through the 1950's. Historic agricultural practice ranged from intensive cotton farming over large areas to truck farming of fruits and vegetables. The trend throughout the area has been from intensive land use for market crops to less intensive pastureland and grazingland for livestock production. Forestry activities, although controlled to some extent by regional vegetation, have ranged from intensive production of saw-logs to harvesting timber for pulpwood operations. Land uses associated with commercial/industrial activities include oil and gas operations and lignite mining.

The primary geologic features associated with Texas lignite include three geologic units - the Wilcox Group, Jackson Group, and YEGUA Formation (Kaiser, 1980). These units are associated with three ancient depositional systems - fluvial, deltaic and strandplain/lagoonal. The Wilcox and Jackson Groups are the most important lignite bearing units with 90 percent of resources occurring north of the Colorado River. Texas Utilities Mining Company lignite mines are all in the Wilcox Group. Economically minable lignite seams range from 2 ft thick or thicker at depths ranging from 20 to 200 ft.

Soils associated with these mines are predominately of the soil orders Alfisols and Ultisols. Alfisols are characterized by gray to brown surface horizons with medium to high base supply, and with subsurface horizons of clay accumulation. They are usually moist but may be dry during the warm season and occur on gently or moderately sloping areas of rangeland, small grain and irrigated crops. Ultisols are characterized as usually moist soils on moderately sloping to steep areas in woodland and pasture with a horizon of clay accumulation and a low base supply. Soil and overburden material characteristics generally show pH and acid-base accounting values higher in the oxidized sediments than the reduced sediments.

### **Coal Combustion By-Products (CCBP)**

The major fossil fuels used throughout Texas by electric utilities are natural gas, western coal from the Powder River Basin and Texas lignite. Texas Utilities uses a variety of fuel resources to diversify fuel use and to balance fuel cost. Fuel resources, in order of use, include lignite, natural gas and nuclear. Since the use of western coal is new at Texas Utilities, only CCBP from the combustion of lignite will be addressed in relation to Texas Utilities Mining Company and TU Electric operations.

On average, Texas Utilities produces 30,000,000 tons of lignite annually for use by generating facilities. From this production, approximately 5.7 million tons of CCBP are produced in the following categories.

Tons	Type of CCBP Produced
3,400,000 tons	fly ash
1,600,000 tons	bottom ash
726,000 tons	flue gas desulfurization material

CCBP include fly ash, bottom ash and flue-gas desulfurization material. Each is defined as follows:

- Flv ash is the fine, light residue carried out of the boiler in the exhaust gases. It is removed from the air by an electrostatic precipitator or a baghouse.
- The larger, heavier material, bottom ash, falls to the bottom of the boiler/furnace system and is collected in a hopper.
- Flue-gas desulfurization material (FGD) results from exhaust gases passing through scrubbers, where pulverized limestone reacts with sulfur particulate and binds together forming these materials.

The volume of CCBP produced is related to the constituents within combusted material. Constituents within Texas lignite are variable between geologic groups and even within lignite seams at the same mine. Typically, lignite of the best quality occurs in the Wilcox Group north of the Colorado River and the poorest quality material is from the Jackson Group with YEGUA lignite intermediate between Wilcox and Jackson. Btu/lb values range from 7,500 to 4,500. Wilcox lignite on average has 33 percent moisture, 15 percent ash, 0.9 percent sulfur and a heat value of 6,000Btu/lb.

#### Bottom Ash Use by Texas Utilities

Bottom ash is the primary CCBP used by Texas Utilities. Of the 1.6 million tons produced annually, approximately 230,000 tons of bottom ash are beneficially used each year at lignite mines and generating facilities.

Bottom ash is beneficially used by Texas Utilities Mining Company for various purposes related to transportation. These uses are beneficial due to economic benefits, material availability, product adaptability and Texas Utilities commitment to recycling and use of CCBP.

Bottom ash is used primarily as a cost-effective surfacing material for ramps and access roads in active mining and reclamation areas. All weather access is a critical component to the management of coal mining and reclamation activities. Lignite mining is a year round process that is done 24 hours a day. Access into mine pits is accomplished through the use of ramps. Ramps are constantly being moved or extended as the mine pits progress to keep up with the dynamics of the mining operation. Bottom ash is used to surface ramps to maintain suitable traction for 100 to 150 ton lignite haul trucks and service vehicles moving in and out of pits. As mine areas progress, reclamation activities immediately follow. A system of roadways is necessary to gain access for leveling and revegetation operations. Many of these roads are surfaced with bottom ash. Once reclamation is complete, the access road system may remain as a beneficial feature for future management of the land. The physical characteristics of bottom ash and its availability provide a durable and economical source of surfacing material for transportation uses at lignite mines.

Construction and maintenance of the transportation system for each mine operation are a major undertaking in relation to capital expense and size. Traction control is required on the curves of major haulage roads. for service roads and for infrequently used access roads, Use of bottom ash as construction material. primarily as road base and surfacing material, is a primary area of CCBP use. Approximately 110 miles of roads have been constructed using 100,000 tons of bottom ash since mine operations began in 1976.

At certain mine locations, railroad construction is a major area where bottom ash is used as a construction material. Rail lines are an integral part of some Texas Utilities Mining Company mines. They may be used to connect mine areas within a mine, mines to generating facilities or to connect generation facilities to CCBP disposal areas. It is estimated that a rail spur currently being constructed will use approximately 12,000 tons of bottom ash to set drainage culverts. The use of bottom ash instead of purchased material for this project alone will result in an estimated savings of \$125,000. In another operation, temporary rail spurs at a CCBP disposal operation are constructed using bottom ash. To date, approximately five miles of rail spur using 9,000 tons of bottom ash have been constructed.

Lignite storage areas, parking lots and temporary 'lay down' yards are other examples of beneficial uses of bottom ash at mine facilities. In one application, 20,000 tons of bottom ash were used as base material for a lignite storage area.

TU Electric began using bottom ash at generating facilities as early as 1976 as light duty paving of temporary access roads, parking lots, drive ways and storage yards. Later, as generating facilities expanded, plant island piping and culverts are bedded with bottom ash due to its granular shape.

#### Other CCBP

Texas Utilities uses fly ash in other applications at lignite mines and generation facilities. Fly ash is used as an additive in concrete and as road base stabilization in conjunction with lime. These uses are infrequent and require only minimal amounts of fly ash compared to fly ash production.

No uses for FGD have been developed at lignite mines or generating facilities.

#### Environmental Issues and Milestones

Reclamation activities that prepare mine soils for planting are one area where Texas Utilities does not use CCBP. Stringent State regulations on postmine soil quality and the possibility of future liability are critical factors affecting the decision to use CCBP in reclaimed soils at Texas Utilities lignite mines. Fly ash and FGD, produced by Texas Utilities, contain trace elements (specifically heavy metals) which if added to reclaimed soils may elevate trace element concentrations above regulatory limits. Federal and State limits on trace elements in reclaimed minesoil make it difficult to justify the use of these by-products as amendments in reclaimed soils.

In 1993, after 20 years of study, the Environmental Protection Agency (EPA) affirmed that CCBP are nonhazardous solid waste and thus fall under the jurisdiction of the states. In Texas, the Texas Natural Resources Conservation Commission (TNRCC) regulates CCBP. The TNRCC, in a letter to the Texas Coal Ash Utilization Group, recognized that CCBP are not waste when used as road base, subbase and subgrade material when covered by a wear surface and used as road construction material. The Railroad Commission of Texas (RCT) has followed the lead of the TNRCC in accepting the use of bottom ash as a useful and environmentally safe material. CCBP are not considered, by the TNRCC, industrial wastes until they are to be disposed.

CCBP are typically either a Class 2 or Class 3 waste material. The definitions of solid waste classes as adopted by the TNRCC are as follows:

- Class 3 Waste - any industrial solid waste which is inert and essentially insoluble. A material's waste classification, among other things, is based on its leachable metals. The leachate must meet drinking water standards set forth by the US EPA.

- Class 2 Waste - any industrial solid waste which cannot be classified as a Class III waste.
- Class 1 Waste - this includes materials which are toxic or carcinogenic or bioaccumulative. Hazardous wastes are determined by the US EPA and are listed in CFR Title 40.

CCBP that are not beneficially used are disposed of according to TNRCC requirements. There are no requirements for the disposal of Class 3 Waste bottom ash from TUMCO's Monticello or Big Brown mines. Bottom ash produced at the Martin Lake mine is a Class 2 waste since its selenium leachate exceeds drinking water limits. Fly ash and FGD material are Class 2 Waste. Class 2 Waste must be disposed in a registered landfill that is typically lined with 3 feet of impermeable clay or a double layered synthetic liner containing a leachate collection system. At the Monticello mine, TU Electric demonstrated to the TNRCC that the soil stratum within mine pits is suitable for containing Class II waste and as a result, a traditional constructed landfill is not necessary.

#### Texas Utilities Off-site Use of CCBP

All forms of CCBP are marketed by Texas Utilities for off-site use in asphalt roofing shingles, concrete, wallboard, commercial carpet backing, plastics, oil field drilling cement and for soil stabilization material. Approximately 330,000 tons are marketed annually for off-site use and recycling. Other uses are being researched to increase beneficial use of these materials and reduce expensive disposal options.

#### **Summary**

CCBP can be used in economical and environmentally sound ways. Texas Utilities has demonstrated that on-site use is practical; although the volume of materials used at mines and generating facilities cannot meet the volumes produced. Excluding elevated trace element levels, fly ash incorporation into reclaimed soils may have potential for positive benefits. Benefits include improved texture and neutralization of natural soil acidity. Further study on this issue is warranted.

Initial impediments to development of beneficial uses were regulatory in nature. Acceptance by regulatory agencies has renewed interest in CCBP recycling opportunities and increased interest in legitimate, beneficial and economical uses. The groundwork for future development of CCBP uses will be continued study and further documentation showing that CCBP have no negative environmental impact.

#### **Acknowledgments**

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**A SUMMARY OF SOIL ISSUES RELATED TO  
COAL COMBUSTION RESIDUES AND SURFACE MINES:  
SITE CHARACTERIZATION FROM A MID-WESTERN PERSPECTIVE**

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**Abstract**

The Midwest is blessed with highly productive soils and a landscape of relatively low relief that offers opportunities and challenges to the coal industry. While the coal itself is a product of an ancient warm landscape during the geologic age known as the Pennsylvanian, Midwestern soils and surficial geology are largely products of the glacial epoch, the Pleistocene. During the Pleistocene, continental glaciers repeatedly overrode the landscape, removing and burying preexisting soils and landscapes and depositing fresh geologic materials, till and outwash, while subduing the terrain. At the close of the last glaciation, the Wisconsinan, wind blown silts, called loess, were deposited over much of the area. Loess is what gives the Midwest productive soils, with its high water holding capacity and supply of nutrients, it is naturally fertile. The chemistry and productivity of Midwestern soils is related to their parent material, age, and initial calcium content. In general, there are abundant, high quality soils and geologic materials.

Acid mine drainage is not as big a problem as in the Appalachian coal areas. Because of the very productive soils, reclamation of surface mines is held to a high standard. Where prime farmlands were mined, productivity of reclaimed surface mines must meet target yields set on nearby unmined areas. Coal combustion residues (CCR) may be disposed of in active mines or serve to increase productivity of reclaimed soils that are deficient in pH or the nutrients that it can supply. Residues may also be used as an aid to revegetate abandoned surface mines that have similar deficiencies. However, the application of CCR materials must be done with an achievable objective in mind and with both the site characteristics and the properties of the CCR materials carefully considered.

**Introduction**

The history of surficial geology and soils in the Midwest is the story of glaciation (Fehrenbacher et al. 1984). Several times in the Pleistocene, known as the Ice Age, much of the Midwest was overridden by continental glaciers. These glaciers served as giant bulldozers that reduced the relief and removed preexisting materials and deposited fresh materials, till and outwash, on the landscape. Till is material moved directly by a glacier. It is of variable texture and may be compacted due to the weight of the ice. Outwash is material washed away from a glacier by running water. It tends to be stratified and coarse textured.

During glaciation, older, infertile soils were removed or buried and replaced with younger, more fertile soils. At the end of the most recent glacial period, the Wisconsinan, vast deposits of wind blown silts, called loess, blanketed much of the Midwest, even beyond the glacial margins. Loess was an added bonus of glaciation. It is inherently fertile, rich in calcium to the point of being calcareous initially, and has a high water holding capacity. Soils that develop from loess parent materials are among the most productive in the world. This high productivity presents a challenge to reclamation specialists because of the high expectations for reclaimed mine soils,

Surface mining exposes buried geologic materials or overburden. Some of these materials are of reasonably good quality, and some are undesirable. Pleistocene deposits may be lacking or a minor portion of the overburden but are occasionally deep and also comprise most of the parent materials for Midwestern soils. Deep deposits of loess and till are usually calcareous, but buried paleosoils may be infertile. Outwash can be sandy and drouthy, or of a more desirable medium texture. The Pennsylvanian aged rocks below the Pleistocene materials include sandstones, limestones, and shales and the coal itself.

Pyrite may be associated with the coal. If allowed to oxidize, it will form sulfuric acid. Sandstones tend to be infertile and produce coarse fragments. Shales are often calcareous, as are unweathered Pleistocene materials and limestone, so acid mine drainage is generally not as significant an issue as in the Appalachian coal fields. The low relief of the Midwest also contributes to the rarity of acid mine drainage because acid generating materials are easily buried as part of reclamation and there are few high walls exposed which could allow acid seeps.

Coal combustion residues (CCR) can make a contribution to reclamation of surface mines in the Midwest. Despite the generally favorable nature of the soils and geological materials, there are areas with low pH and low contents of calcium and other nutrients that CCR might supply. In addition, in some situations, the moisture holding capacity of the soil may be improved by the addition of appropriate CCR materials. However, some characteristics of CCR materials may be undesirable under certain circumstances. The application of CCR materials must be done with an achievable objective in mind and with both the site characteristics and the properties of the CCR materials carefully considered.

### **Site Characterization**

Post surface mining landscapes in the Midwest range from virtual “moonscapes” to areas where a casual observer could not detect evidence of mining. Most of this range in possibilities was driven by changing state and federal laws that required increasing amounts of reclamation over the years. Pre-law mined areas largely reflect nature’s ability to recover from disturbance. Midwestern natural landscapes have generally low relief that is relatively easy to mimic in reclamation and the high natural fertility of many of our soils and geologic materials allows vegetative growth to cover the scars in many instances. Depending on local conditions, soil infertility due to the presence of acid generating material or to the lack of nutrients may be a problem. Soil erosion can also be a problem on steep or unvegetated sites. Plant productivity can also be a problem due to drouthy conditions caused by poor moisture holding conditions, or poor rooting depth due to soil compaction. Soil compaction is especially a problem where soil materials were placed with rubber tired vehicles. It is important to know the characteristics of the site in question before reclamation efforts are undertaken.

#### Physical Properties of Soils

Soils are a three-phase system, solids, gas, and liquid. The solids in soils include organic and inorganic material. Organic materials in soils include decomposed plant and animal remains and generally account for less than 5% of the total mass. Organic materials increase soil fertility but are generally lacking in mine soils. Inorganic material includes minerals formed in the soil and rock fragments inherited from the parent geologic material. As a rule of thumb, inorganic materials account for more than 95% of a soil’s mass and 50% of a soil’s volume. Materials <2mm in diameter are included in conventional soil analyses and material >2mm are considered coarse fragments and include material ranging in size from gravel to boulders, Inorganic materials provide mechanical support and serve as a water and nutrient reservoir. Soil fluids and gases occupy void spaces between the solids. The composition and relative abundance of air and water in soil is quite variable, depending on rainfall patterns, temperature, and other climatic and soil variables. The amount of void space in a soil depends on soil texture, structure, and compaction. Access to the appropriate amount of water and air by plant roots is necessary for plant productivity and survival.

Soils exist as part of a landscape. Topography, or relief, is the most obvious aspect of any landscape. Surface mining greatly alters topography because the very act of mining requires removal of all the materials above the coal. The post-mining landscape is largely dictated by the laws in place at the time of the mining. Pre-law surface mines are often composed of irregularly sloping piles of overburden or a series of sub-parallel, steep sided ridges. These piles and ridges are composed of a highly variable mixture of materials moved in the mining process. Soils in this situation tend to be erosive, high in coarse fragment content, low in fertility, and drouthy compared with the pre-mining, undisturbed soils. As reclamation regulations strengthened over the years, post-mining landscapes became more similar to

the pre-mining conditions. Most recent law, the Surface Mining Control and Reclamation Act (SMCRA), requires grading to roughly the original topography and replacement of topsoil and rooting media of similar thickness and composition to the pre-mining soils. The resultant soils are not the same as the pre-mining soils. Removal, storage, transport, and placement of soils all influence the quality of the reclaimed soil. Soils tend to become compacted during handling, particularly if rubber tired scrapers are used. Much of the microbial population dies in storage. These problems can be corrected with careful soil handling and appropriate tillage and amendments.

### Chemical Properties of Soils

Soil chemistry includes consideration of both the presence of adequate nutrients to support desired plant growth and the absence of undesirable or toxic materials. Soils have the capacity to store chemicals as cations or anions sorbed to mineral surfaces or as dissolved species in soil water or as a solid part of the soil matrix itself. Ions sorbed to soils can be released to plant roots or to the soil water. The capacity to sorb cations is called the cation exchange capacity (CEC) and is often included in soil fertility tests because most plant nutrients are cations. Soils with high CEC have the ability to store nutrients and resist changes in pH. Soil pH, the measure of hydrogen ion activity, is the most common chemical measurement made in soils. Low pH indicates acid conditions, high pH indicates basic conditions. Most agricultural plants prefer a near neutral pH in the range of 6.0 - 6.5, and liming materials are routinely added to soils to maintain their proper pH (Illinois Agronomy Handbook, 1994). CCR materials may serve as liming agents if they contain calcium carbonate or other suitable alkaline materials. Along with pH and CEC, soil fertility tests can include primary, secondary, and micronutrients.

Major nutrients include N, K, and P. These nutrients, along with lime, are routinely added to agricultural soils. Nitrogen (N) is often not tested because the results are difficult to interpret. Potassium (K) is often abundant in mine soils. Phosphorus (P), may be low in mine soils. CCR materials would generally not be a source of these nutrients. Secondary nutrients include Ca, Mg, and S. Calcium generally is not limiting in soils with a pH above 5.5. Magnesium is generally not limiting in Midwestern soils except in acidic or sandy conditions. Mine soils with low pH could be deficient in these nutrients. CCR materials would be expected to be rich in these nutrients. Sulfur deficiency in agricultural soils is becoming an increasing concern because a major source was air pollution. The S that no longer contributes to air pollution is now contained in some CCR materials that could be applied to ameliorate S deficient soils.

Micronutrients are often not included in routine soil fertility tests because of costs and because they may not be limiting. The fresh geologic materials exposed by mining may be rich in micronutrients. An important micronutrient to test for when considering adding CCR to soils is boron (B), which may be plentiful in CCR materials, deficient in soils, but is toxic in large amounts.

A consideration of applying large amounts of CCR materials is the salt content. Depending on the drainage of the soil and its CEC, salt may be dissolved in the soil water, or accumulate in the soil. Salts and other chemicals in soil water may be flushed from the soil and move with the groundwater.

Solid materials generally do not play an important role in soil chemistry unless they dissolve or otherwise become water soluble. An important example of this is the mineral pyrite that can oxidize to form sulfuric acid, which creates serious consequences for reclamation. Alkaline materials in some CCR materials such as calcium carbonate can be used to counteract the potential acid generating materials in mine soils and wastes.

### Summary

Soils found in areas that have been surface mined are a highly variable mixture of everything that was left near the surface after mining. In pre-law mines, it is called "overburden" and consists of a

mix of Pennsylvanian bedrock fragments and Pleistocene materials. Landscapes are as the mining machines left them; sloping ridges or chaotic piles. Erosion, excessive coarse fragment contents, drouthiness, infertility, and acid generation can all be problems in these areas. Modern reclamation regulations essentially require replacement of the original soil and landscape. With modern reclamation, soil chemistry and other characteristics are reasonably similar to the pre-mining conditions, however soil compaction can be a problem. Coal combustion residues can be simply buried in active mines or serve as amendments to increase soil fertility, micronutrients, pH, or moisture holding capacity. However, they may also contribute excess salts or toxic materials to the soil or groundwater. In working with surface mined areas and coal combustion residues, the important thing to remember is to have a reasonable objective and to properly characterize the soils and coal combustion by-products or other soil amendments of interest.

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## **POTENTIAL USE OF COAL COMBUSTION BY-PRODUCT (CCB) IN THE EASTERN COAL REGION: SITE CHARACTERISTICS**

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### **Abstract**

The Eastern mining region presents numerous beneficial re-use environments for CCBs. Chief among these are use as an amendment for minespoil and coal refuse. These materials are difficult to reclaim due to low water holding capacities and in many cases high levels of acidity. In addition both spoil and refuse contain iron pyrite ( $\text{FeS}_2$ ) and have the potential to produce acid mine drainage (AMD). The addition of alkaline CCB's would modify the coarse textures of spoil and refuse and add alkalinity needed to neutralize acidity. The mission of the American Coal Ash Association (ACAA) is to advance the use of coal combustion byproducts (CCBs) in ways that are technically sound, commercially competitive and environmentally safe. The use of CCBs is affected by local and regional factors including production rates; processing and handling costs; transportation costs; availability of competing engineering and manufacturing materials; seasonal factors; and the experience of materials specifiers, design engineers, purchasing agents, contractors, legislators, regulators and other professionals.

### **Introduction**

The Eastern coal mining region stretches from northern Alabama to northern Pennsylvania, and includes the coalfields of Tennessee, eastern Kentucky, Virginia, West Virginia, Ohio, and Maryland. In 1993 the region produced 409 million tons of coal of which 45 % was extracted using surface methods with the remainder extracted by deep mining (EIA, 1996; Table 1). About 60% of the regions production comes from the coal fields of West Virginia and E. Kentucky. The region contains two large coal fields and the boundary between these fields is situated in West Virginia. The coal fields of Northern WV, PA, MD and OH, generally contain higher sulfur and than the coals of southern WV, KY, and VA. The coal bearing strata are mid-Mississippian to Pennsylvanian in age. Coal beds are interstratified with shales, siltstones and sandstones. The average seam thickness is 5.5 ft. and some seams may be as thick as 12 feet.

Within the region it has been estimated that > 1.2 million acres of surface mined lands need to be reclaimed (Sutton and Dick, 1987). This figure does not take into account the acreage of coal refuse piles which also need to be reclaimed. Minespoil, overburden material blasted and moved during the surface mining process, and coal refuse, the material cleaned from the coal at a coal preparation plant, are the two waste materials from coal mining in which the beneficial reuse of CCB's could take place. Both minesoils and coal refuse are being produced by active mining activities and are found on abandoned mined land (AML) sites. Active operations have an advantage in potential CCB reuse in that equipment for incorporation of CCB's is on site. On most AML sites CCB use would be limited to surface applications which may not effect the acid generation from the whole pile of material.

### **Minespoil**

Minesoil (soils derived from minespoil) properties, like soil properties, vary due to differences in geology, topography, climate, vegetation, the actions of organisms. Minesoil properties also depend on the mining and reclamation methods, which could be considered the acts of organisms. During the mining process in the Midwest and West, the A, B, and C horizons are often separated, stockpiled and then replaced after mining. Often the soils in the eastern region are too thin to allow the separation of

horizons and minesoils are formed from all material above hardrock that can be moved with a bulldozer. In other cases mines are granted a permit variance and the minesoil is formed from suitable crushed rock from the minesite itself. In either case the resultant minesoil bears little resemblance to the native soil. During the mining process soil structure is destroyed and flow paths are disrupted. Often the materials are severely compacted during placement. The large coarse fragments in the material may also bridge and create large voids in places. A network of these voids may give areas of a spoil pile a pseudo-karst hydrology in which water may move very rapidly.

Table 1. Coal Production from the Eastern Region for 1993 (EIA, 1996).

State	Tons Mined (Millions)	Tons Surface Mined (Million)	% Surface Mined
AL	24.8	9.6	38.7
E. KY	120.1	61.4	51.1
MD	3.3	0.8	25.1
OH	28.8	18.5	64.2
PA	59.6	24.5	41.1
TN	3.0	1.2	38.0
VA	39.3	12.2	31.3
N. WV	33.6	8.5	25.3
S. WV	96.9	47.6	49.2
Total	409.4	184.5	45.0

In modern mining, testing allows the operator to determine which strata will produce the best minesoils and strata which are high in iron pyrite are isolated from drainage and buried to avoid the placement of potentially toxic material at the surface. When oxidized iron pyrite produces acid mine drainage (AMD), and is the source of the high levels of acidity associated with these sites. In older sites and AML sites such technology was not used and unsuitable materials were placed at the surface. These sites often require the use of large amounts of liming agents for reclamation.

#### Coal Refuse

Coal refuse is known by other names such as minestone, coal mining wastes, colliery spoil, colliery discard, mine gob, and slate. Coal refuse is primarily waste rock material that is mined along with the coal and subsequently removed at a coal preparation plant. The source of this waste rock is portions of the mine roof and floor mined along with the coal, partings in the seams, and other geological waste in the coal seam. After separation, refuse is disposed in a pile or valley fill near the preparation plant. Depending upon the coal seam, the refuse may comprise from 10-50% of the mine run material. The passage of the federal Surface Mining Control and Reclamation Act (SMCRA) of 1977 set management guidelines and rigorous geotechnical standards for these areas. The SMCRA standards also apply to surface mined areas. Prior to SMCRA, refuse piles were more loosely constructed, and erosion and spontaneous combustion were common problems. After SMCRA, refuse piles were constructed differently. Coarse refuse (>0.5 mm) was commonly used to build an impoundment dam, behind which the finer material (slurry) was pumped and subsequently dewatered. These "zoned" fills are now commonly employed in valley heads throughout the Appalachian coalfields.

The federal SMCRA further required that these areas be reclaimed with a 1.2 m (4 ft.) lift of topsoil and a diverse, self-sustaining (5 yr) vigorous plant cover. Generating that much topsoil cover from the thin native soils of Appalachia was difficult, and interest in direct-seeding refuse led to varied research in the use of amendments and reduced topsoil thicknesses on coal refuse (Daniels et al., 1989;

Joost et al., 1987; Nickerson, 1984; Jastrow et al., 1981). Other research has examined refuse from the aspects of mineral recovery (Robl et al., 1976), soil characterization (Delp, 1975), material characterization (Buttermore et al., 1978; Stewart and Daniels, 1992), and engineering properties (Skarzynska, 1995; Albuquerque, 1994).

### Coal Refuse Properties

*Particle Size:* Most modern coal preparation plants handle the coarse (> 0.5 mm) and fine (< 0.5 mm) coal refuse in different cleaning circuits. Coarse coal refuse initially contains very little fine material, which can change as weathering takes place. A study of refuse piles in West Virginia (Moulton et al., 1974) determined that fresh refuse contained 68-95% coarse material, while 18 month to 30 year-old material contained 47-80% coarse material. A decrease in coarse fragment content with increasing silt and clay were also reported. Coarse fragment content of 79 inactive bituminous refuse piles in Pennsylvania ranged from 56 to 69% (Davidson, 1974). The mean coarse fragment content of the piles sampled by Delp (1975) was 60%, which concurs with the findings of Stewart and Daniels (1992) who report a mean coarse fragment content of 60% for 27 refuse piles from Southwest Virginia. The <2 mm fraction had a mean soil texture of sandy loam with 19% clay (Stewart and Daniels, 1992). These coarse textures and high coarse fragment contents result in refuse having a very low water holding capacity, which was identified as the chief physical factor limiting plant growth on coal refuse.

*pH:* Low pH is likely to be the chemical factor most limiting to plant establishment and growth on coal refuse. Although many refuse materials have a near neutral pH when originally placed in the pile, the pH of refuse usually drops rapidly as pyritic materials weather and produce acidity. The detrimental effects of low pH on plant growth have been expounded on by different authors (Brady, 1990; Bohn et al., 1985; Thomas and Hargrove, 1974).

The reported pH values for weathered coal refuse are usually in the acid, to extremely acid range. A range of refuse pH values from 3.0 to 8.3 was reported for 27 refuse piles from southwest Virginia (Stewart and Daniels, 1992). A study of five refuse piles in Illinois produced a mean pH of 2.8 with a range of 2.4 to 3.0 (Haynes and Klimstra, 1975), and a study of four piles revealed pH values from 2.3 to 3.0 (Nawrot, et al., 1986). Refuse pH was found to range from 5 to 10 in Spain, 4 to 7.9 in Poland, and 2.8 to 9.6 in the United Kingdom (Skarzynska, 1995). Refuse with pH values >3.0 are commonly associated with S contents of >2% (Stewart, 1990) and low pH and associated toxic levels of Al, Fe, Mn, and other ions were found to be the chemical factor most limiting plant growth (Stewart and Daniels, 1992).

*Electrical Conductivity:* Coal refuse tends to have high electrical conductivity (EC) values indicating high levels of dissolved salts. These salts are produced during pyrite oxidation and subsequent acid attack on minerals. Electrical conductivity values of  $0.4 \text{ S m}^{-1}$  are considered to inhibit the growth of salt sensitive plants (Bower and Wilcox, 1965). In a study of five refuse piles in Illinois, Haynes and Klimsta (1975) reported EC values from 0.03 to  $0.30 \text{ S m}^{-1}$ . Medvic and Grandt (1976) studied two piles in Illinois, where EC values ranged from 0.2 to  $0.62 \text{ S m}^{-1}$ . A mean EC of  $0.09 \text{ S m}^{-1}$  with a range of 0.01 to  $0.55 \text{ S m}^{-1}$  was reported by Stewart and Daniels (1992). The EC of refuse undergoing active pyrite oxidation will be high, but once oxidation has run its course and salts are leached away, the EC values may decrease.

*Elemental Content and Mineralogy:* The elemental content of coal refuse has been examined by several researchers (Skarzynska, 1995; Stewart and Daniels, 1992; National Academy of Sciences, 1978; Rose et al., 1978). Coal refuse contains some unrecoverable coal; which can comprise up to 30% of the refuse (Skarzynska, 1995). The SiO<sub>2</sub> content ranges between 19 and 78%. and the relative amounts of Al, Fe, K, Ca, and Mg oxides indicate a mineralogical suite that contains alumino-silicate clays such as muscovite and kaolinite along with quartz. In addition to these minerals, smectites, hydroxy-interlayered vermiculite, mixed layer illite montmorillonite, chlorite, feldspars, and iron pyrite have been identified in coal refuse (Skarzynska, 1995; Stewart, 1990; Bamhisel and Massey, 1969). Quartz is usually the

dominant mineral with lesser amounts of the alumino-silicate clays. Again, this suite of minerals is relatively low in charge, and the high amount of coarse material in coal refuse further dilutes the charge on a mass basis.

The properties of spoils and refuse that restrict plant growth and limit thier productivity are acidity, compaction near the surface, and course texture. On outslope these problems are compounded by erosion, runoff and difficulty in operation machinery. Application of CCB's could remedy some of these problems. Many ashes are alkaline in nature and could neutralize acidity. Ashes are also fine in texture and water holding capacity may be improved through the application of ash.

### Coal Combustion Byproducts (CCBs)

CCBs are manufacturing and engineering materials, and their uses are similar to the uses of competing virgin and processed materials. The most recent data published by ACAA shows that in calendar-year 1994, approximately 90 million tons of CCBs was produced in the USA. As shown in Table 2, the annual production of CCBs in the USA during calendar-year 1994 was greater than and on the same order of magnitude as portland cement and iron ore. The mineral resources that were produced in quantities greater than CCBs during this same period were crushed stone and sand and gravel, both of which exceeded CCB production by an order of magnitude.

Table 2. Comparison of CCBs to Other Mineral Resources (ACAA, 1994)

Mineral Resources: Annual Production in USA (million tons)	
Crushed Stone	1,200
Sand & Gravel	900
CCBs	90
Portland Cement	80
Iron Ore	60

Approximately twenty-five percent (25%) of the annual CCB production was used, and the remaining seventy-five percent (75 %) was disposed.

It is clear from survey data compiled by ACAA since 1966 that the annual use of CCBs has continued to increase both as a percentage of production; and in terms of the tonnage used (Figure 1). At the same time, there has been a generally steady upward trend in total CCB quantities produced. The overall amounts of fly ash, bottom ash and boiler slag used in the USA, for the years 1966 through 1994, are shown in Figure 1 as combined percentages of those three types of CCBs produced in those years. Also shown in Figure 1 are the similar combined percentages of fly ash, bottom ash, boiler slag and FGD material used in the USA, for the years 1987, the first year FGD material was included in ACAA's survey, through 1994.

In 1994, a total of 12.93 million tons of fly ash was used. This represented almost fifty-nine percent (59%) of the cumulative amount, 22.08 million tons, of all CCBs used in 1994. Clearly, the use of fly ash is greater than the use of other CCBs, both individually and combined. The leading applications of fly ash in 1994 are shown in Figure 2 as percentages of the total fly ash used in that year. The top five uses of fly ash in 1994 were as follows:

### Fly Ash Applications

cement and concrete products million tons	57.4%	7.42
structural fills	9.4%	1.21
road base and subbase	5.5%	0.71
flowable fill	4.9%	0.64
waste stabilization <sup>1</sup>	0.8%	0.23
all other	21.0%	2.72
Total:	100%	12.93 million tons

Opportunities exist for at least a doubling of CCB use within the construction industry. For example, structural fill and flowable fill applications, which compete with traditional fill materials such as soil and construction rubble, provide major avenues for market development. In addition the use of CCBs as a reclamation amendment and as a material for mine sealing and grouting is a topic of great interest.

Currently, about 54 million tons of fly ash are produced each year in the U.S. (ACAA, 1996). Fly ash makes up about 80% of the wastes associated with the burning of coal. Presently only about 24% of the ash generated is utilized with the remaining material being deposited in landfills and surface impoundments (ACAA, 1996). Disposal of fly ash poses the greatest environmental impact of coal combustion waste at the present time. Recently, the environmental impacts of fly ash were reviewed by El-Mogazi et al. (1988) and Carlson and Adriano (1993).

Fly ash is mainly composed of silt sized glassy spheres (Fisher et al., 1976), some of the spheres are hollow, termed cenospheres, or spheres filled with smaller spheres termed plerospheres. During the combustion and subsequent cooling process many different metal oxides can precipitate and concentrate on the surfaces on these spheres. These oxides control the chemical properties of the ash, and tend to vary from ash to ash. The oxides may also affect the physico-chemical properties of some fly ashes, especially the pozzalonic (cementitious) reactivity.

*Physical Properties:* The physical properties of fly ash depend upon a number of factors, including the type of coal burned, the boiler conditions, the type and efficiency of the emission controls, and the disposal method (Adriano et al., 1980). Certain characteristics tend to be similar in most ashes. Fly ash is mainly composed of silt-sized materials having a diameter from 0.01 - 100  $\mu\text{m}$  (Chang et al., 1977). When compared with mineral soils, fly ash has lower values for bulk density, hydraulic conductivity, and specific gravity. Both crystalline (mullite) and amorphous (glass) phases have been identified by X-ray diffraction in fly ash (Mattigod et al., 1990).

*Chemical Properties:* The chemical properties of fly ash will largely be determined by the metal oxides that were surface adsorbed during particle formation. In the U. S., fly ash from eastern coals, which usually are higher sulfur coals, tend to be higher in Fe, Al, and S and lower in Ca and Mg when compared to western coals. Ashes from eastern coals also tend to be higher in the trace elements As, Cd, Cr, Pb, V and Zn (Roy et al., 1981). Most of these elements can substitute into the iron pyrite structure, and coals higher in pyrite therefore tend to produce fly ashes which contain higher levels of these elements. The element Se does not seem to be correlated with any particular coal property. Selenium is known to be a volatile element and its behavior may be highly dependent upon the burning conditions within the boiler.

One property of certain fly ashes which makes them attractive as reclamation amendments is their liming potential. In a study of 23 ashes from across the U.S., Furr et al. (1977) found that ash pH ranged from 4.2 to 11.8. Most low pH ashes came from eastern coal sources. Ash pH values of up to 12.5 have been reported (Chang et al., 1977) for western sub-bituminous coal derived ash. Fresh unweathered fly ashes can have pH values higher than 9 but it is rare to find pH values higher than 8.5

for weathered fly ash. Many ashes are high in Ca and Mg oxides and have a significant neutralizing capacity. Fly ashes with neutralizing capacities of up to 10 % calcium carbonate equivalent (CCE) have been reported, but CCE values of 1-6% are more common (Aitken, et al., 1984). Thus, more than 20 tons of most fly ash would be required to replace 1 tonne of ground limestone. This indicates that ash would not be effective in raising a low pH, highly buffered system due to the large amount of ash needed, but may be more effective in poorly buffered, coarse textured systems, such as coal refuse. Water soluble Ca content was found to be the best indicator of ash potential to produce alkalinity (Theis and Wirth, 1977). Unweathered fly ash also contains high levels of soluble salts. Ash from lignite and sub-bituminous coals tend to have the highest salt levels (Adriano et al., 1980), and the application of 179 Mg ha<sup>-1</sup> of unweathered fly ash was found to increase soil salinity 500 to 600% and causing significant increases in soluble B, Ca, and Mg (Page et al., 1979). Values for saturated paste conductivity for fly ash can be as high as 6 S m<sup>-1</sup> (Page et al., 1979).

**Fly Ash as a Soil Amendment on Agricultural Land :** Fly ash has been proposed as a soil amendment due to its previously mentioned neutralizing capacity and potential to improve soil physical properties. The reported effects of fly ash application are summarized in Table 3 (Carlson and Adriano, 1993). This table is split into the effects of weathered and unweathered ash.

Since fly ash contains many silt-sized particles its addition at high rates to soils high in sand or clay can change the soil texture (Chang et al., 1977, 1989). When ash was added to five soils with sandy textures the bulk density decreased, while ash addition to three soils with clayey textures increased bulk density. This difference could be due to the structural position where the fly ash resides after incorporation. In sandy textured soils the ash is likely to reside between grains, pushing them apart. In a clayey soil, the fly ash likely would reside in voids between the peds (Chang et al., 1989). This would tend to increase the bulk density when ash is applied to clayey textured soils.

Ash additions have also been found to increase the water holding capacity of soils. Addition of 10 % ash to fine (0.2-0.5 mm) and coarse (1.4-2.0 mm) sand fractions increased the available water by 7.2 % and 13.5 %, respectively (Campbell et al., 1983). Ash alone was found to have > 40% available water in 11 of 13 Australian ashes tested (Aitken et al., 1984). Improvements in available water in ash amended soils have also been reported by other researchers (Salter et al., 1971; Chang et al., 1977; 1989). It is unclear whether the increases in water holding capacity also result in increases in plant available water; Chang et al. (1979) report that water in fly ash amended soils is less available. Other studies have noted a lack of yield response to the increase in water retention. This could be due to other growth limiting effects of the fly ash, such as B toxicity or high soluble salts. The yields of carrot (*Daucus carota*), beet (*Beta vulgaris*), radish (*Raphanus sativus*), and bean (*Phaseolus vulgaris*) showed no improvement in response to the application of fly ash to a sand and sandy loam soil, even though the water holding capacity had increased (Salter et al., 1971). These researchers hypothesized that water may not have been a growth limiting factor in this experiment and only one treatment showed a yield response when irrigation water was applied later in the experiment.

Some studies do report yield increases due to fly ash application. An ash that had been leached to remove soluble B content was found to increase the yield of Rhodes grass (*Chloris gayana* Kunth) and French bean (*Phaseolus vulgaris* L.) (Aitken and Bell, 1985). These researchers also report that the high levels of B in the ash caused a yield decrease, but the removal of B allowed a yield increase which was attributed to an increase in available water. Improved corn (*Zea mays* L.) yields have also been attributed to ash addition (Plank et al., 1975). A study in which the ash was applied in bands on sandy Michigan soils produced some interesting results. Soil moisture was increased by 2570% during a droughty growing season (Jacobs et al., 1991), and plant roots were found to have grown into the ash bands, which were higher in moisture than the surrounding soils.

Table 3. Potential and observed effects of fly ash amendment on soil properties (Carlson and Adriano, 1993).

Soil property	Typical agricultural soil	Soil amended with weathered ash	Soil amended with unweathered ash
Aeration	high	higher	higher
Bulk density	1.3 (avg)	lower	lower
Cation Exchange Capacity	medium 12 cmol/kg	lower	lower
Cementation	low	low	may increase due to alkaline ash
Electrical Conductivity	low	moderate to higher	higher
Hydraulic conductivity	high	increased by low rates; decreased by high rates	increased by low rates; decreased by high rates
Modulus of rupture	high	lower	lower
Nutrient availability	balanced supply of nutrients	deficient in N, P, and potentially Cu, Mn, Zn; potential for food chain concern with Mo and Se	deficient in N, P, and potentially Cu, Mn, Zn; potential for food chain concern with Mo and Se
Nutrient content	all nutrients present.	very low N, potentially high B; others present	very low N, often excessive B; others present
Organic matter	high	lower	lower
pH	6.0 - 7.5	<6.0 to 8.0	<6.0 to 12.0
Plant available water	high	no effect to large increase	no effect to large increase
Salinity	low	moderate	high but decreases with time
Temperature	adequate	higher	higher
Toxic salts	none	may have enough B to toxic to sensitive plants	High B and soluble salts of Ca, K, Mg, and Na
Erosion	resistant	more susceptible	more susceptible
Water holding capacity	high	higher	higher

*Elemental Uptake.* Application of fly ash to soil can affect soil and plant chemical composition. The concentration of trace elements can be greatly effected. Wheat (*Triticum* spp.) seedlings grown on an ash amended soil showed decreases in some metals due to a high pH ash, while other ashes produced increases in seedling metal content due to metals in the ash (Petruzzelli et al., 1987). In research on a Virginia soil, Martens and Beahm (1976) reported that fresh ash added to a Tatum (Typic Hapludult) soil increased the Mo concentration in alfalfa. They were not able to isolate whether the increase was due to added Mo from the ash, or an increase in Mo availability from a pH increase.

Due to the relatively high concentrations of some trace elements in fly ash many researchers have investigated the use of fly ash as a trace element source, and in some cases as a macro-element fertilizer. For a review of these studies and which elements were examined. see Carlson and Adriano (1993). Ash

application can also increase the plant content of the non phyto-essential element Se. Selenium is required by animals and is deficient in some forages grown on the soils of the southeastern U.S. When using ash as a trace element source, care must be taken because over-application can result in phytotoxic levels of B and sufficiently high levels of As, Mo, and Se to pose a potential threat to animal consumption (Doran and Martens, 1976; Tolle et al., 1983).

In a study of elemental uptake of grasses from fresh and weathered ash dumps, Nass et al. (1993) found that grasses grown on unweathered ash had Mo, Pb, and Se levels that exceed the maximum tolerable limits for domestic animal feed. In grasses grown on weathered ash the Mo, Pb and Se concentrations were below the maximum tolerable limits. They pointed out that Mo levels may be sufficiently high to induce a Cu-deficiency and suggested the necessity to monitor all animals feed grasses grown on ash.

*Fly Ash as a Mine Reclamation Amendment:* Disposal of coal fly ash in coal refuse piles and minespoil heaps is a common practice in other countries (Skarzynska, 1995; Twardowska, 1990), but is not currently a widespread practice in the U.S. The USEPA recently excluded coal fly ash from regulation as a hazardous waste (USEPA, 1993) which has led to an increased interest in returning fly ash to the coalfields for disposal. Provisions that call for coal producers to accept back-haul and disposal of fly ash are now being written into many coal contracts. This presents an opportunity for this ash to be used in the reclamation of coal refuse. Use of ash in this manner would represent utilization of a coal combustion waste to reclaim wastes generated in coal extraction. The use of coal fly ash in reclamation of coal refuse has been the subject of several experiments (Adams et al., 1972; Jastrow et al., 1981), but has not become a widespread practice in the U. S., primarily due to regulatory constraints and the lack of ash sources within many mining districts. The addition of fly ash to coal refuse and minesoils has been shown to lower bulk density, increase water holding capacity, and neutralize acidity (Capp, 1978; Jastrow et al., 1981; Taylor and Schuman, 1988).

Nearly all coal refuse piles in the Appalachian coal basin are located on or near streams, and can be the source of significant stream pollution from sediment and AMD. The AMD results from iron pyrite oxidation, which may be native to the refuse material or was separated from the coal during the cleaning process. The addition of an alkaline fly ash would raise the pH of the coal refuse, lower its hydraulic conductivity, and lower the rate of gas exchange with the atmosphere. These principles are the basis of the mine and spoil grouting work that has been done by several researchers, (Kim and Ackman, 1995; Baker et al. 1992; ) Ash incorporation could greatly decrease or halt the oxidation of pyrite in a mixture of coal refuse and fly ash. The mixing rate must necessarily be fairly high due to the low neutralizing power of fly ash. Very high rates of fly ash application, up to 1600 ton a<sup>-1</sup> (Capp, 1978) may be needed to raise the pH of the refuse above 7. The placement of layers of fly ash within a coal refuse pile has led to improved drainage quality from a pile in Poland (Twardowska, 1990). In most studies, the ash has been surface applied to coal refuse and minespoils (Bhumbla et al., 1993; Capp, 1978). While this practice affects the surface of the pile, the vast majority of the bulk of a waste pile are not affected. Blending fly ash with refuse in bulk would treat the entire refuse pile.

Work has also been done in Ohio (Stehouwer et al, 1995) and West Virginia on the use of some of FGD as amendments in reclamation. These materials offer higher liming capacities than fly ash but do not have the bulkiness and abundance of silt sized material. Some researchers have used mixtures of fly ash and FGD materials (Kim and Ackerman, 1995) as amendments in mine sealing.

### **Regulatory and Legislative Issues**

In the Energy Policy Act of 1992 [Public Law No. 102-486, October 24, 1992] the U.S. Secretary of Energy was charged with the task of conducting a detailed and comprehensive study on the "institutional, legal and regulatory barriers to increased utilization of CCBs by potential governmental and commercial users" and reporting the findings to Congress. The U.S. Department of Energy (DOE) report was published in July 1994 [DOE, 1994].

The report has had a significant effect on the continuing efforts to advance the use of CCBs. The recommendations in the DOE report address a network of related barriers which can be overcome only through cooperative efforts among federal and state government agencies and industry. ACAA has addressed many of these issues in its activities and will continue to do so in the future.

### Summary

Throughout ACAA's history, its goal has been to gain recognition and acceptance of CCBs as engineering and manufacturing materials that compete in an open market with virgin and processed materials. As we continue to advance the use of CCBs in ways that are technically sound, commercially competitive and environmentally safe, the number and quantity of CCB applications will grow as well. Minesoils and coal refuse are hard to reclaim and limited in their productivity due to coarse particle size, and high levels of acidity. Coal Combustion Byproducts, particularly those that are alkaline in nature, could be used as an amendment to ameliorate these problems. Application of alkaline CCBs and in particular alkaline fly ash would decrease particle size, and neutralize acidity if applied in large quantities. This would result in the beneficial reuse of ash and in improved reclamation results.

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Figure 1. Combined Percentages for CCBs Used: 1966-1994

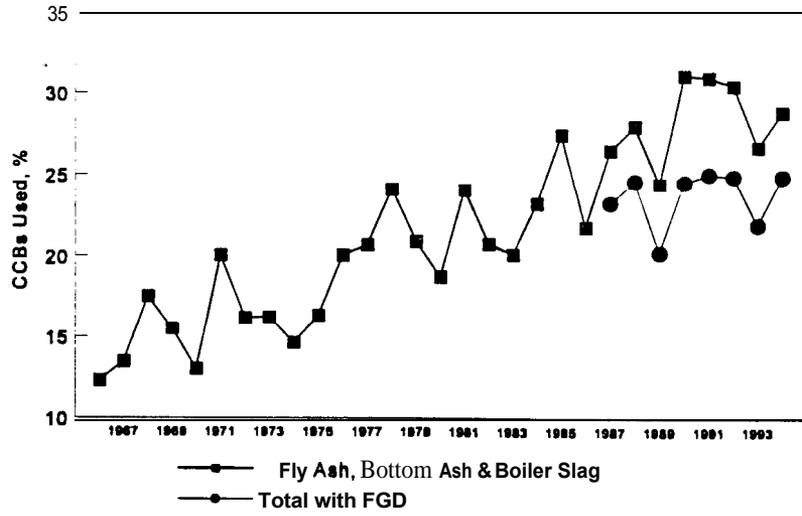
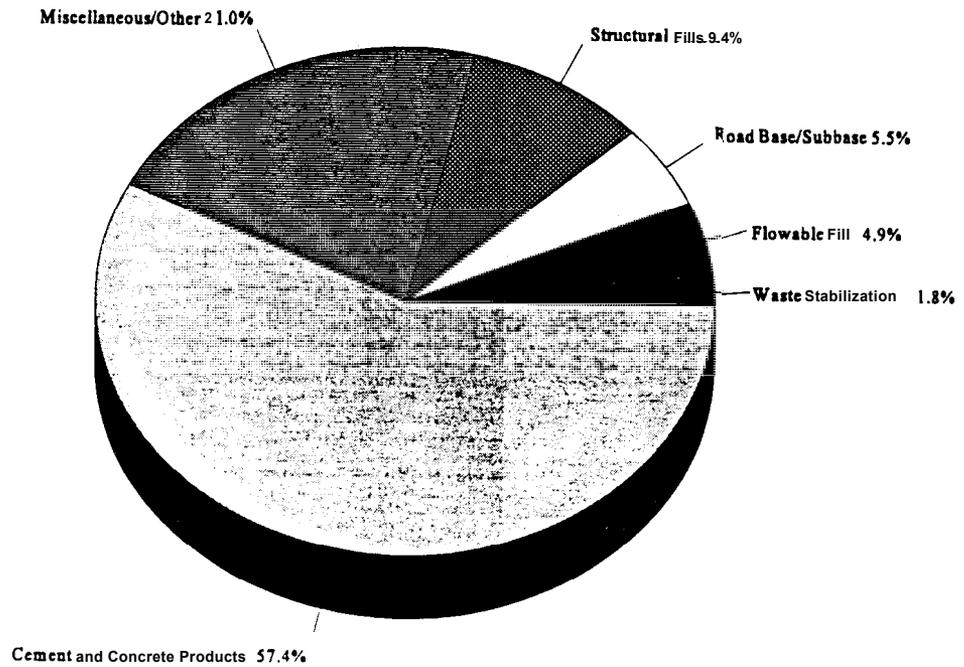


Figure 2. Leading Fly Ash Applications - 1994



**Session III:**  
**REGULATORY REQUIREMENTS**

**Session Chairs:**

**John Richardson**  
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**Dan Wheeler**  
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## REGULATION OF COAL ASH PLACEMENT ON SURFACE COAL MINES IN INDIANA

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### **Abstract**

In 1988 the Indiana General Assembly enacted legislation which placed the regulatory jurisdiction for placement of coal combustion by-products on coal mines within the authority of the Indiana Surface Mining Control and Reclamation Act (I-SMCRA) and its regulations. As a result, in 1992 the Indiana Department of Natural Resources, Division of Reclamation (DOR) began to implement a program for regulation of placement of ash materials on permitted coal mines using the I-SMCRA regulations. This paper describes some of the literature, research data and rationale for the I-SMCRA regulatory approach adopted in Indiana. It was concluded, based upon all available information, that like most coal ash, Indiana ash is environmentally benign and could be properly regulated using the environmental conservation and public protection and public participation regulations of the Indiana surface mining act. A copy of the Indiana program for addressing coal ash on surface mining sites is included with this paper.

### **Introduction**

Like the purpose set forth in the federal Surface Mining Control and Reclamation Act (SMCRA) of 1977 (P.L. 95-87) at Section 102(f), responsible management of natural resources must "strike a balance" between environmental protection and economic impacts upon society. The framers of SMCRA were visionary in recognizing that environmental programs come with a monetary price to society through taxes and cost of goods and services. This important concept of balance is just now being recognized by many other non-SMCRA environmental regulatory agencies and opinion leaders in the country – some 20 years after the passage of SMCRA. Indeed, cost-benefit considerations were an important component of the United States Environmental Protection Agency (USEPA) 1993 Final Regulatory Determination on coal combustion by-products (hereafter referred to as "coal ash") regulation discussed below.

### **Literature Review**

Suloway (1983) showed alkaline coal ash leachate tests met primary drinking water standards (PDWS) 76% of the time. Envirosphere (1982) made over 4,000 observations of ground water near 25 coal ash disposal sites in the U.S. and found PDWS to be exceeded only 3% of the time. Franklin and Associates (1984) made 15,000 observations of ground water from wells near coal ash disposal sites nationwide; primary drinking water standards were exceeded only 7.4% of the time. Jackson and Moore (1984) through a U.S. Department of Energy study, compiled the results of 2,492 separate extraction tests for eight PDWS constituent metals and found that most leached at concentrations less than 1/10 the hazardous limit; none exceeded PDWS by 50 times.

Arthur D. Little (1985) conducted a study sponsored by USEPA, which revealed no EP toxicity level in the extracted leachates of any samples. In field studies by Little (1985) only 5% of the down gradient observations exceeded the PDWS. Natural soils apparently attenuated RCRA elements at some of the power plants studied. Mason and Carlisle (1985), who conducted a study sponsored by the Electrical Power Research Institute (EPRI), found leaching samples averaged 1/4 the RCRA metals limit using acidic leachate methods. Radian (1985) conducted an EPRI study which showed the only coal ashes to exhibit EP toxicity were those containing untreated boiler cleaning acid chemical wastes. Beaver et al. (1987) found in a comprehensive long term study of ground water associated with ash burial on a North Dakota surface mine that ash disposal did not make any significant incremental difference in groundwater mineralization levels. It was also determined in many settings, liners were not considered appropriate, because liners can cause concentration of elements. When

disposal sites are unlined, elements can be released slowly to allow natural attenuation.

### USEPA Findings

The USEPA's 1988 Report to Congress, Wastes from the Combustion of Coal by Electric Utility Power Plants analyzed most of the above literature and concluded in part:

1. Coal combustion wastes generally are not EP toxic, although there are some exceptions. The exceptions were determined to be "quite rare", as "average levels are substantially below 100 times PDWS."
2. Each ash source should be tested on a site specific basis to verify that it falls within the expected benign norm.
3. While there is some rare evidence that hazardous constituents have occurred from coal ash disposal sites, "ground water contamination does not appear to be widespread. Only a few percent of all ground-water quality observations indicate that a PDWS exceedance has occurred,..."
4. When ground-water contamination does occur, the magnitude of the exceedance is generally not large.
5. There are few cases considered to be documented evidence of groundwater contamination or any other damage from coal combustion waste disposal.
6. Additional regulation under RCRA standards was estimated to cost about \$5 billion if all existing facilities were capped and closed and new facilities were constructed with liners, leachate collection systems, flood protection and ground water monitoring. The cost of generating electricity with coal could increase by several percent.
7. Preliminary finding "EPA does not intend to regulate under Subtitle C fly ash, bottom ash, boiler slag and flue gas desulfurization wastes. EPA's tentative conclusion is that current waste management practices appear to be adequate for protecting human health and the environment."

On August 9, 1993, following up on the 1988 report, USEPA issued its Final Regulatory Determination, wherein the original preliminary findings were largely affirmed. USEPA found that "regulation of the four large-volume fossil-fuel combustion [FFC] wastes as hazardous waste under RCRA subtitle C is unwarranted" (emphasis added). Human health impacts were found to be negligible. Overall it was found that "the extent of actual damage/environmental harm cases associated with large volume FFC waste management appears limited." Only 6 sites out of an estimated 500 sites which exist in the nation were found to have caused damage and "only one case can clearly be attributed to fly ash management alone." However even this single damage case was not due to ground water leachate contamination, but rather was due to failure of a levee which released a large volume of ash directly into a river. The remaining 5 cases involved co-disposal of coal ash with other wastes, such as petroleum by-products. It was concluded that regulation of coal ash as hazardous material would be "inappropriate for these wastes...It is more appropriate for individual states to have the flexibility necessary to tailor specific controls to the site or region specific risks posed by these wastes."

### Discussion

It would seem that policy makers around the country are coming to a consensus that surface coal mines, as regulated under SMCRA, are proper coal ash sites, which is not surprising for several reasons. State programs share the common under-pinning of the comprehensive environmental conservation and citizen protection principles of federal SMCRA, which effectively addresses potential impacts from coal ash. In addition, coal ash is accepted by most in the scientific community to be of an environmentally benign nature (see the Literature Review); thus, it would not be effective to install expensive control systems such as liners and leachate control systems for materials which are not hazardous. Back haulage of coal ash to its place of origin holds promise for reducing storage and disposal cost for electric utilities, therein providing a potential

reduction of utility costs for consumers. Finally, it is good public policy to save our valuable and limited landfill space for substances which are truly a threat.

Indiana public policy determinations have been similar and have followed the lead of several other states who have surface coal mine ash programs. However, while the enabling legislation was passed in Indiana in 1988, the I-SMCRA regulatory approach was not approved by the Indiana Natural Resources Commission, the policy-making board for the Department of Natural Resources, until 1992. Now in 1996, the Indiana coal mining industry has only within the last year begun to implement approved coal ash plans under the I-SMCRA program. As of April 1996 Indiana had received 17 coal ash applications but only 4 permitted mine sites were placing ash in surface mined pits. Nearly all permit decisions have been challenged by an environmental group; one permit issuance has been affirmed by an administrative law judge and another has been pending an administrative decision for over a year. A total of 116,000 tons of ash have been placed in active surface mines in Indiana, but only 116,000 tons of material at sites operating entirely under the 1992 regulatory approach.

Much information was taken into account by the Division of Reclamation (DOR) prior to the 1992 adoption of the I-SMCRA regulatory approach. Specifically, a study of Indiana coal ash conducted by the University of North Dakota Energy and Mineral Research Center, Mining and Mineral Resource Research Institute (discussed below), data in the literature, site specific information from an Indiana wet disposal site in an unlined coal mine impoundment, data submitted for permit applications, the determination of the USEPA and consultation with the scientific community. It is clear from the body of coal ash knowledge known at this time, that it is generally considered an environmentally benign substance in the vast majority of circumstances.

#### Indiana Ash Study

In order to verify whether Indiana coal ash was similar to ashes described in the literature, the DOR facilitated a study of Indiana coal ash by the University of North Dakota Energy and Mineral Research Center (UND), in cooperation with environmental and citizen groups, the power industry and the coal industry. Extensive short-term (18 hour) and long-term (30 day) leachate tests were run on Indiana coal ashes representing about 33% of all ash produced at Indiana utility plants. UND concluded none of the Indiana coal ashes tested were hazardous using any testing method. Moreover, the study concluded the use of liners may not be necessary to provide adequate environmental safe guards. The results showed only 4 of the 8 RCRA elements leached in sufficient quantities to generate meaningful data, arsenic, barium, chromium, and selenium leachate results showed that all four elements were only sparingly leachable.

UND's calculation of the maximum possible concentration (MCP) of these four elements also revealed the low risk of the Indiana coal ash. The MCP represents the maximum leachate which could occur, in a hypothetical situation, where every atom of the element leached all at one time. The MCP's showed only chromium could theoretically reach RCRA limits, but leachate tests showed that chromium exhibited extremely limited leaching as chromium was well within PDWS in all tests (PDWS = 0.05, Average leachate = .002).

It is important to note that these leachate results represent raw laboratory results which did not take into account field conditions such as dilution, dispersion and attenuation. For example, the highest leachate for arsenic was found at 7% of the Resource Conservation and Recovery Act (RCRA) limit (or 7 times drinking water standards). However, actual field data from ground water monitoring wells at the unlined final cut impoundment wet disposal site, where this material had been placed for 3 years, showed achievement of PDWS for arsenic in wells only 50 feet down gradient from the edge of the disposal site. Consistent with UND's findings, the DOR concluded: The testing procedure is probably conservative and tends to exaggerate leachate concentrations upward. And, physical, chemical and hydrological factors present in a surface mine setting can be effective in naturally remediating the small amount of leachate generated in unlined coal ash disposal sites.

#### DOR Application File Data

Finally, the DOR reviewed its own permit files which contained over 700 hundred elemental sample results from EP toxicity tests and ground water monitoring results from a surface mine coal ash disposal site.

The test results in the DOR files were consistent with trends identified in the literature, by the UND study and by USEPA.

### **Indiana Regulatory Approach and Rationale**

With this background, the following represents a summary of the approach and the rationale behind Indiana's coal ash program regulated under I-SMCRA

1. Wise natural resource management suggests a safe approach to disposal of coal ash is to return it to its original location, i.e. where the coal seam was removed. In this way, no new elemental species will be introduced into the hydrogeologic system associated with the disposal site if that site is the same geologic and hydrogeologic setting from which the feed coal was obtained (Beaver et al. 1987).
2. Wise natural resource management would suggest minimizing disturbed areas, when possible. Why disturb 2 areas when you need disturb only one to accomplish both recovery of coal resources and disposal/use/recycling of coal ash?
3. Once the decision has been made to allow surface mining, placement of coal ash, even in a saturated disposal setting apparently will not make any incremental difference in ground water mineralization levels (Beaver et al. 1987). In other words if surface mining is to be allowed, some mineralization of water is to be expected and accepted. Based upon over 6 years of ground water monitoring data from a wet disposal site in a surface mining impoundment in west-central Indiana, coal ash has not caused mineralization to significantly increase, if at all (Division of Reclamation permit records).
4. The existing surface mining regulations provide the necessary environmental safeguards and opportunities for public participation to safely and responsibly reclaim coal ash placed on mine sites.
5. Coal ash is a benign material in the vast majority of circumstances. Tests reveal it has chemical characteristics in common with many coals, topsoils and mined overburdens, which are all resources addressed in the SMCRA program. The literature previously reviewed overwhelmingly shows coal ash poses little threat to the environment, drinking water or public health. Currently, in Indiana most disposal of coal ash is not subject to the extent of scrutiny practiced by the DOR under the surface mining program as only 8 of the 25 major coal ash producers in Indiana are subject to the Indiana Department of Environmental Management's site hydrogeologic characterization according to a report composed by the Hoosier Environmental Council (1991). Moreover, no ground water demonstrations or monitoring are required on these 17 coal ashes that produce about 4 million tons of ash annually. This represents 83% of the total ash produced in Indiana. Therefore, the I-SMCRA approach can be more effective regulation of 83% of Indiana's coal ash, because the DOR addresses quality of ground water, surface water, soil cover, revegetation and bonding requirements.
6. Calcareous spoil in the majority of Indiana mines will place coal ash in a neutral to above neutral pH environment which will serve to limit leaching of metals.
7. When placed in an ongoing surface mine operation, the ash will be distributed in smaller quantities relative to the amount of overburden, thereby matimizing the effectiveness of attenuation. The fragmented nature of mine spoil provides greater surface area for chemical reactions to occur, which can bind up leachate through natural processes.
8. Disposal without liners will allow a gradual release of elements which may be leached, therein allowing the environment to naturally assimilate them (Beaver et al. 1987); however, liners can be required by the DOR if site specific circumstances warrant.
9. The approach is modeled after other state programs which have effectively dealt with coal ash placement on surface coal mines.

10. Flexibility, as provided under I-SMCRA will allow appropriate reaction to a wide variety of scenarios to better manage environmental and citizen protection

11. The approach follows many of the recommendations received from interested parties. For example, many of the items recommended by the Hoosier Environmental Council in a preliminary report titled, Disposal of Coal Combustion Wastes in Indiana: An Analysis of Technical and Regulatory Issues (Boulding 1991) were adopted including suggestions as follows:

- a. An initial screening of elements
- b. Leach tests which assess long term leaching and approximate disposal site conditions.
- c. Dust control plans.
- d. Ground water monitoring.

12. Most of the recommendations of the UND researchers, who have perhaps the most research experience in the nation on placement of ash on coal mines, were adopted.

13. Site specific hydro-geological assessments including background data as required by Indiana SMCRA regulations address hydrologic balance protection. Ground water monitoring is required until release of the bonded acreage.

14. Coal ash is not considered for mine placement if the leachate is greater than one-fourth the RCRA level. DOR believes leaching characteristics are best “modeled” by a neutral leachate test, because a neutral solution more closely approximates field conditions. Testing with acidic solutions is not considered appropriate, in most circumstances, as it is not representative of most Indiana ground water. Quarterly monitoring of the ash is required to assure the source characterizations remain consistent.

15. Liners, in most circumstances, are not required so that elements will release gradually naturally remediate the minimal levels of leachate through attenuation and dilution.

16. Burial of the waste on the pit floor or a minimum 5 foot soil cover will prevent plant uptake of elements.

17. The RCRA-based approach incorporates the safety factors built into drinking water standards, which should minimize risk and ensure environmental conservation and citizen protection.

18. Landowner concurrence assures protection of landowner rights.

19. Requirements that ash proposals be done through the SMCRA permit or significant revision process assures opportunities for complete public participation.

### Summary

The DOR found the state of knowledge regarding coal ash to reveal a safe and largely environmentally benign substance, which could be addressed under the environmental and public protection provisions of I-SMCRA. When one considers the acceptance of coal ash as a raw material in drywall for our homes, road fills, concrete, grout, ceramics as well as its usage for land application on agricultural lands as fertilizer and use as a road application material to alleviate winter driving conditions, it is indeed enigmatic that this same material could be viewed as problematic by some when returned to and backfilled on surface mines. Essentially, use of this material as part of the backfill at a surface mine represents just another recycling usage of a product which otherwise would become waste. Combined with the body of scientific data and the SMCRA-required environmental regulatory controls which already exist, placement of coal ash on surface mines appears to be good public policy.

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MEMORANDUM 92-1

TO: ALL OPERATORS AND INTERESTED PARTIES

FROM: MICHAEL SPONSLER, DIRECTOR *M. Spensler*  
DIVISION OF RECLAMATION

DATE: JUNE 8, 1992

SUBJECT: DISPOSAL OF COAL COMBUSTION WASTE ON SURFACE COAL MINES

As a result of approval by the Natural Resources Commission, the disposal of coal combustion waste (CCW) on lands permitted for surface coal mining will be regulated by the Division of Reclamation through existing authority of IC 13-4.1 and 310 IAC 12.

Applications seeking initial approval to dispose CCW on surface coal mines shall be submitted as a new permit or a significant revision to an existing permit.

In order to assist applicants and to facilitate permit application preparation of required waste characterization, site specific hydrogeologic monitoring and design requirements, a pre-submittal meeting with Division staff is highly recommended.

The following emphasizes certain required information necessary for the permit application:

A. Site Specific Characterization

Both geology and hydrology information shall be presented as a detailed, integrated evaluation of the hydrogeologic conditions beneath and adjacent to the proposed disposal site that adequately describes the production and migration of any coal combustion waste derived leachate. Information on the capability of in situ materials to contain and or attenuate any leachate levels before off-site migration will be useful.

A qualitative and quantitative analysis of the effects of the emplacement of CCW in the existing hydrologic regime must

be addressed. Hydrogeologic data must be based on a systematic investigation utilizing data from borings, piezometers, water wells and other nearby water sources, the chemical characteristics of subsurface waters, and other available information. Baseline data will be a critical feature of applications for CCW disposal. As always a minimum of 6 months of data will be necessary. Landowner concurrence for the disposal of CCW is required. Appropriate existing data, information and plans may be referenced.

B. Waste Characterization

Initial screening of the coal combustion waste shall be done to determine the leachability of trace elements from coal combustion waste. The screening procedure must fully satisfy the following objectives:

1. Identify trace elements of environmental significance, including those of primary drinking water standards and others present at significant total concentration levels, and include them in the leachate testing.
2. Determine the total amounts of all identified trace elements in each sample submitted for evaluation.
3. Measure and compare the leachability (mobility in water) of the identified trace elements using short term (18 hours) and long term (30 days) leaching tests that meet ASTM standards.

Table I summarizes the required testing parameters for waste quantity (concentration present) and quality (total amount leachable).

Table II summarizes the required groundwater monitoring parameters.

Testing and monitoring requirements will be based upon baseline data and may be revised as data and testing methods are refined and appropriate parameters are identified.

MS:pep

Attachments



REGULATORY APPROACH TO

DISPOSAL OF COAL COMBUSTION WASTE

I. Coal combustion waste (CCW) may be disposed in the permit area, only if approved by the Director pursuant to 310 IAC 12-3-105 thru 12-3-119. Landowners shall be notified and consent granted to the applicant for proposed CCW disposal operations. Approval shall be based on a demonstration by the person who conducts surface mining activities in the permit area, using hydrologic, geologic, geotechnical, physical, and chemical analyses, that disposal of such materials does not:

- (1) Adversely affect the quality of surface and groundwater;
- (2) Create public health hazards; or
- (3) Affect the establishment of vegetation which supports the approved postmining land use of the permit area.

coal combustion waste, which exceeds one-fourth (291) of the RCRA limit for any one RCRA element shall not be considered for disposal on land under permit for coal mining operations.

**II.** APPLICATION REQUIREMENTS

**A.** Site Characterization

Each application for a permit to dispose of coal combustion waste shall comply with the requirement of 310 IAC 12-3-28 through 12-3-54 and contain a thorough evaluation of the area hydrology and geology, including the presence of aquifers, permeability of natural materials and whether natural buffers or liners exist. Previous information may be referenced. Also include, maps, plans and cross sections which show the extent of the disposal area, including the expected rate and direction of groundwater movement in the vicinity of the disposal area.

Each application proposing to dispose of coal combustion waste shall contain a description of how minimization of adverse impacts upon the prevailing hydrologic balance will be accomplished. This description shall include, but is not limited to:

- (1) The anticipated interaction between the mine spoil, liners, or buffer materials, and the coal combustion waste.

The effects the coal combustion waste will have on the hydrologic balance, including a discussion of the risk potential of contaminating any water bearing strata,

- (3) A minimum of six months of baseline monitoring for surface and ground water in and within 1000 feet of the permit area in accordance with 310 IAC 12-3-32 and 12-3-33.

For the purpose of baseline monitoring of both surface and ground water the parameters in Table II shall be monitored. Parameters other than those specified above may be required by the Director in order to ensure the protection of public health and safety and the environment.

**B.** Waste Characterization

Each application proposing to dispose of coal combustion waste shall contain a thorough characterization of the waste material including:

- (1) The generating facility. Consideration for disposal will be limited to CCW generated in Indiana or CCW generated from burning Indiana coal.

- (2) The types of coal combustion waste to be disposed. (Fly ash, bottom ash, etc.)

- (3) Total volume of coal combustion waste to be disposed over the life of the operation and ratio of waste to spoil. Disposal shall not exceed ten feet in thickness unless approved as a monofill.

- (4) Initial waste characterization testing as approved by the Director shall be conducted as follows:

- (a) Screening for chemical constituents using bulk analysis.
- (b) Short term, 18 hour leaching test meeting ASTM standards for the chemicals in Table I.
- (c) Long term leaching test meeting ASTM standards for 30 days for the elements in Table I.

Data from the initial screening shall be used to calculate maximum possible concentrations of the elements identified in the screening test.

Periodic coal combustion waste sampling and analyses for each active waste stream shall be conducted at least quarterly according to a schedule approved by the Director. Sampling frequency may later be reduced based upon the consistency of the analyses.

TABLE I

INDIANA COAL COMBUSTION WASTE TESTING AND  
MONITORING PARAMETERS

.Arsenic	.Boron
.Barium	.Chloride
.Cadmium	.Copper
.Chromium	.Fluoride
.Lead	.Iron
.Mercury	.Manganese
.Selenium	.Molybdenum
.Silver	.Sodium
.Sulfate	.Total Organic Carbon
.Total Dissolved Solids	.Zinc
.Nickel	.Sulfide

Acid/Bass Accounting

The following shall be measured:

Potential acidity  
Neutralization potential  
Net neutralization potential  
pH

Parameters other than those specified may be required by the Director *in order* to ensure the protection of public health and safety and the environment.

Any new source of CCW, must be identified and approved prior to disposal, and is subject to the requirements as stated herein.

Evaluation of a proposal to dispose CCW on surface coal mines will consider, at a minimum, the risk assessment factors described as follows:

- (a) Proximity of public and private water supplies or other critical off-site features.
- (b) CCW characteristics including MPC (maximum possible concentration) calculated from solids concentration and appropriate leachate tests.
- (c) Geologic and hydrologic site characteristics, such as type and extent of aquifers, overburden characteristics, expected spoil characteristics.
- (d) Expected attenuation, dispersion and dilution.
- (e) Direction of ground water flow.
- (f) Baseline water quality and quantity.
- (g) Volume of waste proposed for disposal.
- (h) Impact of natural liners, artificial liners, compaction, capping or other operational features.
- (i) Type of proposed disposal operation, i.e. backfill, monofill.

## III.

**SITE SPECIFIC DISPOSAL PLANS**

- A. Operations Plans. Disposal methods shall be described in detail by providing the information required by 310 IAC 12-3-41 through 12-3-45 and demonstrating compliance with 310 IAC 12-5. The application shall describe any proposed compaction, methods to reduce infiltration or contact with water, liners, caps, co-disposal with coal processing waste, etc. Detailed maps, plans, and cross-sections shall be provided.
- B. Reclamation Plans. A detailed reclamation plan shall be submitted pursuant to 310 IAC 12-3-46 through 12-3-55 demonstrating compliance with 310 IAC 12-5. Restoration of approximate original contour, post-mining land Use and revegetation shall be described. The plan shall provide for a minimum soil cover of five (5) feet of non-toxic earthen material.

- C. Dust control. A plan to control dust in a manner which prevents damage to public or private property pursuant to 310 IAC 12-5-69 through 12-5-71 shall be provided. Specifically plans shall discuss techniques to show how wind erosion and dust will be prevented during transport, placement, and disposal of CCW.
- D. Water Monitoring. Water monitoring programs will be dependent on site specific conditions. Ground water shall be monitored at both upgradient and downgradient locations with at least one monitoring well in the expected path of leachate migration.

A plan for monitoring surface and ground water during the disposal of coal combustion waste and through final bond release of the permit area shall be provided as approved by the Director. This plan must specify the frequency of monitoring both surface and ground water, locations of monitoring points, parameters to be monitored and the location and availability for inspection by the Director of all monitoring records. The results of this monitoring plan shall be submitted to the Director in accordance with a schedule approved by the Director.

**TABLE II**

**INDIANA COAL COMBUSTION WASTE WATER TESTING  
AND MONITORING PARAMETERS**

The operator must determine the concentration or value of the following parameters for assessing groundwater quality. Metal parameters should be reported as total.

Field measurements:

Arsenic	Boron
Barium	Chloride
Cadmium	copper
Chromium	Fluoride
Lead	Iron
Mercury	Manganese
Molybdenum	Nickel
pH	Selenium
Silver	Sodium
Specific Conductance	Sulfate
Sulfide	Temperature
Total Organic Carbon	Total Dissolved Solids
Zinc	

Acid/Base Accounting

The following shall be measured:

Cation/Anion balance  
Neutralization potential  
Net neutralization potential  
pH (lab)  
Potential acidity  
Specific conductance  
Temperature

Parameters other than those specified may be required by the Director in order to ensure the protection of public health and safety and the environment.

## **STATE OF KENTUCKY REQUIREMENTS FOR DISPOSAL OF COAL COMBUSTION BY-PRODUCTS IN SURFACE MINED AREAS**

C. Ball

Natural Resources and Environmental Protection Cabinet  
Department for Surface Mining Reclamation and Enforcement  
Frankfort, Kentucky

### **Abstract**

The Department for Surface Mining has received the authority to set requirements for the disposal of coal combustion by-products in the Commonwealth of Kentucky. Senate Bill #266, became law in April 1994, and will allow the mining industry to dispose of coal combustion by-products while maintaining environmental integrity. The Senate Bill was passed with the intention of encouraging the production of coal and allowing flexibility in the placement of the coal combustion by-products. The requirements that must be met in coal combustion by-product disposal emphasizes protection of the Commonwealth.

### **Introduction**

The Department for Surface Mining Reclamation and Enforcement (DSMRE) regulates mining and reclamation operations under KRS Chapter 350. DSMRE may issue a permit to dispose of CCBP at coal mine sites under KRS 350.270. However, if the applicant chooses to propose disposal of CCBP on mine sites in a method other than addressed in KRS 350.270, the applicant must apply for a dual permit from DSMRE and her sister agency, Division Of Waste Management, which is regulated through KRS Chapter 224.

### **Materials Eligible for Disposal**

Senate Bill #266, defined "coal combustion by-products" in the Kentucky statute KRS 350.010 to mean fly ash, bottom ash, scrubber sludge, and waste from fluidized bed combustion, produced by the combustion of coal. The definition excludes boiler slag and residues of refuse derived fuels, such as municipal solid waste, tires, and solvents.

The remainder of the provisions contained in the bill were codified in the statute KRS 350.270. "Applicability" provisions authorize disposal of certain materials and exclude others. Disposal of waste from burning clean oil or gas with coal is allowed only if the oil or gas is used for startup or flame stabilization.

The Bill excludes disposal of any CCBP for which a special waste formal permit or a special waste registered permit-by-rule is required by administrative regulations.

Also excluded is disposal of any CCBP that exhibit hazardous waste characteristics, or that have been mixed or otherwise co-managed with low volume waste or with materials that exhibit hazardous waste characteristics. The exclusion of any CCBP generated prior to July 15, 1994, is also included unless the applicant can demonstrate that these by-products have not been mixed or otherwise co-managed with materials that exhibit hazardous waste characteristics.

Finally, the Bill excludes underground injection of CCBP

## **Permitting Procedures for Disposal of Coal Combustion By-Products**

### General Procedures

An applicant may propose disposal of CCBP when a surface mining application is originally submitted, or may propose to add such disposal to a permit that has already been issued.

An application to modify an existing permit to include disposal must be an amendment or a major revision application. All of these applications require publication of public notice.

If an existing permit includes disposal of CCBP, and the applicant wishes to modify the permit to increase the amount or mixture of by-products, or to change the facility from which the by-products are received, the application may be submitted as a minor revision. However, if the department determines that the change will result in a potential increase of heavy metal concentrations or that public notice is necessary, the change must be made through submission of a major revision or an amendment application.

### Major Items in Application

The application must include the following information:

- a. The legal right to dispose of coal combustion by-products must be demonstrated by a conveyance that grants or reserves the right to dispose of waste materials such as CCBP. If the mineral and surface property estates have been severed, the applicant must submit written consent from the surface owner to dispose of CCBP on his property.
- b. The location, business name, mailing address, and telephone number of the facility that will generate the CCBP, and the name and title of a contact person at the generating facility.
- c. Identification of each component of the CCBP that will be disposed of, and the approximate amount that will be received from the generating facility annually, and for the term of the permit.
- d. Results of representative sampling and laboratory analysis of each component of the CCBP for contaminants shall be submitted. Any contaminant must not exceed levels pursuant to KRS Chapter 224 and Resources Conservation Recovery Act (RCRA). The analysis must also include neutralization potential and potential Acidity.
- e. A description of the proposed handling and disposal methods, and record keeping method.
- f. A determination of the probable hydrologic consequences (PHC) of the disposal to the permit area and adjacent areas.
- g. Six (6) months of baseline information on surface water and ground water including the standard parameters required for any permit application, and including four (4) months of information on the additional parameters of arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver, or different parameters determined by DSMRE based upon the demonstrated characteristics of the CCBP.
- h. Maps and drawings of all areas and facilities to be used in the permit area for disposal of CCBP.
- i. A description of the measures to be used to prevent the CCBP from becoming airborne.

### Operating Requirements and Environmental Protection Performance Standards

- a. The performance bond must cover the disposal of CCBP.
- b. Disposal areas designated in the permit application must be designed, located, maintained, and operated in a manner not to pose a threat to human health, and to minimize disturbance to the hydrologic balance in and adjacent to the permit area.
- c. The permittee must keep records of the source and amount of each shipment of CCBP received and make this information available to DSMRE.

- d. The permittee must prepare and maintain accurate maps showing each location where CCBP have been disposed of, and the volume disposed of at each location.
- e. The permittee must provide representative samples of the CCBP to DSMRE if requested, or if required by the issued permit.
- f. The permittee must annually submit a laboratory analysis for the CCBP.
- g. Placement of the CCBP must be four (4) feet above the seasonal water table that is projected after mining.
- h. CCBP must not be placed within four (4) feet horizontally of a final highwall, exposed coal seam, or coal outcrop.
- i. Areas selected for disposal must minimize water contact with the CCBP.
- j. The volume of CCBP disposal must not exceed the in-place volume of the marketable coal seams to be removed, and DSMRE may decrease the disposal volume if necessary.
- k. The disposal must not cause the amount of excess spoil to be greater than would exist without the disposal of CCBP.
- l. The thickness of the CCBP must not exceed forty (40) feet at any point, and DSMRE may decrease this thickness if necessary.
- m. The CCBP must be covered as contemporaneously as practicable with at least four (4) feet of nonacid-forming spoil material.
- n. The permittee must monitor and report the quality of surface water and ground water until final bond release on the permit area. The monitoring must be conducted quarterly, except monitoring for the extra parameters due to disposal of CCBP must be conducted semi-annually. Monitoring for the extra parameters may be reduced if those parameters show no increases of regulatory levels after four (4) monitoring events.

As of July 1996, DSMRE has issued one permit and received one additional application to dispose of CCBP at surface mines under KRS 350.270. However, we expect application to increase significantly in the next several years as the availability of this method of disposal becomes more widely recognized.

**PENNSYLVANIA'S REGULATORY REQUIREMENTS FOR  
USE OF COAL COMBUSTION ASH AT COAL MINING OPERATIONS**

Nevin Strock  
Chief  
Surface Mine Permit Section  
Bureau of Mining and Reclamation  
Pennsylvania Department of Environmental Protection  
Harrisburgh, Pennsylvania

**Background**

Coal combustion ash is regulated in Pennsylvania under the state's Solid Waste Management Act (PA SWMA). In 1986, the PA SWMA was amended to exclude coal ash from the definition of solid waste and to establish provisions for the beneficial use of coal ash. The provisions for beneficial use of coal ash apply to fly ash, bottom ash or boiler slag resulting from the combustion of coal. Wet scrubber sludge and ash generated from combustible waste fuels (e.g. petroleum coke) co-fired with the coal are not considered coal ash. Regulations relating to the beneficial use of coal ash were adopted as part of Pennsylvania's Residual Waste Management Regulations (25 PA Code Chapter 287) in 1992. The coal ash beneficial use regulations allow for coal ash to be used as a soil substitute or soil additive and as placement for fill material at surface coal mines, coal refuse reprocessing operations and coal refuse disposal sites.

The Pennsylvania Department of Environmental Protection (PA DEP) administers the program for the beneficial use of coal ash at coal mining operations. The Bureaus of Mining and Reclamation and District Mining Operations have program responsibilities for use of coal ash on active coal mining operations and the Bureau of Abandoned Mine Reclamation has program responsibilities for use on abandoned mine lands. The Bureau of Land Recycling and Waste Management within PA DEP has program responsibility for the beneficial use of coal ash at sites other than coal mining operations.

**Permitting Procedures and Requirements**

The beneficial use of coal ash at active coal mine operations is accomplished through the coal mine permitting process. Two additional permit application modules were developed for use with the coal mine permit application for evaluating proposals for beneficial use of coal ash. Module 25 was developed for placement of coal ash as fill material and Module 27 for use of coal ash as a soil substitute or additive.

Proposals for the beneficial use of coal ash at coal mining operations must include an identification of the sources(s) of the coal ash, the quality and quantity of the coal ash to be utilized, an operation and reclamation plan, a locational map, and a signed statement by the landowner acknowledging and consenting to placement of coal ash on their property. A chemical analysis of the coal ash and coal ash leachate is required using applicable procedures in EPA's Test Method for Evaluating Solid Waste (SW-846) and SW-846 Method 13 12, Synthetic Precipitation Leaching Procedure (SPLP). The chemical analysis of the ash leachate is compared with "groundwater parameters" for each constituent analyzed. The "groundwater parameters" are based upon human health and environmental protection standards. For a coal ash to be approved for beneficial use, metals and other cations in the leachate may not exceed 25 times the "groundwater parameter". Anions may not exceed the "groundwater parameter" except that up to 10 times the "groundwater parameter" for anions may be approved if the applicant can demonstrate that use of the coal ash will result in an improvement in pre-existing groundwater degradation.

Generally the quantity of coal ash for placement as fill material may not exceed the amount of coal, coal refuse, culm or coal silt removed from the mine site. It may be exceeded, however, if the coal

ash is generated by a fluidized bed combustion facility and is needed for contouring abandoned unreclaimed mine land as part of a coal remining operation or the coal ash is part of an approved pollution abatement plan of a coal remining operation. The quantity of coal ash placed at mining operations involving reprocessing coal refuse banks or piles may not result in rebuilding the bank or pile. In addition, the quantity of coal ash used a soil substitute or additive may be limited based upon metal analyses of the ash to avoid plant toxicity and to comply with established maximum lifetime metal loadings in conjunction with land reclamation.

The operation and reclamation plan in the permit application must address handling and on-site storage of the coal ash, method(s) and equipment for coal ash compaction/incorporation, dust control measures, monitoring coal ash quality and quantity, monitoring water quality, and final grading and reclamation of the site. Plans for ash placement as fill material must include groundwater monitoring. At least one monitoring well must be placed at a point, hydraulically up gradient of the proposed ash placement area and be representative of groundwater quality unaffected by the mining and ash placement. At least three monitoring wells must be located down gradient of the ash placement area. Six months of background groundwater data is required for placement of coal ash as fill material. Trigger levels for groundwater constituents are established which require groundwater assessment and abatement if the levels are exceeded during the operation. The trigger level for each constituent is established as the higher value of either, the "groundwater parameter" or the background level for the constituent.

In addition to the above, public notice of the proposed coal ash placement as fill material is made by the Department and the coal mine operator. The Department publishes notice of the proposal in the Pennsylvania Bulletin. The mine operator publishes notice of the proposal in a newspaper of general circulation in the locality of the proposed coal ash placement activity.

#### Operational Reuirements And Performance Standards

The following requirements and standards apply to the beneficial use of coal ash for placement as fill material at coal mining operations:

- Ash may not be placed in surface water drainage areas for streams designated as High Quality or Exceptional Value Waters, unless the Department approves ash placement for the purpose of improving degraded surface or groundwater quality.
- Final site grading must minimize percolation of precipitation and surface runoff into the coal ash placement area. The surface grade may not be less than 3%.
- The operator must isolate the coal ash deposits from coal seams, coal outcrops, and the pit floor using barriers of natural, compacted soil or backfill material at least 8 feet (2.43 meters) thick.
- Underground mine openings within the site must be sealed in a manner approved by the Department.
- Ash placement must be at least 4 feet (1.21 meters) above the premining seasonal high groundwater table or perched water table, and at least 8 feet (2.43 meters) above the regional groundwater table. The regional groundwater table may not be artificially manipulated to achieve the above.
- Coal ash must be spread and compacted in horizontal layers which are no more than 2 feet (.60 meters) thick. Each layer must be compacted to attain at least 90% of the maximum dry density as determined by the Modified Proctor Test or 9.5% of the maximum dry density as determined by the Standard Proctor Test.

- A final cover of at least 4 feet (1.21 meters) of non-acid forming materials must be placed over the ash placement area and must not include any rock over 6 inches (15.24 centimeters) in diameter. The top 1 foot (.30 meter) layer must not have a coarse fragment content exceeding 60% by weight of particles that do not pass the number 10 mesh sieve (2 millimeter opening).
- The pH of the coal ash delivered to the mine site must be in the range of 7.0 to 12.5. The pH of the ash may be adjusted at the site where it is generated. The ash and leachate analyses must be reported after pH adjustment.
- Each coal ash source must have a chemical analysis and a leachate analysis at least once every six months. The Department may require more frequent analyses depending on the variability of the coal ash.
- Each coal ash source must have a laboratory analysis for optimum moisture content and maximum dry density (Standard Proctor or Modified Proctor Test) at least once every six months. The Department may require more frequent analyses depending on the variability of the coal ash.
- Upgradient and downgradient monitoring wells must be sampled and analyzed annually for total and dissolved metals and quarterly for all other constituents.

The following requirements and standards apply to the beneficial use of coal ash as a soil substitute or soil additive for reclamation of coal mine operations:

- The pH of the coal ash and the pH of the soil must be in the range of 6.5 to 8.0 when mixed together. Lime may be used to adjust pH.
- Coal ash must be incorporated into the soil within 48 hours of application, unless otherwise approved by the Department.
- Coal ash must be applied at a rate per acre that will protect public health, public safety and the environment.
- Coal ash may not be applied to soil being used for agriculture where the soil pH is less than 5.5.
- Coal ash may not be applied if the resultant chemical or physical soil conditions would be detrimental to biota.
- Coal ash, soil, vegetation and surface and groundwater quality must be monitored in accordance with the approved plan.

#### **Distance Limitations For Coal Ash Utilization**

Distance limitations have been established for utilization of coal ash. Coal ash may not be applied:

- Within 100 feet (30.48 meters) of an intermittent or perennial stream or a wetland other than an exceptional value wetland.
- Within 300 feet (91.44 meters) of an exceptional value wetland.
- Within 500 feet (152.40 meters) upgradient of a surface drinking water source or within 300 feet (91.44 meter) of a groundwater source.

- Within 100 feet (30.48 meters) of a sinkhole or drainage area to a sinkhole.
- Within 300 feet (91.44 meters) of an occupied dwelling unless the owner provides a written waiver.

### **Extent of Beneficial Use of Coal Ash At Active Coal Mines**

Pennsylvania has over 70 coal mining operations (includes coal refuse reprocessing operations) where coal ash is being used under the beneficial use provisions of PA SWMA. In 1995, over 6,700,000 tons (6,082,260 metric tons) of coal ash had been used as fill material at coal mining operations within the state. An additional 6,500 tons (5,900 metric tons) of coal ash had been used as a soil substitute or soil additive.

### **Future Direction of Program**

Pennsylvania's regulations on the beneficial use of coal ash are currently in the process of being revised. Several of the present operational requirements and performance standards are viewed as being too prescriptive and would be deleted from the regulations. For example, the requirement for a surface grade of not less than 3% (for operations involving coal ash placement as fill material) would be deleted under the revisions currently in process. The revised regulations include provisions for the certification of coal ash sources for specific beneficial uses. Certification guidelines would be developed which identify the acceptable physical and chemical characteristics of coal ash for various beneficial uses. A coal ash generator may request to have their ash certified for specific beneficial uses by demonstrating that the ash quality meets the acceptable physical and chemical characteristics. Once the coal ash has been certified, use of the ash at coal mining operations may be authorized without providing additional data on the quality of the ash. In addition, technical guidance would be developed to facilitate review of beneficial uses of coal ash at coal mining operations. The guidance would identify operational requirements and performance standards for the specific beneficial use.

## **NEW MEXICO'S REGULATORY REQUIREMENTS FOR THE USE OF COAL COMBUSTION BY-PRODUCTS**

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The Mining and Minerals Division (MMD) of the Energy, Minerals and Natural Resources Department of the State of New Mexico currently regulates two mines where disposal of coal combustion materials has been approved. Aside from regulation by the Mining and Minerals Division, coal combustion by-products are specifically exempted from regulation under the State of New Mexico's solid waste regulations by definition of a "solid waste".

In 1982 the MMD received an application from the San Juan Mine to dispose of approximately 1.5 million cubic yards of coal combustion by-products per year as part of its backfill and regrade operation. Several factors favored this scenario, not the least of which was the mines' location in an arid environment, receipt of annual rainfall amounts between four and six inches per year and this usually occurring in the form of short, intense, summer, thunderstorms. The area also has a pan evaporation rate of 67 inches per year. The potential for direct infiltration of rainfall as recharge appeared to be very low, except in areas of concentrated runoff.

Geological conditions also appeared to be favorable for disposal of coal combustion by-products. The only horizon that could be considered as an aquifer was the lowermost coal seam that was scheduled to be mined. This seam is separated from a lower sandstone horizon by a shale interval that should restrict flow between the two horizons.

To demonstrate the favorable nature of the site for long-term disposal of coal combustion wastes the mine also was required by MMD to conduct several other investigations. These included sampling the water qualities of the coal seam aquifer, conducting leachate studies of the spoil/combustion waste and determining the impact on the quality of the waters of the coal seam. In addition, compaction and permeability tests were performed on composited spoil/combustion waste materials as a means to assess the post-mining hydraulic properties of the reclaimed mine area. Leachate transport studies were conducted and once significant pathways were identified, an analysis of projected travel times and flow volumes was performed.

Upon approval of the coal combustion disposal plan additional requirements were placed in the permit as part of the disposal plan. Specifically, all disposal areas are to be covered by a minimum of ten feet of spoil material in addition to topsoil material. Drainages that run above disposal areas should have low drainage gradients to reduce the possibility of down cutting. Disposal areas are mapped to determine the location of the material as far as depth of disposal and thickness of the material. These maps are submitted to the MMD in the annual report.

Recently, a permit requirement was added and two porous cup lysimeters were installed to determine whether irrigation waters were infiltrating the topsoil and spoil material. One lysimeter was installed to the top of the waste material and the other through the waste material to the bottom of the combustion waste. To date, all indications are that the combustion material is remaining dry and not producing leachate.

The second application for disposal of coal combustion waste was received in September of 1993 from the Pittsburg & Midway Coal Mining Company, York Canyon Mine Complex, in northeastern New Mexico. The application was for the disposal of a pelletized fly ash from Wisconsin Electric Power Company from coal that was mined at the York Canyon mine complex. The pelletized fly ash is comprised of spherical cement nodules, approximately 3/8 inches in diameter and would be placed in the mined out pit floors as part of the backfilling and grading process.

The climate of the area is arid to semi-arid, with annual rainfall at the site of about 15 inches. Local relief in the area varies from 500 to 2000 feet and is dominated by incised canyons and arroyos. Drainage is by intermittent or ephemeral streams which are tributary to a perennial, high quality, trout stream. Regional ground water is below the deepest proposed mining level. Mining is essentially a mountain-top removal operation.

As part of the application, the HELP, version 2.05, program was used to quantify surface infiltration and potential leachate generation rates. Input from the HELP model was used to estimate a steady-state infiltration rate through the spoils and ash system and into the natural ground water flow system. The HELP model results were integrated with geologic data and materials properties to develop input for a MODFLOW evaluation. The MODFLOW program, version 3.0, was used to evaluate the potential for vertical and horizontal ground water flow patterns beneath the site. Finally, a program called Geochemist's Workbench™ was used to estimate the potential chemical concentrations of fluids produced by flow through the various spoils and ash systems.

In addition to the above tests, ASTM leaching procedure D-3987-85 was performed on samples of pelletized fly ash using locally obtained groundwater samples as the leaching medium. This test was repeated on samples of overburden using deionized water as the leaching medium. A TCLP analysis was required on the pelletized ash and was compared to a TCLP analysis of the leachate obtained from the overburden.

It was determined that the disposal of combustion waste in the form proposed as part of the mining operation carried little measurable risk to the surface or ground water environment and the proposal was approved. The MMD added the requirements that the waste be end-dumped only in the pit bottom and not between spoil ridges as originally proposed, to assure that high material wasn't inadvertently placed in the root zone. The Approximate Original Contour(AOC) was also designed to remove water as quickly as possible without resulting in erosive velocities and to avoid infiltration. A barrier of oxidized coal was also to be left around the outcrop and all ash was to be covered by a minimum of two meters of spoil material in addition to the topsoil. Following reclamation, a system of lysimeters were to be installed to monitor any resaturation that may have occurred.

Although the permit was issued in a timely manner, contract problems between the mine and Wisconsin Electric Power Company resulted in the project not being carried through. Any future application for coal combustion waste disposal would carry similar requirements prior to approval.

**Session IV:**

**DESIGN/ENGINEERING/PLANNING**

Session Chairs:

Y. Paul Chugh  
Mining Engineering Department  
Southern Illinois University at Carbondale

Gary Brendell  
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Panelists:

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# ASSESSING THE WATER QUALITY IMPACTS OF FLY ASH STRUCTURAL FILL PROJECTS

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## Abstract

The beneficial use of coal combustion by-products (CCBs), such as fly ash as structural fill, is becoming more prevalent within the United States. Prior to using fly ash as fill material, many state agencies required an environmental assessment based on comparison of fly ash leachate, as determined by short-term laboratory tests, with a conservative groundwater protection standard. This approach fails to take into account project specific considerations such as volume and composition of fill materials, rates of infiltration, constituent migration and attenuation, existing ground water quality, and present and future groundwater uses. This paper reviews traditional approaches used to characterize potential environmental impacts of fly ash utilization, summarizes recent research findings on the mobility and fate of the constituents of fly ash leachates and suggests adoption of risk-assessments to assess potential environmental impacts at fly ash utilization sites.

## Background

Over 1.2 million tons of coal fly ash were used in the United States during 1994 as structural fill material for site development projects, highway embankments, dikes and levees, and other bulk fill applications<sup>1</sup>. Fifteen states have adopted beneficial use regulations or policies allowing fly ash structural fills and similar policies are being considered in other states<sup>2</sup>. Some of the impetus for this interest in reuse of fly ash derives from the 1993 United States Environmental Protection Agency (USEPA) final regulatory determination on large-volume electric utility wastes<sup>3</sup>. This study found that CCBs, such as fly ash, would not be regulated as hazardous waste and that the beneficial reuse of these by-products should be encouraged. The USEPA further stated it had found no evidence of environmental damage resulting from the use of high-volume coal combustion wastes<sup>3</sup>.

The use of fly ash in structural fills is currently regulated by the states, many of which require an environmental assessment consisting of a comparison of the fly ash leachate with conservative ground water protection standards. This approach fails to take into account project-specific considerations such as volume and composition of fill materials, rates of infiltration, constituent migration and attenuation rates, existing ground water quality, and present and future land and ground water uses.

This paper will summarize leachate testing procedures which have historically been used to characterize fly ash leachate and discusses the short-comings of the use of these methods when characterizing potential environmental impacts at fly ash utilization sites. As an alternative, the use of risk assessments are proposed to evaluate potential environmental impacts at fly ash utilization sites.

## Regulatory Leaching Procedures

### Toxicity Characteristic Leaching Procedure

A commonly used test used to determine the leaching characteristics of fly ash is the toxicity characteristic leaching procedure (TCLP). The TCLP test is the USEPA leaching procedure for determining the characteristics of hazardous waste. Land disposal of a material which is determined hazardous using this procedure is not permitted by the USEPA. Many state regulatory agencies have adopted the TCLP for characterization of solid wastes which are not federally regulated. This test was designed to simulate leaching in a sanitary landfill under co-disposal conditions.

The TCLP uses end-over-end agitation, a 20-to-1 liquid-to-solid ratio, and an 18-hour equilibration time. The test uses two leaching solutions. The solution used for the test is determined by the alkalinity of the waste to be leached. Alkaline materials use a solution that has a pH of 2.88 which is buffered using acetic acid and less alkaline materials use a solution with a pH of 4.93 which is buffered using sodium hydroxide.

#### Synthetic Precipitation Leaching Procedure

The synthetic precipitation leaching procedure (SPLP) is a USEPA test which is designed to determine the mobility of analytes present in samples of soils, wastes and wastewaters with precipitation as the leaching solution. If analysis of the extracted fluid shows that the concentration of any regulated substance exceed the applicable regulatory level, then the material is classified as hazardous.

The SPLP uses end-over-end agitation, a 20-to-1 liquid-to-solid ratio, and an 18-hour equilibration time. The extraction fluid used for the SPLP test is determined by the geographic location of the proposed utilization site. One fluid is specified for simulating leachability of wastes east of the Mississippi River and the other is for simulating leachability of wastes west of the Mississippi River. The extraction fluids are prepared by adding a 60/40 weight percent mixture of sulfuric and nitric acids to reagent water until a specified pH is obtained. The specified pH values are  $4.20 \pm 0.05$  and  $5.00 \pm 0.05$  for east and west of the Mississippi River, respectively.

#### **Other Tests**

#### Synthetic Ground-Water Leaching Procedure

The synthetic ground-water leaching procedure (SGLP) was proposed and developed by Hassett<sup>4</sup>. This method is designed to simulate actual field conditions in utilization scenarios. The test used end-over-end agitation, a 20-to-1 liquid-to-solid ratio and an 18-hour equilibration time. The major differences between this method and the TCLP and the SPLP procedures is the leaching solution. The specified leaching solution is synthetic ground water that has a pH and major cation and anion concentrations that are similar to ground water in the area where utilization is proposed. This test may be performed for a longer period of time to develop information on mineralogical changes in the fly ash which may impact the leachability of constituents.

#### **Discussion of Leaching Tests and Leachate Characteristics**

Regulatory tests, such as the TCLP and the SPLP tests, provide information which characterize CCBs as hazardous or non-hazardous substances. However, these tests do not adequately simulate the chemical composition of leachate in real world utilization scenarios.

Non-regulatory tests, such as SGLP, more adequately simulate utilization scenarios. However, this test is limited because it is performed for only a short time period. For laboratory scale tests, properly designed long-term tests (months in duration) provide the most accurate depiction of environmental conditions in utilization scenarios.

Fly ash consists mainly of glass material that is essentially inert. However, materials do exist on the glassy surfaces which are readily exchangeable and may produce leachate when exposed to water. However, leachate which is produced by fly ash is rarely hazardous<sup>5</sup>.

The chemical characteristics of the leachate are determined by the chemical and physical characteristics of the ash (which are related to the coal source and the combustion process), and the soil-water medium through which the leachate flows. The principal reactions controlling leachate composition are dissolution/precipitation, adsorption/desorption, and redox transformation'. Wet or dry

placement characteristics also control **leachate** characteristics because wet placement fly ash materials tend to undergo partial leaching prior to placement.

Major dissolved constituents in the **leachate** are calcium and sulfate, with lesser amounts of magnesium, sodium, potassium, and silicon. The concentrations of most of these elements in fly ash **leachate** are a function of **leachate pH**, with the lowest trace metal levels occurring over the **pH** range of 6.0 to 8.0<sup>6</sup>. Not all elements in fly ash are equally susceptible to leaching. For example, arsenic, boron, and chromium are preferentially concentrated on and in **the** surfaces of fly ash particles while lead and other trace elements are preferentially concentrated within the interior matrix of fly ash **particles**<sup>7</sup>. Elements concentrated on the surfaces of fly ash particles are more susceptible to leaching than the elements concentrated in the interior of the fly ash particles. Therefore the concentrations of these and other individual **leachate** constituents are dependent upon their availability and reaction chemistry, rather than on their total concentration.<sup>?</sup>

Each of the leaching tests described in this paper rely on the fact **that** water will come in contact with the fly ash material in a utilization scenario. Utilization projects typically place fly ash in a moistened-compacted state, or in a cementitious mix which has a relatively low hydraulic conductivity (low permeability). Low permeability cover materials and surface drainage which limits infiltration are also typically employed at fly ash utilization sites. Each of the above-mentioned factors tend to decrease the amount of surface water and ground water that infiltrates into and moves through the fly ash. Therefore, soluble elements present in fly ash are not exposed to significant quantities of water at properly designed utilization sites and dissolution and transportation of these elements is, therefore, limited.

Several mechanisms in all natural soils and ground waters act to attenuate or reduce the mobility and concentrations of elements in ground water. Mechanisms which contribute to the attenuation process include:

- Precipitation and adsorption with solids
- Dispersion and dilution of ground water

These attenuation mechanisms are predominantly controlled by the **pH** of the soil, **leachate** and ground water, the ionic strength of the **leachate** and ground water, and the physical and chemical characteristics of the porous media. Each of the laboratory leaching tests described in this paper fail to account for these attenuation processes, and these tests consequently do not yield adequate **leachate** characteristics data.

The inadequacy of short-term laboratory tests is evidenced by the results of several studies which show that the concentrations of trace metals in ground water at disposal sites is lower than the concentrations predicted by laboratory leaching tests<sup>8</sup>.

The Electric Power Research Institute (EPRI) performed reconnaissance investigations at five road construction sites which used **CCBs**<sup>9</sup>. These investigations were conducted to gather preliminary information on leaching and migration of chemicals from **CCBs** to soils, ground water and vegetation. As part of the studies, soil and ash, ground water and vegetation samples were collected and analyzed. The studies concluded that at all sites, regardless of age, climate and soil type, the impact of chemicals leached from fly ash are retained in soils immediately below (0 to 6 feet) the road base or embankment. Therefore, natural attenuation of soluble elements present in the fly ash must have occurred. In addition, the results also suggest that analytes typical of fly ash had concentrations which were either not elevated above background concentrations or were below USEPA drinking water standards.

In summary, short-term tests do not adequately simulate the chemical composition of **leachate** at fly ash utilization sites. These tests only identify which constituents are most likely to leach under conditions which are typically not encountered in utilization scenarios. Accordingly, long-term

laboratory tests should be used instead of traditional short-term regulatory tests such as the TCLP and the SPLP tests. However, since the chemical makeup of leachate produced by fly ash is variable and is dependent upon the fly ash itself, as well as the conditions present at a particular utilization site, long-term tests also fail to adequately simulate leachate characteristics. Accordingly, each utilization scenario should be evaluated independently based on the characteristics of the particular project, and evaluation of environmental conditions based solely on laboratory tests should be avoided, if possible.

### **Risk Assessment**

Because laboratory tests fail to account for all of the processes that control the fate and transport of elements that originate from fly ash at utilization sites, the use of risk assessments is recommended to predict environmental impacts at proposed fly ash utilization sites. Risk assessments can be performed to determine if the proposed utilization of fly ash poses a significant risk to human health or other ecological populations. Risk is the probability of injury, disease, or death under specific circumstances.

In order for risk to human health to exist, toxic chemicals must be present and humans must be exposed to the toxic chemicals. Therefore, prior to conducting a complete risk assessment, an investigator should conduct a qualitative impact assessment for the proposed project. A qualitative impact assessment, based on available information, determines if toxic chemicals are present and if likely receptors are located near the site. If neither of these are present, a risk assessment is probably not required and fly ash utilization will most likely pose no significant risk.

Risk assessments are performed in an attempt to answer one or more of the following questions:

- What chemicals pose significant risks?
- Who may be exposed to the chemicals?
- What are the exposure pathways and frequencies?
- At what concentration can chemicals exist on site without posing an unacceptable risk to the receptors which could be exposed to them?

Risk assessments generally consist of the following steps:

- Data collection and interpretation
- Toxicological evaluation
- Dose-response evaluation
- Exposure assessment
- Risk assessment

Information obtained during the data collection stage include types of contaminants present in the fly ash and site characteristics. This information is typically available from previous investigations and it is supplemented when necessary for the risk assessment<sup>4</sup>. The toxicological evaluation determines whether or not the chemicals identified during the data collection stage could have an undesirable health effect on the target population. The target population usually consists of humans; however, plants, animals and other ecological receptors may be considered. The toxicological evaluation is typically based on published research that identifies the types and severity of potential health hazards associated with specific chemicals.

The dose-response evaluation is performed only if the toxicological evaluation suggest that a chemical may have adverse impacts on the target population. The dose-response evaluation is conducted to investigate relationships among the dose and duration of chemical exposure as well as severity of its adverse health impacts. The result of this evaluation is the identification of a exposure dose that will result in no observed adverse health impacts to the target population. This evaluation often considers chronic or long-term impacts as well as acute or short-term impacts.

An exposure assessment considers actual or potential routes which the target population is most likely to be exposed to or the most susceptible exposure rate as well as the duration of exposure. Typical exposure routes include ingestion, inhalation and dermal contact. This process frequently includes computer modeling of fate and transport of chemicals through air, soil and water to characterize transport pathways and predict actual exposure concentrations. The end result of the exposure assessment is estimates of exposure doses for specific toxic chemicals at potential receptors.

The risk characterization combines all previous steps to estimate the statistical probability that adverse health effects will result in the target population due to exposure. The total potential risks are then compared to levels of acceptable risk which are established by regulatory agencies.

Risk assessments can be applied to fly ash utilization projects by showing that concentrations in air, soil and water will not exceed concentrations that will cause an unacceptable level of risk to exposed populations. Likewise, fly ash utilization projects should be designed so that the level of risk associated with the project is minimized.

### Summary

Coal combustion by-products such as fly ash can successfully be used as structural fill. Short-term regulatory laboratory **leachate** characterization methods such as the TCLP and SPLP tests do not adequately characterize **leachate** produced by fly ash. At best, these **leachate** tests simply identify which constituents in fly ash are most likely to leach under conditions that are not typically encountered in utilization scenarios. Long-term non-regulatory laboratory tests provide a more accurate representation of the potential leaching characteristics of fly ash. However, when used alone to predict potential environmental impacts at proposed fly ash utilization sites, both long-term and short-term tests fail to account for site-specific considerations such as volume and composition of fly ash fill material, infiltration rates, constituent migration and attenuation rates, existing ground water quality, and present and future land and ground water uses. When performed and applied properly, risk assessments account for all of the above factors. Therefore, risk assessments should be used to adequately evaluate the potential environmental impacts at proposed fly ash utilization sites.

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## DESIGN AND MANAGEMENT OF COAL COMBUSTION BY-PRODUCT MINE BACKHAUL PLACEMENT AREAS

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### **Abstract**

Mine backhaul operations are a relatively new, but firmly established, way of maintaining viability under increasing competition and regulation. A successful backhaul operation must carefully consider many factors in the design and management of the placement areas. CCB characteristics, site conditions, transportation methods, mine operations and final reclamation plans are among those factors. This paper will try to elaborate on as many of these factors as possible in a short paper.

### **Disclaimer**

Most of the material presented in this paper is drawn from experience and conversations with other people involved in this field. Many generalizations are made, all of which have exceptions. When dealing with coal combustion by-products, familiarity with the particular by-product being handled is necessary to avoid surprises. It is up to the reader to judge whether the information presented here is appropriate to the case at hand.

### **Overview**

The return of coal combustion by-products to an active or inactive coal mine for permanent removal has grown in popularity during the last several years. The ultimate purpose of this type of operation is to reduce the fuel cost to the coal customer. The cost of off site by-product disposal is high enough to warrant serious investigation of beneficial reuse of coal combustion by-products even though the percentage of by-products being reused is still a small number. Mine backhaul operations may be a last resort for many coal consumers when no other economical use exists. In other cases, the amount of coal combustion by-products produced is not large enough to be attractive to by-product consumers. Since most coal is burned by utilities or industrial plants, it is hoped that backhauling will reduce the cost, or at least the rate of rise of the cost, to the consumer. It must be assumed that there is no alternate commercially economical use for the by-products that are brought to the mine, although there may be beneficial uses at the mine level.

Aside from reduced cost, there are several potential benefits to coal combustion by-product backhaul operations. One of these is the potential for land use conservation. If the by-products are returned to the place where the coal was extracted, then the need for land till volume at the customer's site is reduced. If the coal customer was disposing the by-products in a commercial land-fill, then there will be more space available in that landfill for the other types of waste that humans generate. Properties of many coal combustion by-products indicate that there may be uses for them in mine reclamation, subsidence control, acid mine drainage abatement and coal mining waste stabilization. In order to accomplish these things, the cost of mine placement of by-products must be minimized and the long term liabilities of the coal customer and the mining company must be stable and known to all. For these and other reasons, it is very important that the placement plans and operations be well thought out and carried through by knowledgeable people.

The volume of CCB's to be returned to the mine and the length of the term of the backhaul operation are among the first pieces of information necessary. If the coal customer's plant is already in operation, then the normal CCB production can be evaluated. Be aware that changes to the customer's plant or in the method of operation can cause large variations in CCB production rates and that the customer's demand may have wide swings. The basic procedure is to determine the annual volume of CCB's,

the peak volume and the length of the peak. Some coal consumers may want to haul CCB's only on certain days of the week. This may mean large volumes to be handled on those days and minimal volumes on others. An operation with wide swings in CCB handling rates will require a workforce that can respond to rapid changes in workload. It is seldom possible to keep a stable workforce when the activity is volatile and the cost will be high if it is not possible to plan around the peak activity. An important thing to remember is that CCB production continues year round and construction, reclamation and beneficial reuse activities peak in the summer months. When the alternative uses are in operation, the backhaul amounts may fall off. When the alternative uses cease operation, the backhaul quantities may rise quickly. The backhaul activity usually peaks when the weather is so bad that the other uses can't operate. This usually means that the backhaul operation is busiest when the weather conditions are worst. Since the coal customer's CCB storage volume is usually rather small, continued backhaul operation is very important.

A mine backhaul operation must consider the by-product characteristics and properties first. Many generalizations are made about coal combustion by-products, but there are significant differences between different types that may cause difficulties in the operation. Physical and chemical properties must be determined. This includes all the standard tests for chemical constituents, mineralogy, leaching products and engineering physical properties as well as what might be called "offhand observations" about the materials that may determine the suitability of various handling and placement schemes. It is well to be wary of the results of short term laboratory testing when long term results are desired. Coal combustion by-products usually fall into one or more of the following types:

### Slag

A vitreous material drawn from the bottom of cyclone boilers. Since slag has been fused, there is very little chemical activity and leachate is not normally contaminated. Slag has many uses including blasting grit, roofing granules and highway traction aid. Slag is normally the major portion of the by-products produced by a cyclone boiler. Very little slag is backhauled unless the particle size is too small to be used in alternate applications.

### Bottom Ash

A coarse ash drawn from the bottom of pulverized fuel boilers and stoker fired boilers. This may be partially vitrified or clinkered, but is friable and not suitable for many of the slag applications. Some bottom ash is used for road traction applications. Bottom ash will often show metals in the leachate and may tend to be acid producing. Bottom ash is usually a small portion of the total ash produced by the boiler.

### Stoker Ash

An ash drawn from the bottom of grate type burners, a type of bottom ash, but more likely to contain unburned coal particles.

### Conventional Fly Ash

A fine dusty ash removed from the flue gases of stoker, pulverized coal or cyclone boilers. This ash will not normally contain spent sorbents. There are two main types of fly ash, Class F (low lime) and Class C (high lime). Class F fly ash is typically associated with eastern U.S. coals and Class C is associated with western U. S. coals. High quality conventional fly ash will contain very little sulfate compounds or unburned carbon. This ash has many uses in cement replacement and flowable or flash fills.

### Scrubber Sludge

This is the spent sorbent from flue gas desulfurization scrubbers. It may be dry, but is commonly delivered as filter cake. Scrubber sludge is normally high in calcium sulfites and sulfates. The filter cake may be very difficult to remove from dump trucks or hopper cars. Filter cake is not difficult to handle after dumping, but is soft and usually too wet to compact. Some scrubber sludge is suitable for use as gypsum board feed stock, but much is not reused at present.

### Fluidized Bed Fly Ash

This is the ash collected from the flue gas of fluidized bed boilers. This ash resembles conventional fly ash, but contains spent sorbent and is produced at lower temperatures. FBC fly ash is normally highly alkaline and can be used to treat acid producing mine waste. The high alkalinity tends to minimize metals in the leachate. High sulfate content can make FBC fly ash unsuitable for many structural applications. Sulfate may be present as anhydrite which expands as it is converted to gypsum, a process which may take some time. The mineral ettringite is commonly formed during the hydration of FBC fly ash and is generally considered undesirable in concrete mixes. FBC fly ash may gain considerable strength on hydration, but usually weathers considerably when exposed to air, moisture and freeze-thaw cycling. The strength and rate of gain of strength of FBC fly ash appears to be related to the amount of water used to hydrate the ash, in much the same fashion as cement grouts. A low water ratio will usually produce higher strengths as long as sufficient water is used. FBC fly ash usually releases considerable heat on hydration. This heat can cause temperatures exceeding the boiling point of water in a matter of minutes and must be considered in any placement scheme. It may be desirable to hydrate the ash in stages with cooling between stages. Unconditioned FBC fly ash will usually contain considerable dust, much of which may be under 10 microns particle size. During hydration, ash particles react with water and may break down, resulting in new dust unless there is enough water to bind the particles together.

### Fluid Bed Boiler Spent Bed

This is excess bed material that must be removed from the boiler to hold the bed level constant. The composition of spent bed should normally be the same as the active bed material and spent bed usually contains considerable unreacted sorbent. Spent bed is normally withdrawn after the fly ash has been removed and is not normally very dusty. Spent bed may be used as a low cost low grade lime substitute.

There are two basic types of operations that will be discussed. The first is an operation that places CCB's in the same place that the coal was extracted from, that is, in seam. The most common operation of this type is to place the CCB's against a highwall in a stripping operation. Coal waste products may be mixed with the CCB's or CCB's may be incorporated in the spoil. This is usually done when the spoil is potentially acid producing. Another option is injection of CCB's into underground workings for subsidence or acid mine drainage control. This is not yet common, but is being done. The second type of operation is that where the CCB's are placed in an area developed specifically for that purpose. Again, coal waste products may be, and usually are, mixed with the CCB's. The resulting mixture may have properties superior to the individual components. CCB's may be used to stabilize coal processing wastes or to reduce the acid producing potential of these wastes.

There are two general types of placement methods, dry and wet. Dry placement is any method that results in a solid material that does not bleed water. Wet placement is any method that results in an excess of water that must be handled after the CCB's have been placed. There is a gray area where the CCB's are placed as a paste, but the water is consumed in hydration, much the same as placing concrete or flowable fill. Each method has advantages and disadvantages. Dry placement may avoid leaching, but the CCB's may not be compactable and dust may be a problem. Wet placing avoids dust, but may not flow as well as expected or may result in a low strength material. In the end, CCB's may be placed dry,

just as received, with water added to control dust and aid compaction or wet as a paste or slurry, all at the same site. The decision is based on the lowest cost after evaluating the materials, the site, the equipment and the operational hazards.

### **Preliminary Evaluation**

One of the first CCB properties to determine is the in place density of the CCB's. This is not necessarily the same thing as the as received bulk density. Moisture may be added or removed. Mineralogical changes may occur. Compaction may take place, but be offset by expansion due to changes in the structure of the CCB's. If CCB's and coal mine waste products are blended, the resulting mixture may have properties quite different from the original constituents. After all of these have been considered, it is hoped that the volume occupied by one ton of CCB is known and the volume required to hold the total amount of CCB's expected during the term of the contract can be calculated. This calculation is not a trivial thing and needs to be updated periodically to avoid end of term surprises.

Site conditions must be evaluated. The site location will normally be dictated by proximity to mine operations and the backhaul operation will be tailored to the site. If the mining operation already exists, many of these conditions will be known. Site topography, surface and ground water sources must be evaluated. Existing water quality and hydrological conditions should be determined. Soil types and properties must be investigated. The mining operations plan may have an effect on the by-product handling plan.

If the CCB's are to be placed in an excavation or earth embankment, the permeability and nature of the groundwater flow must be determined before proceeding. The current tendency is to restrict groundwater flow through CCB placements, but there are cases where groundwater has been improved by passing through CCB's. There are cases where CCB's are being placed on the ground surface with conventional earthmoving equipment, the only water handling being perimeter berms and ditches leading to a settling pond. Periodic soil cover and revegetation serve to limit the infiltration of water into the CCB's. Encased fills are sometimes allowed under beneficial reuse regulations. Some regulations require that the CCB's be placed above the water table, but exceptions may be allowed. The quantity, quality and current use of the groundwater will help guide the operator in the choices. Background monitoring of groundwater is generally required before placement operations can begin. Periodic monitoring during placement is also required. Considering the wide variations in soil types and CCB's, it is not really possible to generalize about construction methods and requirements. The methods currently used for coal refuse disposal areas, impoundments and embankments are all generally applicable to CCB's, but the specific cases have to be considered.

If the CCB's are to be placed against a highwall or in a pit at an active stripping operation, different groundwater considerations are presented. Beyond the highwall, natural conditions prevail. Unless the ground is highly fractured, the flow may tend to be parallel to the bedding planes of the strata. In the spoil, there is no set pattern of groundwater flow. Where the mine is on hilly ground, water may flow into the spoil on the upstream side, down through the spoil and exit at the toe. Where the pit is on level ground, there may not be any obvious groundwater flow. Water may infiltrate the spoil from the surface until saturation is reached. In underground mines, the CCB's will typically be pumped from the surface into old works. If the coal seam outcrops and there is surface water flow into the old works, the CCB's may seal the passages that water is flowing through. There are current projects that use CCB's to fill voids in abandoned mines where acid mine drainage is flowing to an outcrop. CCB's could be used to form a barrier to water flow from one underground mine to another. If the old works are dry, a common occurrence where no access to surface water exists, then there will be no contact between CCB's and groundwater. The natural conditions that allow coal to be formed often result in an impermeable layer of rock above the coal seam. As long as an impermeable layer exists and the coal seam is well below any aquifers, the likelihood of groundwater contamination from the CCB's is remote. Mining methods that result in intentional subsidence normally fracture the strata above the coal seam and can allow surface water to penetrate to the coal. This does not preclude the placement of CCB's in these areas, but does

tend to complicate the process. If the CCB's are to be mixed with coal refuse, the groundwater considerations are much the same, but the mixture may behave in a different manner than the individual components.

Transportation methods will probably influence the by-product handling facilities. Most traffic will move to and from the mine by truck or rail. Truck transportation is the most flexible, but over the road trucks may not be appropriate for on site material handling. Rail cars will normally have to be unloaded at a dedicated facility that may or may not be on the mine site. The trucks may **also** be handled in the same fashion. If the CCB's properties are suitable, it may be possible to unload trucks at the placement site and avoid double handling. Mine operations and the type of mining methods used may influence the choice of the on site material handling system. If haul trucks are used to bring coal from the area where the CCB's are to be placed, then it may be possible to use these same haul trucks to carry the CCB's to the placement site. In any case where the same containers are used to haul both coal and CCB's, care must be exercised in order that cross contamination does not occur. It is not too difficult to see why contamination of the coal product is undesirable, but contamination of the by-products with coal may also be a problem. There are specific cases where coal mining waste and coal combustion by-products will be intentionally placed together. In this case, the properties of the coal waste, by-products and the combination of these materials will need to be evaluated.

Weather can affect backhaul operations in the most direct ways. Construction jobs normally shut down when the weather is too wet or too cold, but backhaul operations have to operate in all types of weather under all sorts of adverse conditions. Reclamation work is probably most productive between the months of April and October. If CCB's are being used to aid reclamation, where do they go in the winter? Sometimes they can be stockpiled and placed later, but this rehandling can get expensive. Power plants run 365 days per year and the operators get pretty upset when the CCB silos are full and the trucks aren't moving. Weather affects backhaul operations in another very important way. Water is almost always a necessary part of the backhaul process. The amount of water required and the point of use vary. Water requirements should receive careful consideration to ensure adequate supplies and economical distribution. Reservoirs may be required to maintain the water supply and by-pass structures may be necessary around the CCB placement areas.

### **Backhaul Operations**

A backhaul operation begins at the point where the CCB's are delivered to the mine operator and ends when the coal is loaded into the conveyance. Truck haulage is the most common method of delivery. Trucks are preferred when the haul distance is short and the quantities are reasonable. With large quantities of CCB's, traffic control may become a problem. Rail haulage is used when distances are longer and when quantities are greater. Rail haulage requires a central dumping location and some other method for handling the CCB's on site. In both cases, quantity measurement must be allowed for. In some cases, the shipper will weigh the conveyances, in others, the mine operator. If neither the shipper nor the receiver has weighing facilities, then some other method may be required. It is important to know the weight of incoming material and may be required by some regulations. Knowing the weight of delivered CCB's and the volume of space required for them is useful for estimating the life of a facility. If specific blends of CCB's and other materials are to be used, the weights will be useful in controlling the mixes.

Truck haulage is the most flexible method of transportation. The truck may dump the CCB's at a central location or may drive to the final destination of the CCB's and then dump. The choice depends on a number of factors. If the conditions on site are not suitable for over the road trucks, the mine operator may want to consider a central dumping location. If the mine haul roads can be maintained in a condition that will allow all weather access and the dump location maintained in a firm and level condition, it is possible to have the trucks dump directly and not have to rehandle the CCB's. This is desirable if no further treatment of the CCB's is necessary and dust is not a problem. Some rail receiving facilities load the CCB's into trucks, both off road and over the road. The trucks then transport the CCB's to the point of use. The central dumping station may add water to the CCB's or blend the CCB's with other materials,

such as coal processing wastes. The economic analysis and logistics of locating a central dump station are complex. Once a station has been built and placed in operation, it is very difficult to make changes or additions that may be required by changes in traffic or materials.

If the condition of the CCB's at dumping allows conventional earthmoving techniques and equipment to be used, spreading and compaction of the CCB's may be the best approach. If the CCB's require hydration or are uncompactable or powdery and dusty, a useful approach may be to dump against a berm or into a trench or pit and then to cover the CCB's with spoil or other inert material before water is added to hydrate the CCB's. This will contain the dust that might form during hydration and can allow slow penetration of the CCB's with water. Direct spraying of very dusty CCB's may cause airborne dust where the water stream impacts the dust. A gentle sprinkling or misting will be required in these cases. Water may be added with sprinklers and other irrigation equipment. The most common problem encountered with sprinklers and fine sprays is that wind will blow the water in a different direction than that desired. This usually means frequent moving of sprays and piping, a costly and time consuming process. Flood irrigation may cause a crust to form on the CCB's which prevents water penetration into the CCB's. Later excavations may uncover dry dusty material that has not been properly hydrated. Weathering of CCB's may result in surface conditions that are unsuitable for travel by over the road trucks. In some cases fresh CCB's may be used to provide a driving surface. In cold weather, it will be important to provide a location where unhydrated CCB's may remain undisturbed until it becomes warm enough to add water to them. Wet, sticky CCB's may be very difficult to handle in cold weather. Any CCB's that stick in the nose of a semi-trailer may cause the trailer to become unstable and tip over. In some cases, frozen CCB's may be perfectly acceptable as a driving surface, but when thawing starts may become very unstable.

Other transportation modes may be used to remove CCB's to the point of use. These include dilute phase and dense phase pneumatic, conventional slurry and paste pumping. Pneumatic methods are best suited to short hauls that are mostly horizontal. The equipment is expensive, requires high horsepower and the capacity is low. Slurry placement is high capital cost, but low operating cost. The biggest disadvantage of slurries is the amount of water required and the need to handle this water after placement of the CCB's. Slurry system capacity can range from low to high and can operate at low throughput rates, if there is adequate water handling capacity. The low slurry densities require expensive impoundments with room for settling and decant systems for the clarified water. Pipelines can run long distances, but must be capable of being moved at the discharge point as solids collect. At high throughput rates, the pipes may have to be moved quite frequently. The slurries will probably flow over long distances after leaving the pipeline, if there is a favorable gradient, but will eventually build up at the discharge. Paste transportation removes much of the water from the mixture and does not require as much attention to excess water past the discharge, but will not usually flow as well as dilute slurries and requires higher horsepower. Mixing equipment varies from simple to complex. The less water desired in the final mix, the more complex the mixing equipment. If the CCB's are reactive, then multistage mixing may be required. The water may be consumed in the first stage, and considerable heat may be given off. Changes in the behavior of the CCB's may occur as the water content changes. It is much easier to add water to CCB's than to remove it later on, so monitoring the water content during mixing and transportation is the best way to ensure that excessive water is not being used.

Drainage control structures may often be constructed of CCB's. The type of structure desired and the properties of the CCB's will determine the methods of construction. Simple heaped structures are often useful, but will usually leak and are subject to slope failures. It is possible to use a heaped structure to contain a hydraulically placed cementitious CCB till. The voids in the heaped fill are often filled by the flowable mixture and the heaped fill is stabilized. This type of structure can be used as a containment and can be raised in lifts. It is important that the engineering properties of the structure be determined so that stability is maintained. Compacted fill structures may be built with CCB's. Some CCB's are suitable in the as received state, while others may require conditioning. The permeability of these structures may be too high to allow them to be used as impoundments, but they often serve as roadways and windbreaks. Blending CCB's with coal mining or processing wastes may result in a compactable mixture with superior

properties to the individual components. If the coal wastes contain clays, they may help to lower the permeability of the blend, while the CCB's may increase the strength. High lime content CCB's may help reduce the acid forming tendencies of some coal wastes. The weathering properties of these blends may require attention and heaving may occur because of mineralogical changes to the blend. These are not normally considered problems when the materials are used in an active mining and backhaul operation due to the short active life time of the structures.

## **DESIGN AND CONSTRUCTION GUIDELINES FOR COAL COMBUSTION BY-PRODUCT UTILIZATION IN ABANDONED MINE LAND SETTINGS - A CASE STUDY**

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### **Abstract**

The Midwestern Abandoned Mine Site is located in the heart of the Illinois Coal Basin in Pike County, Indiana. This site consists of approximately 550 acres of previously surface mined land that adjoins, and in some areas intersects, abandoned deep mine workings in the same coal seam. The most severely impacted portion of this site is located in the vicinity of an abandoned portable preparation plant where exposed coarse and fine coal refuse are surrounded by highwalls, associated final cut pits and poorly vegetated spoil. Due to the limited supply of low-permeability soil in this area the reclamation plans for this site included the use of coal combustion by-products to facilitate and enhance the reclamation program. Poz-O-Tec, a mixture of flyash, flue gas desulfurization (FGD) and quicklime, was used to create a low permeability cover over the exposed coal refuse while a combination of Poz-O-Tec and alkaline coal ash was used to backfill existing highwalls. Locally available mine spoil was used to establish a vegetative cover. This is the first significant application of coal combustion by-products at an abandoned mine land project in Indiana. Approximately 600,000 cubic yards of coal combustion by-products were utilized to meet material requirements at the site. Material properties have met and, in some instances, exceeded the anticipated characteristics. Chemical quality of both groundwater and surface water will be monitored by the Indiana Geological Survey for a two-year period (1997 and 1998). This data will be compared to baseline water quality for evaluation of application viability.

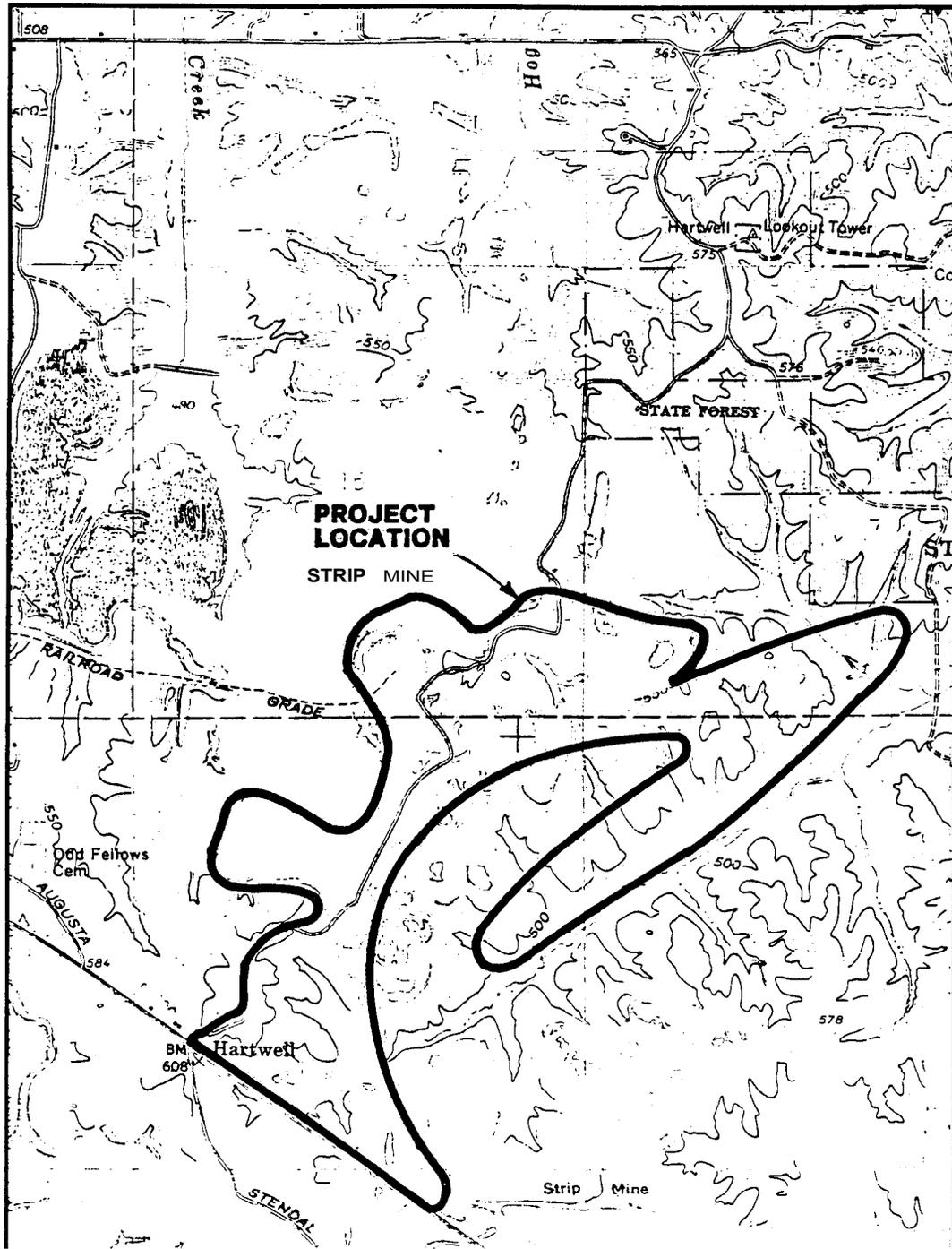
### **Introduction**

The Midwestern Mine Reclamation Project is located within portions of Sections 14, and 27 of Township 2S and Range 7W in Pike County, Indiana, approximately 4 miles east of Arthur. As illustrated in Figure 1, the project area is generally bounded by State Route 64 to the south an unnamed tributary to the Patoka River to the east and Pike County State Forest to the north.

The Midwestern Mine Site is positioned within a 6000 acre tract of land referred to as the Mill Creek Abandoned Mine Land Area that was initially investigated and partially reclaimed in the early 1980's as part of Indiana's Abandoned Mine Land Program. Much of the area that was reclaimed was subsequently deeded to the State of Indiana and incorporated into the Pike County State Forest. Due to the presence of the state forest and adjoining surface mined areas that have been reclaimed to enhance the wildlife setting, the Mill Creek area has significant value as a wildlife habitat. The 550 acre Midwestern Mine Site was not eligible for funding through the abandoned mine land program at the time of the Mill Creek Reclamation Project but has since become eligible due to bond forfeiture. ATC Associates, Inc. (ATC) prepared the reclamation plan for the Mill Creek area and was retained by the Indiana Department of Natural Resources Division of Reclamation (IDNR-DOR) to prepare design plans and specifications and provide construction support services for the Midwestern Mine Site.

The intent of the current reclamation project is to improve site safety conditions by backfilling or removing dangerous highwalls, to lessen the potential for acid mine drainage, to dispose of derelict mining equipment and to reduce erosion by regrading and revegetating disturbed areas. Additionally, the project includes the construction of new wetlands and improvements to existing wetlands and ponds to enhance the wildlife habitats.

Figure 1. Location Map



TAKEN FROM: U.S.G.S. AUGUSTA, INDIANA 7.5 MIN. TOPOGRAPHIC QUADRANGLE  
SCALE: 1 INCH = 2000 FEET

The project was divided into six reclamation sites, five of which generally consist of a combination of poorly graded unvegetated mine spoil, exposed highwalls and acidic ponds in final cut pits. The sixth site, which is the focus of this case study, is located in the vicinity of an abandoned portable preparation plant and generally consists of exposed coal refuse, unreclaimed minespoil, exposed highwalls, unreclaimed slurry ponds, areas of ponded water next to the exposed highwalls and within the minespoil, and acid seepage from abandoned underground mine workings.

The initial reclamation plan for this area included the regrading of the mine spoil, backfilling of the highwalls and the consolidation and covering of the exposed mine refuse. However, investigations of the areas within and immediately surrounding this site revealed a shortage of low-permeability cohesive soils for use in covering the coal refuse. Further, the quantity of borrow material needed to backfill the highwalls and to create the preferred surface drainage conditions would require the disturbance of a large area of adjoining mine spoil that, although poorly graded, was heavily vegetated. The only locally available borrow area that was not mine spoil was located within mature wooded areas that have significant wildlife value.

After reviewing the reclamation plan and the limitations regarding locally available borrow materials with the IDNR-DOR, it was agreed that off-site borrow sources should be evaluated before proceeding with the project. To date, IDNR-DOR has permitted the use of coal combustion by-products (CCB) in the reclamation of active mine sites but these materials have not been used in the reclamation of any large abandoned mine land sites. However, IDNR-DOR had been discussing the possibility of using CCB on AML reclamation projects with utility companies located within the coal region of Indiana and was looking for an area that could be used as a demonstration site to determine the suitability of using these materials on future AML reclamation projects. Given the close proximity of the Midwestern Site to the Indianapolis Power and Light's (IPL) Petersburg Generating Station (18.5 road miles) and the desirable characteristics of the CCB, it was agreed that the use of these materials on this project would be beneficial in enhancing the quality of the water discharged from this site while providing a reliable borrow source. Further, the use of these materials would limit the disturbance of adjoining wooded areas of both previously mined and undisturbed lands.

Since this project will serve to demonstrate the suitability of using CCB materials on future AML projects, it was agreed that it would be prudent to limit its use to one area to facilitate the monitoring of the long term impact of these materials on both surface water runoff and ground water quality. Therefore, the use of the CCB materials will be limited to the area surrounding the abandoned portable preparation plant since all of the surface runoff and at least some of the ground water appear to flow toward a slow meandering wetland area of an unnamed tributary to the Patoka River which borders the east side of the Midwestern Site.

#### Utilization of Coal Combustion By-Products: Review of Available Data

Once it was agreed that the use of CCB's appeared to be a viable reclamation alternative at this site, a literature review was performed. Further, state, federal and coal ash advocate organizations were solicited for case studies and other relevant data. A review of state and federal regulations was also performed to verify that these materials could be utilized for this purpose without obtaining variances or exclusions from agencies other than IDNR. A bibliography of relevant reports is provided at the end of this paper.

IDNR-DOR reviewed the results of laboratory tests provided by IPL to evaluate both the short and long term leaching of deionized and acidified water through various CCB materials. The results of these tests were well within tolerances set by IDNR-DOR for the use of CCB in the reclamation of mined lands. Quarterly testing of the CCB was completed during the active period of reclamation to confirm the consistency of the material.

Three site visits were also undertaken to view production and utilization conditions of the various CCB. The IPL Generating Station located 18.5 miles from the project was first visited to observe the manufacture of Poz-O-Tec. It was evident during the site visit that the various components of Poz-O-Tec could be easily modified depending upon requirements dictated by site and/or haulage conditions. For example, additional quicklime could easily be added during cold conditions to catalyze the pozzolanic reaction.

Three areas within the plant were inspected to determine handling, placement and long term strength characteristics of various CCB. The first area observed was an area in which Poz-O-Tec was being placed for structural fill. Compactive effort requirements, and the need to roll the site with a smooth drum vibratory roller prior to precipitation events were reviewed with the site personnel

The second area observed within the plant was the current IPL restricted waste landfill where CCBs of various curing ages were excavated to determine long term materials properties of compacted Poz-O-Tec, flyash and bottom ash. Observations of one year old compacted Poz-O-Tec revealed material with compressive strengths that are comparable to weak shales. It was also evident that bottom ash and flyash could also be successfully placed as long as no large areas of predominately flyash material were placed in marginally stable areas.

The third area observed during the plant visit was the ash storage ponds where bottom ash and flyash were being decanted. Once decanted, the surface of the ash generally provided a stable driving and/or loading surface. Rubber tired hydraulic excavators are suitable for loading trucks while providing the opportunity for selective handling of the materials excavated. The ash appeared to be highly erosive and could cause significant dust problems if not periodically wetted. Therefore, a water truck was required at both the loading area and in the placement area of the mine site. Surface water runoff was also routed, to the extent practicable, around the placed CCB and cohesive soil cover and channel lining was placed to keep the materials from eroding.

In addition to the observations made at the IPL facility, A site visit was also made to an Indianapolis area project site where coal ash (bottom ash and flyash) was being used in the construction of an interstate highway on-ramp. The contractor was interviewed to determine handling and placement characteristics of the coal ash. Loading and unloading of the CCB were observed at the local power plant and the construction site, respectively.

Upon significant completion of the reclamation effort involving CCB utilization, the contractor and the INDR-DOR project manager were interviewed to assess potential problem areas associated with using CCB's in an abandoned mine land setting. These observations are site specific, but have been included to help identify some actual working constraints identified during the construction process. Some of the constraints include the following:

1. Daily Delivery Rate: A minimum of 150 triaxle truck loads per day were needed in order to justify dedicating full-time manpower and equipment to both loading and placing the materials.
2. Daily Requirements at the Site: The daily requirements varied significantly depending upon the geometric constraints in the placement zone.
3. Erodibility: The materials are highly erosive. However, a series of three decant structures protected the off-site discharge of CCB's even during a very wet spring that recorded at least five 2.5year storm events.
4. Winter Handling, Poz-O-Tec: Poz-O-Tec placement in the winter could be achieved on almost all days. Care should be taken to avoid excessive FGD sludge and to maintain quick lime content between 1.5 and 2.0 percent. Truck tire embedment was much greater in the winter (up to 1 foot) than in summer months (1 to 3 inches) because of the slowed curing time of the Poz-O-Tec.
5. Winter Handling, Coal Ash: Because the coal ash was obtained from an ash pond setting, water draining from the trucks led to slick, icy patches forming along the haulage route. The coal ash also tended to freeze up in the trucks to the point that a backhoe had to be utilized to empty the trucks. Because of these constraints, it is recommended that no coal ash be hauled when the outside air temperature is below approximately 20 degrees Fahrenheit.

6. Wet Handling Conditions: Approximately 24 hours of dry weather were required after a significant precipitation event before additional CCB's could be placed and adequately compacted.
7. Haulage Cycle Time: Because of congestion at traffic signs and through small towns, the trucks along the haulage route tended to bunch up in groups of 3 to 6, decreasing optimum efficiency.
8. Truck Cycle per Day: This varies from site to site. However, on a given day over a specific 18.5 mile haulage route, truck cycles/day still varied from truck to truck from 6 to 8 truck cycles per day.
9. Unit Weights: Poz-O-Tec has a much lower unit weight than coal ash. The coal ash trucks could not be totally filled because the haulage weight limits of the truck and/or roads and bridges would have been exceeded.
10. Quality Control: Flue gas **desulfurization sludge without the right proportions of flyash and quick lime could** not be compacted and reacted like a very wet clayey soil. The process of producing Poz-O-Tec requires start-up time before the proportions are correct. The FGD sludge is generated earlier in the start-up of the process than the flyash is. This FGD sludge should not be hauled to the minesite.
11. Roadways: Pond ash did not provide an adequate base material for roadways within the mine site. The moisture content was too high and the driving surface failed.

The information obtained from the literature review, off-site observations and during construction of the Midwestern AML project was utilized to develop the technical specifications outlined in the following section. The specifications utilized on this project are provided as an example of handling techniques and placement guidelines that could be utilized on similar projects that utilize CCB materials. It is emphasized that the use of these materials and the handling procedures should be evaluated on a case-by-case basis in accordance with all appropriate state and local regulations. The specifications developed for this project emphasize a balance between overhandling of the CCB and uncontrolled placement of the materials to ensure that the cost of using these materials does not exceed the advantages offered by off-site, low-permeability alkaline materials.

It should also be noted that the IDNR-DOR has contracted with the Indiana Geological Survey to establish background data and monitor the site both during and after reclamation to determine the impact of the reclamation effort on the quality of both surface water and ground water in the vicinity of this site. (Reclamation began in the Fall of 1995 and was significantly completed by the Summer of 1996).

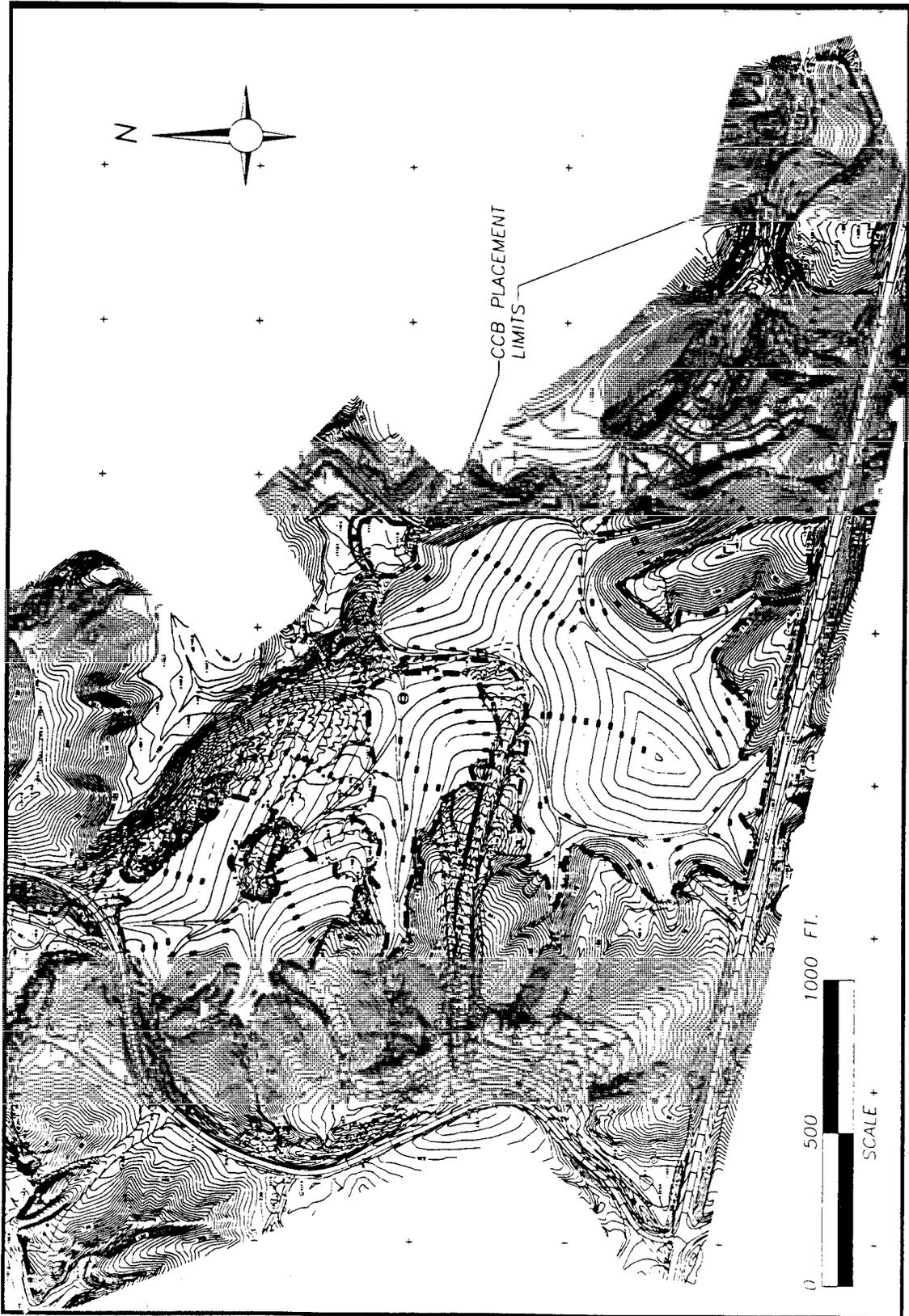
#### **Suggested Technical Specifications for the Utilization of CCB Materials**

##### Scope

The work shall consist of the placing, compacting and covering of Coal Combustion By-products (CCB). For purposes of this project, the Coal Combustion By-products shall consist of

- Coal Ash - A general term used in these specifications to refer to all inorganic materials (including, for the most part, bottom ash flyash and natural soil in varying ratios) contained in the ash ponds at the borrow source.
- Poz-O-Tec - A manufactured material that typically consists of a ratio of 1 part flue gas desulfurization sludge (CaSO<sub>3</sub>) to 0.6 to 1 part flyash to 1.5 to 2.0 percent quicklime (CaO) which is added as a catalyst

Figure 2. Coal Combustion By-Product Placement Plan



The design intent is to utilize the coal ash and Poz-O-Tec as grade-raise fill in final cut pits to eliminate existing highwalls and acidic ponds within the project limits as illustrated on Figure 2. The Poz-O-Tec will also be used to form a low permeability layer above the coal refuse to reduce surface water infiltration and oxidation potential of the coal refuse. Once the materials have been placed to the grades indicated on the drawings, they shall be covered with a minimum of 3 ft of minespoil and/or natural soils and the area seeded in accordance with the appropriate Technical Specifications.

### Material Haulage

The contractor shall construct, improve and maintain haul roads within the project limits at the locations shown on the drawings and augment the haulage route between the borrow site and the project site as required by the state highway department at the time of bidding. At a minimum, this shall consist of upgrading portions of the existing County Road constructing a temporary second lane parallel to a portion of the County Road and creating a haul road that traverses a portion of the site to provide the transport trucks ready access to the areas where the CCB will be spread or stockpiled. The intent is to create a one-way road system to facilitate the movement of the CCB that will be delivered to the site.

Once the subgrade elevation has been established along the new portions of the road alignment, the subgrade shall be proofrolled and all soft or otherwise unstable materials removed and replaced with minespoil compacted in 10 inch (maximum) lifts. Once the subgrade has been approved by the engineer, the haul road subgrade shall be covered with geogrid in accordance with the manufacturer's specifications. The geogrid shall be covered with a 10 inch lift of No. 2 crushed stone which in turn shall be covered with a 6 inch lift of No. 53 crushed stone.

The contractor shall maintain the entire haul road alignment to facilitate the movement of the truck fleet utilized to transport the CCB. In addition to constructing and maintaining the road alignment shown on the drawings, the contractor shall provide and maintain access to all areas within the site where the CCB materials are being stockpiled or spread. This maintenance program will continue until the transport of all CCB has been completed and shall include, but not be limited to, grading of the road surface, removal of mud from the road surface, dust control, construction and maintenance of temporary diversion ditches to control surface water runoff, and any other haul road maintenance functions deemed necessary by the engineer. In the areas where the haul road alignment will not be graveled, the contractor is advised that it will likely be necessary to build a road base out of compacted minespoil to bridge over existing soft and poorly drained areas. With the approval of the engineer, the contractor may use geogrid to reinforce the bridge lift.

Upon completion of the hauling of the CCB, the surface of the haul road shall be removed and all disturbed areas regraded and revegetated to the satisfaction of the engineer. The crushed stone placed along the non-County Road portion of the haul road alignment shall be salvaged and used within the project limits at an area approved by the engineer (i.e., to resurface portions of the County Road or to stabilize haul roads elsewhere in the project) at no additional cost to the STATE. It is emphasized that the design intent is to discourage pedestrian and vehicular access to the site upon completion of the work. To this end, all access routes (except for the County Road) shall be "reclaimed" and revegetated as indicated on the drawings and elsewhere in these Technical Specifications.

### Material Placement

Prior to placing any of the CCB, the contractor shall prepare the surface of the till area in accordance with the Technical Specifications. Further, all existing flooded pits shall be drained in accordance with the Technical Specifications. Unless otherwise directed by the Engineer, the CCB shall not be placed, stockpiled or spread into standing water.

Once the surface has been prepared, the CCB shall be placed in the areas shown on the drawings. The CCB shall be spread in 18 inch lifts and compacted with the construction traffic that shall be evenly distributed across the area. It is the contractor's responsibility to ensure that enough equipment is available to spread the

material as needed to facilitate its unloading. Rubber tired dozers appear to be best suited for placement and compaction. The coal ash may be stockpiled at a location approved by the engineer for later transport into the fill section by the contractor. Stockpiling of the Poz-O-Tec will not be permitted since it undergoes a pozzolanic reaction similar to that of concrete. Poz-O-Tec shall be spread and compacted within 48 hours of delivery to the site. In the event that the contractor's equipment breaks-down or is not available due to maintenance, etc., the contractor shall provide back-up equipment as needed to continue the placement and compaction of the Poz-O-Tec. The contractor is advised that it will typically not be possible to postpone the delivery of the Poz-O-Tec.

The graded surface of the CCB shall be compacted with a minimum of two passes of a smooth drum vibratory roller at the end of each day of placement and prior to any significant precipitation event that may occur during the working day unless otherwise approved by the engineer. The purpose for compacting the exposed surface is to decrease the amount of infiltration into the CCB and to help minimize erosion of the CCB. Throughout the construction period the contractor shall grade the surface of the fill to prevent the ponding of surface water. The contractor is advised that all CCB materials are highly susceptible to pumping if excess water is present.

The CCB will be used to backfill the drained pits. It will not be possible to prevent the temporary ponding of water in these pits following precipitation events during the initial stages of the backfilling operations when the fill is being placed below the elevation of the surrounding grade. To the extent possible, the contractor shall place CCB materials in the pits during periods when the potential for rain is minimal. Coal ash is much better suited for below grade filling than Poz-O-Tec. If the pits are hydraulically connected to deep mine workings, coal ash (consisting of both fly ash and bottom ash) may, with the approval of the Engineer, be used to bridge through and backfill specific pits. Further, the filling operations shall be performed to minimize the size of the below-grade working area and by diverting surface water away from the active fill area to sump pits from which it can be continually pumped. The contractor may isolate the CCB from the potential for inundation in the pit by constructing diversion berms, isolation berms, drainage ditches, etc., at no additional cost to the STATE. In the event that a portion of the CCB fill becomes inundated in the pit during the placement operations, the contractor shall discharge the water in accordance with the Technical Specifications and allow the fill material to dry before proceeding with the filling operations in this area.

Since the CCB's are susceptible to erosion, the contractor shall bring portions of the fill to final grade as soon as possible. Areas that have reached final grade shall be covered with a minimum of 2 ft of the vegetative layer within 10 working days unless otherwise approved by the engineer.

As noted in Figure 3, the vegetative layer shall consist of a minimum of 2 ft of compacted minespoil overlain with 1 ft of uncompacted minespoil and/or natural soils. The compacted zone shall be placed in lifts and the surface compacted with evenly distributed passes of the construction equipment across the entire surface. The surface of the uncompacted layer shall be prepared and seeded in accordance with the Technical Specifications.

In areas where CCB will be present immediately beneath the vegetative layer, the surface of the CCB shall be benched as noted in Figure 4 prior to the placement of the vegetative layer.

The contractor shall maintain drainage through the work area while the CCB filling operations are in progress. To minimize the potential for significant erosion along these drainageways, the contractor shall cover the CCB exposed in the drainageways prior to any significant forecasted precipitation events. The cover shall consist of 1 ft of compacted minespoil, a geomembrane sheet placed over the CCB, or other method approved by the engineer. The placement of the cover shall be done in such a manner that it will not impede the flow of surface water within the drainageway or divert the flow away from the drainageway. The temporary graded surface within the drainageway shall provide a minimum of 2ft of flow depth and 2(H): 1(V) sideslopes.

Figure 3. Vegetative Layer Detail

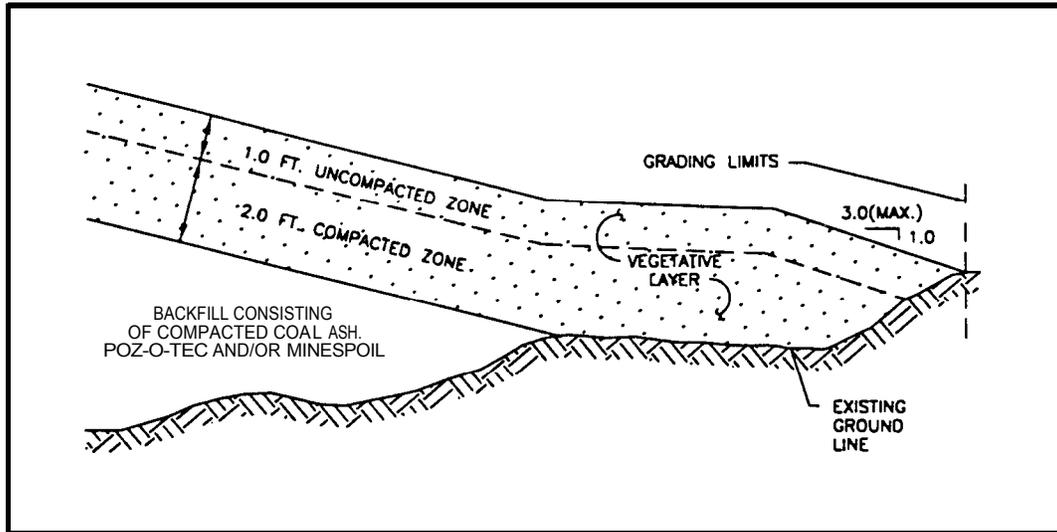
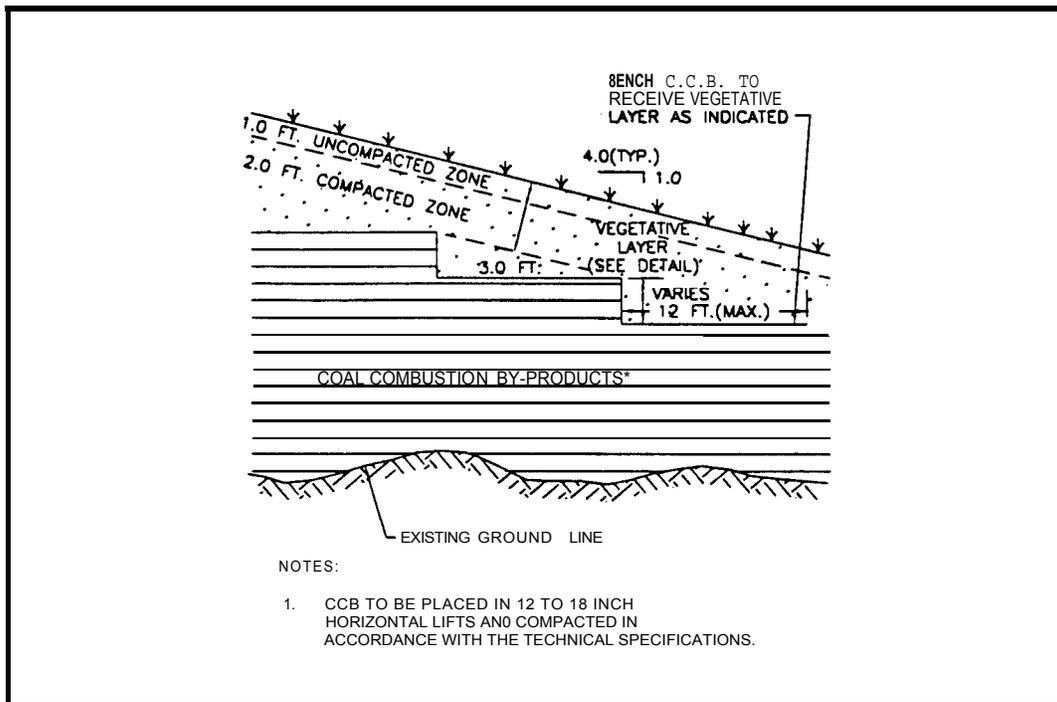


Figure 4. Typical CCB Placement Detail

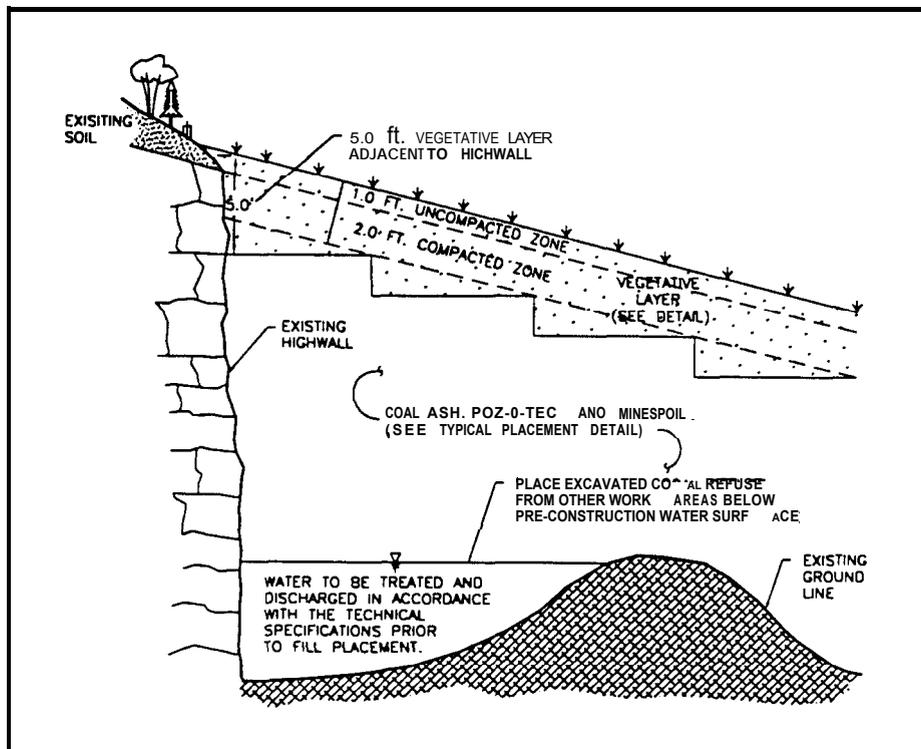


If minespoil is used as the cover, it Figures 3 & 4 can be left in-place as part of the grade-raise fill. If a geomembrane sheet is used as the cover, it must be anchored along the edges to prevent the flow of water beneath the sheet and to prevent it from being lifted in high winds. Further, once final grades have been completed along the drainageways, the contractor shall install the riprap lining within 10 working days unless otherwise approved by the engineer.

The drawings note the locations within the site where the CCB materials shall be placed. Fill placed within the area designated for Poz-O-TEC shall be limited to Poz-O-Tec minespoil unless otherwise approved by the engineer. Fill placed within the areas designated for coal ash may consist of coal ash, Poz-O-Tec and minespoil. In areas where the Poz-O-Tec limits overlap with the coal ash limits, the intent is to place the Poz-O-Tec over the coal ash to limit the infiltration of surface water into the fill.

The contractor shall take all necessary precautions to protect the equipment operators from rockfalls that could occur due to the construction activities in areas where CCB materials will be placed immediately adjacent to the highwalls. Further, it will be necessary to ensure that the fill materials placed next to the highwall are well compacted to minimize the potential for the formation of a crack between the highwall and the fill. Finally, the thickness of the vegetative layer shall be increased to 5 ft in the vicinity of the highwalls as noted in Figure 5 to minimize the potential for the infiltration of surface water into the zone between the fill and the highwall. The surface of the vegetative layer shall be blended and shaped into the existing ground surface to prevent the ponding of water along the interface of the highwall and the backfill.

Figure 5. Typical Highwall Backfill Detail



## Conclusions

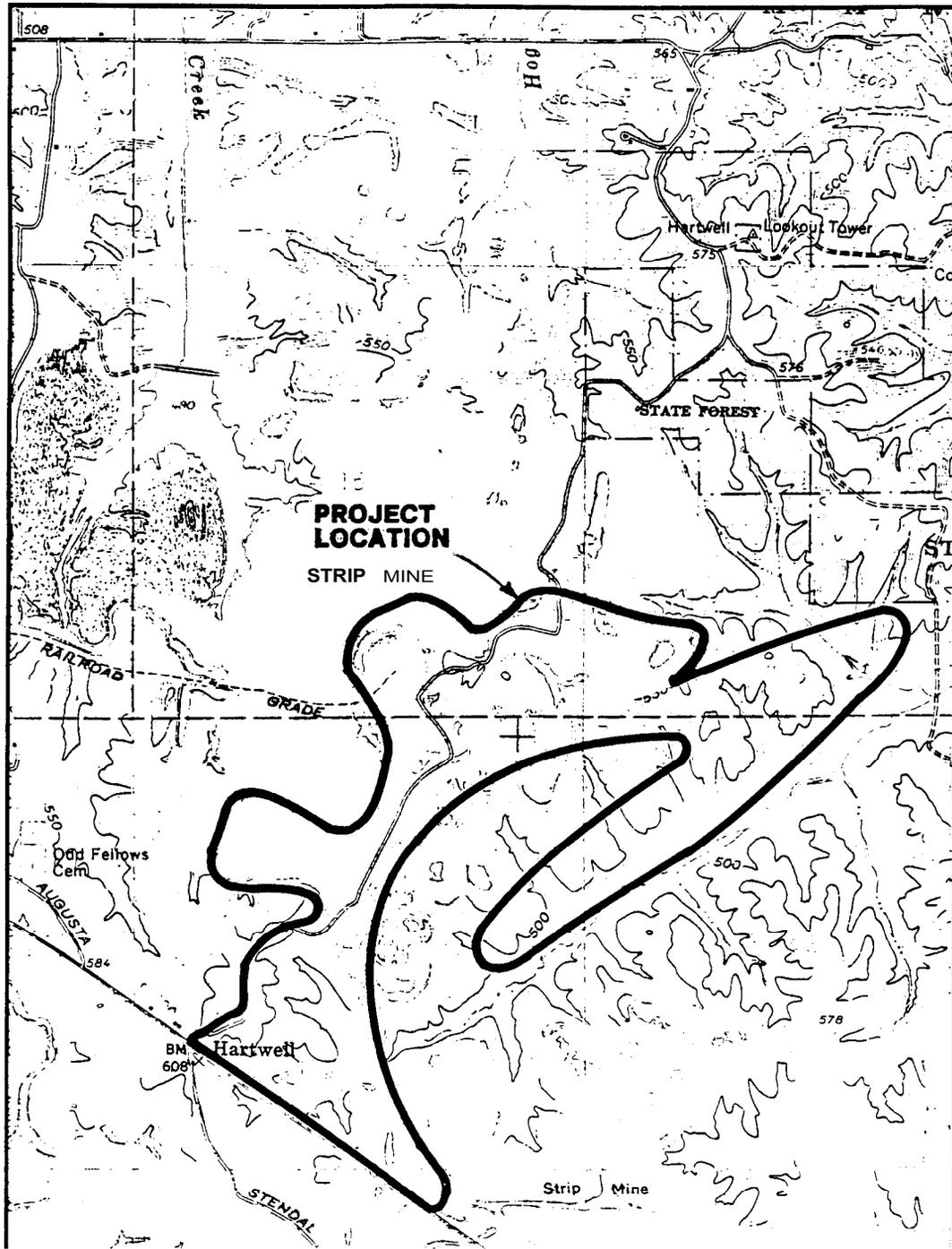
The utilization of CCB materials at the Midwestern Mine Site has significantly enhanced the reclamation plan by reducing the infiltration of surface water through acid producing coal refuse, minimizing the infiltration of surface water into abandoned underground mines and providing a source of alkalinity which should further improve the quality of both the surface water and the ground water at this site. The utilization of these materials has also helped to minimize disturbance of surrounding vegetated mine spoil as well as unmined lands that would have otherwise been needed as a source of borrow soils. This beneficial use of the CCB materials also reduces the volume of the materials that would typically be placed in landfills, thus resulting in cost savings to the utilities and their users.

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Figure 1. Location Map



TAKEN FROM: U.S.G.S. AUGUSTA, INDIANA 7.5 MIN. TOPOGRAPHIC QUADRANGLE  
SCALE: 1 INCH = 2000 FEET

Figure 3. Vegetative Layer Detail

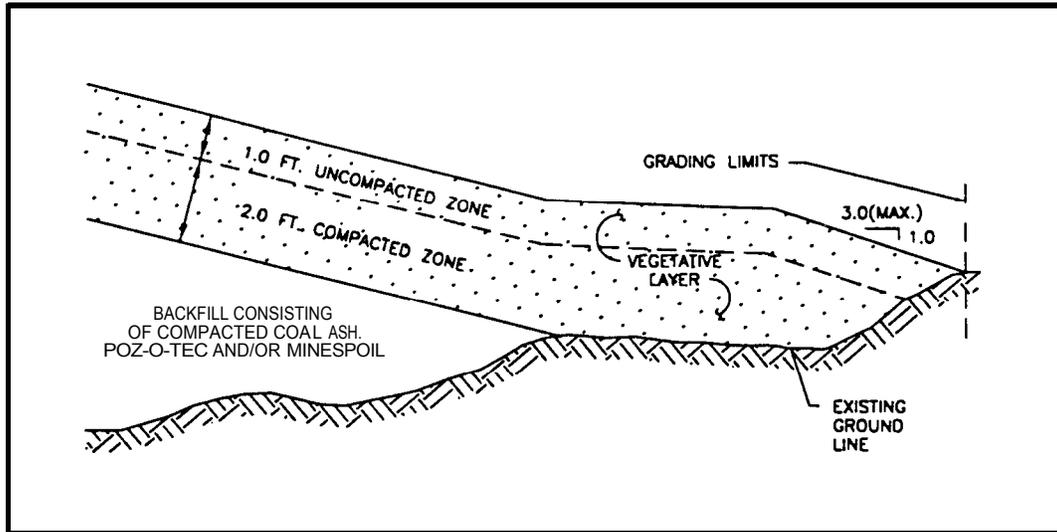


Figure 4. Typical CCB Placement Detail

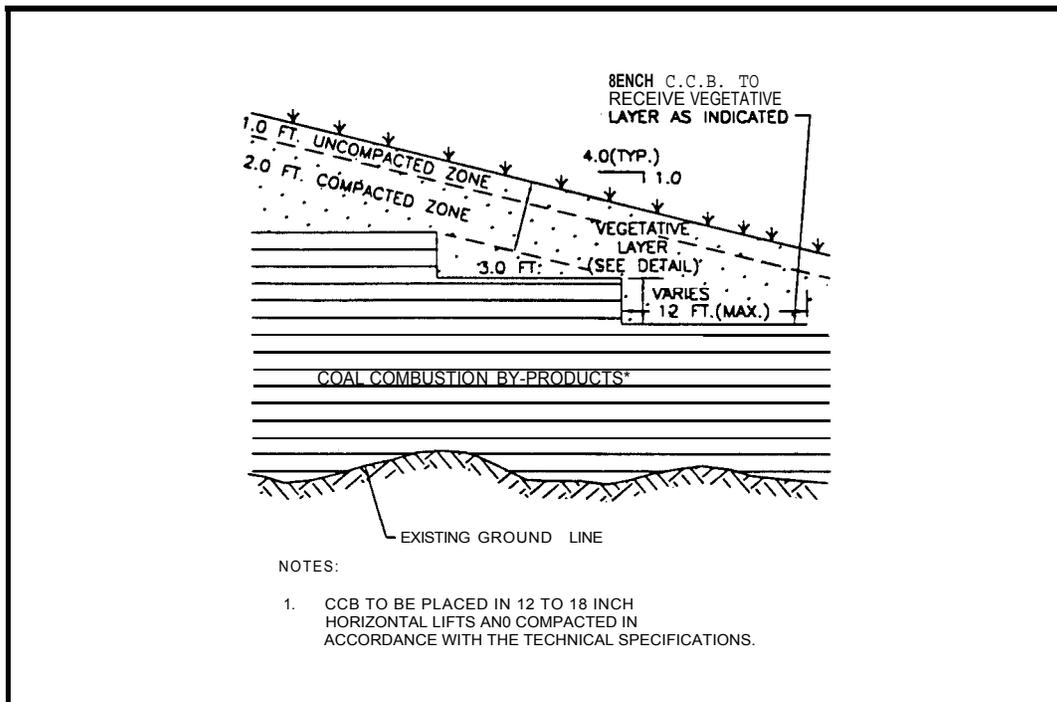
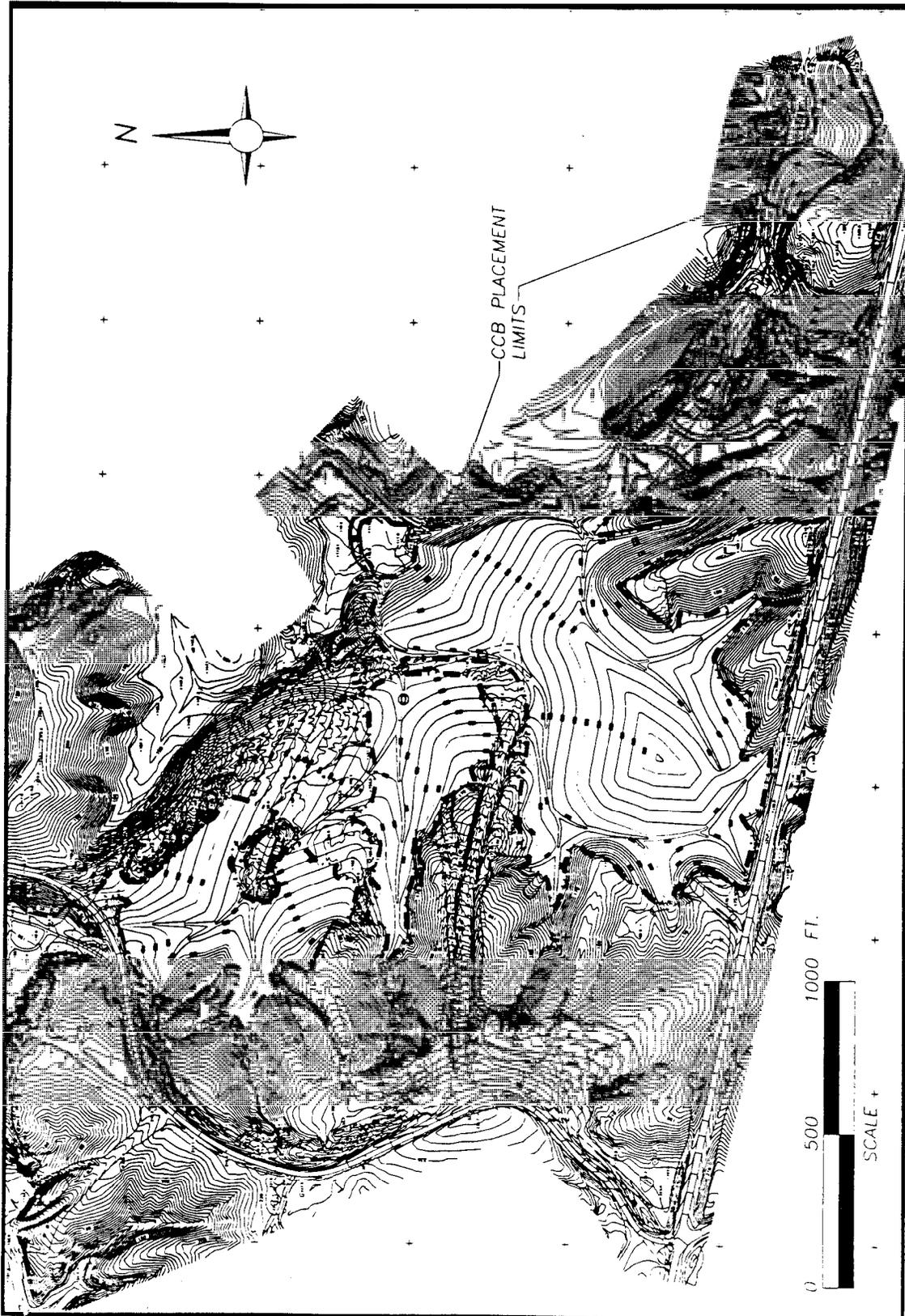


Figure 2. Coal Combustion By-Product Placement Plan



**Session V:**

**ENVIRONMENT: LAND AND WATER**

**Session Chairs:**

**Kim Vories  
Office of Surface Mining  
Alton, Illinois**

**Bill Joseph  
Office of Surface Mining  
Alton, Illinois**

# COAL ASH CHEMICAL PROPERTIES AND POTENTIAL INFLUENCE ON WATER QUALITY

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## Abstract

Disposal and/or any use of coal ash is becoming a major issue because of its potential to contaminate surface and groundwater with arsenic, boron, heavy metals, etc. Knowledge on the chemistry of fly ash is essential in developing a methodology that can predict release rate(s) and concentration(s) of chemical constituents of environmental concern (pollutants). Safe disposal of fly ash with respect to surface and groundwater protection depends on having the know-how to evaluate the potential of a given fly ash to release toxic pollutants. Coal ash is made of three types of solids: 1) chemically water stable solids ( $\text{SiO}$ ,  $\text{FeO}$ ,  $\text{AlO}$ ), 2) relatively water soluble solids (e.g., **metal-SO<sub>4</sub>**, **metal-BO<sub>3</sub>**), and 3) water reactive metal-oxides (e.g., **CaO**, **MgO**,  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ , etc). Ash varies from acidic to alkaline because of the chemical make-up of the source coal. Physical appearance varies depending on coal type and furnace. All fly ash samples are mainly composed of glass-like porous beads that vary in chemical composition with respect to Al/Si/Fe ratio and pH from extremely low (pH near 3) to near pH 12. Alkaline fly ash is often associated with high boron levels and exhibits extremely low pH buffering capacity. Potentiometric titrations show a fly ash  $\text{PZC}_{\text{pH}}$  somewhere around 4.6 with protonation and dissociation constants of  $10^{6.2}$  and  $10^{-7.8}$ , respectively. Low pH buffering capacity appears to make fly ash extremely sensitive to  $\text{pCO}_2$  with respect to pH and boron release. In some coal ashes, increasing  $\text{pCO}_2$  increases boron release but heavy metal release remains unaffected. This suggests that some heavy metals are most-likely strongly chemisorbed. Acid fly ash showed greater metal adsorption potential after pH adjustment than alkaline fly ash.

## Introduction

Ash is the byproduct of burning coal in steam-electric power plants. Statistics show that in the U.S. alone more than 80 million tons of ash are produced annually (Andriano et al., 1980 and references therein). Generally, amounts of ash produced vary with the source and grade of coal, but usually range from 12% to 16% of the coal burned (Terman, 1978 and references therein). Chemical composition of coal ash produced by various types of coal are shown in Table 1. Coal ash disposal is considered by some a major environmental issue because of its potential to contaminate groundwater with heavy metals, arsenic, boron, etc. Generally, composition of coal ash varies depending on the chemical make-up (source) of coal. However, knowledge on the chemical composition of ash is not all that is needed to predict potential release of toxic constituents to soil and groundwater; its chemical make up as well as its surface chemistry are needed to predict potential pollution. Below, a description of the major components of coal ash is presented and how these components could be put to safe use is described. The three major coal wastes by power plants are (a) limestone and other scrubber slurries (b) wastes from fluidized bed combustion boilers, and (c) fly ash. The first two wastes represent products of processes used to remove  $\text{SO}_2$  and many other stack gas pollutants.

## Limestone Scrubber Sludge

Limestone scrubber sludge is generated by scrubbing  $\text{SO}_2$  from stack gases through suspensions of ground limestone. The slurry is usually pumped to ponded disposal sites and stored (Terman, 1978 and references therein). These sludges consist mostly of calcium sulfite hemihydrate ( $\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$ ), limestone ( $\text{CaCO}_3$ ), gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and fly ash. Commonly, 1.3 moles of  $\text{CO}_3$  is needed per mole of sulfur (S) for scrubbing gases produced by the burning coal, or approximately 60 kg of  $\text{CaCO}_3$  per 15 kg of S. For coal containing 3% S approximately 114 kg of  $\text{CaCO}_3$  are needed per ton of coal

burned (Terman, 1978 and references therein). Limestone scrubber sludge could support vegetative growth if mixed with soil and fertilized with nitrogen, phosphorous and potassium. Fresh sludge could be toxic to plants because of boron.

### Chemical and Physical Properties

Chemical composition of limestone scrubber sludge is controlled by the types of coal and limestone, furnace operating conditions, type and location of scrubber, quantity of scrubbing suspension used, suspension to stack gas ratio, and other factors. Fly ash content in the sludge depends primarily on the type of coal burned, and location of fly ash collectors (Terman, 1978). Chemical composition of dried up sludges is shown in Table 2.

The limestone scrubber system effluent with approximately 15% solids is usually pumped to a ponded area where excess water drains away leaving behind a sludge with approximately 50% solids. Further dewatering occurs slowly due to the hydrophilicity of the sludge. Increasing fly ash (fmer coal ash particles) content tends to increase sludge viscosity. Oxidation of the sludge, immediately after  $\text{SO}_2$  absorption, forms  $\text{SO}_4$ . Thus, calcium sulfite hemihydrate ( $\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$ ), formed during  $\text{SO}_2$  absorption, converts to gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ).

Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) has little direct soil liming value. However, when gypsum is added to acid/aluminum rich soils aluminum is removed from the soil solution as relatively insoluble aluminum-hydroxy-sulfates. In addition, Ca limits bioavailability of aluminum. Therefore, the sludge in an indirect way acts as an ameliorant of soil acidity. The direct liming value of the sludge is expected to vary with its content of unreacted lime and the amount and chemical nature of its fly ash.

### **Fluidized Bed Waste**

Fluidized bed combustion waste is formed when fine coal is burned in a bed of inert ash and crushed limestone. The bed is fluidized (held in suspension) by injection of air through the perforated bed at controlled rates (Terman, 1978). The lime reacts with  $\text{SO}_2$  released during combustion of the coal to form sulfates. The bed waste product is a granular solid material composed of  $\text{CaSO}_4$ ,  $\text{CaO}$ , other metal oxides, and fly ash. Upon exposure to moisture and atmospheric air the bed waste forms first hydroxides and then carbonates (Andriano et al., 1980). Because of these reactions, pH is reduced from an initial value of around 12 to around 8, depending on partial pressure of  $\text{CO}_2$ . Chemical composition and ranges of fluidized bed waste material is given in Table 3. Fluidized bed boilers can also utilize residual oil, municipal wastes, sewage sludge, wood wastes, and other materials as heat sources and eliminate the need for costly scrubbers to remove  $\text{SO}_2$  from stack gases (Terman, 1978).

### **Fly Ash**

Generally, fly ash is the finer material (65% to 80%) of the coal ash and its properties vary greatly with coal source, type of coal burned and type of ash collector. Fly ash is a low grade source of phosphorus, potassium, sulfur, boron, and other metals or metalloids, e.g., mercury, cadmium, lead, arsenic, selenium, etc, and its neutralizing value varies from near zero to high (Andriano et al., 1980 and references therein). Uses of fly ash include: a) improving soil moisture-holding capacity, b) serving as a concrete substitute. c) serving as tilling material, and d) forming various zeolites for heavy metal removal from water.

### Chemical and Physical Properties

In general, fly ash is composed of three groups of solid components. The first group exhibits low water reactivity but possesses surface electric charge (may adsorb metal cations, e.g. Cd, Ni, Pb, etc., or oxyanions, e.g. arsenate, borate, sulfate, etc). These solids are made of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ , and  $\text{TiO}_2$  (Terman, 1978; Adriano et al., 1980). About 35% and 75%, respectively, of the fly ash from

mechanical collectors and precipitators typically has a diameter of less than 10 microns (Terman, 1978 and references therein). The ranges of chemical analyses of U.S. fly ashes from different types of coal are shown in Tables 4 and 5.

The second group of components present in coal fly ash represents metals or metalloids adsorbed onto the oxide surfaces. According to Adriano et al. (1980) heavy metals or oxyanions are mostly found adsorbed on to surfaces of oxides (discussed above) which are represented by the smallest of fly ash particles (largest surface area). The chemical behavior and release of heavy metals and oxyanions to water is highly interrelated to the surface electric properties of oxides described above.

The third group includes highly water reactive components. Generally, this group include oxides of Ca (215,000 ppm), Mg ( $\approx$ 16,000 ppm), K ( $\approx$ 23,000 ppm), Na ( $\approx$ 2,000 ppm), Ba ( $\approx$ 1000 ppm) as well as gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), a nearly a neutral salt, and sulfite ( $\text{SO}_3$ ). Some fly ashes from bituminous coal are acidic and have no liming value (Figure 1). Most fly ashes from lignites, however, have a considerable liming value because of their content of alkali oxides and significant quantities of anhydrous Ca- or Mg-sulfates (Roy and Griffin, 1982). Fly ashes from bituminous coal are low in Ca and Mg; hence the fly ashes retain little sulfate.

A great deal of research has been carried out on the chemical make-up of fly ash, and water soluble salts, heavy metals, and oxyanions (Adriano et al., 1980 and references therein; Terman, 1978; Phung et al., 1979; Roy and Griffin, 1982; Elseewi et al., 1978). Additionally, a great deal of research has been carried out on using fly ash as a soil amendment to improve soil physical properties and/or soil pH. Furthermore, research has been carried out on the availability of heavy metals and oxyanions of fly ash to agricultural plants (Elseewi et al., 1978; Adriano et al., 1982). Although information is available on using fly ash as soil amendment, not all available fly ash can be used for this purpose. In other words, fly ash demand for agricultural uses is far lower than the available supply. For this reason, a big portion of the fly ash produced is disposed in landfills or is put into various beneficial uses. The physical-chemical properties of fly ash with respect to pollutant reactions must be known before disposal or any other uses. Roy and Griffin (1982) proposed a fly ash classification scheme based on the physical and chemical properties. The classification scheme and the basis of this classification is given in Tables 6 and 7. The idea of classifying fly ash has great merit but further research work is needed to link classification with potential uses.

#### Surface Properties

Fly ash consists usually of spheres composed of crystalline matter and some residual carbon. Figure 2 shows an overview of a Kentucky fly ash at a 100X magnification. The basic spherical shape indicate that particles were formed under uncrowded freefall conditions and a relatively sudden cooling maintained the spherical shape. In Figure 3 a larger ash-sphere appears broken and filled with numerous smaller spheres. Detailed analysis of a broken sphere in Figure 4 revealed gypsum crystals growing on its inner surface.

#### Acid-base Properties

Titration in a nitrogen gas atmosphere (Figure 5) show ashes to be unbuffered around pH 7. Because of this, pH is expected to be controlled by the partial pressure of  $\text{CO}_2$ . Indeed, when  $\text{CO}_2$  was bubbled into the water-fly ash suspension pH fell almost immediately below 6 (Figure 6). Because  $\text{CO}_2$  is the predominant reactive gas in natural soil-water systems, this pH drop has some implications on metal release from ash. The potentiometric titrations shown in Figure 5 reveal an approximate  $\text{pK}_a$  in the vicinity of 10, which is indicative of  $\text{CO}_3^{2-}$  protonation. Note however, no equal-length titration plateau was obtained in the pH range of 6.2. The latter is indicative of  $\text{HCO}_3^-$  protonation. This suggested that the plateau at pH 10 was not due to  $\text{CO}_3^{2-}$  but most likely due to silicates. On the other hand, when  $\text{CO}_2$  was introduced (Figure 6), the fly-ash titrated at around pH 5. Again, this was not indicative of  $\text{HCO}_3^-$  protonation. Bicarbonate ( $\text{HCO}_3^-$ ) titration behavior was demonstrated by the titration of NaOH plus

CO<sub>2</sub> shown to titrate, as expected, around pH 6. The data in Figure 7 suggested that the surface was most likely composed of -Al-OH functional species.

Figure 8 demonstrates the “zero salt effect” on fly ash potentiometric titrations. It is represented by the cross-over point of the titrations revealing a  $PZC_{pH}$  of approximately 4.6 which is approximately halfway between the  $PZC_{pH}$  of FeOOH and the  $PZC_{pH}$  of SiO<sub>2</sub>. In this pH region, the surface adsorbs both metal cations and oxyanions. Below the  $ZPC_{pH}$  oxides exhibit a net positive charge and prefer to adsorb oxyanions; above the  $ZPC_{pH}$  oxides exhibit a net negative charge and prefer to adsorb metal cations (Anderson and Malotky, 1979). In our own laboratory (Harsin and Evangelou, 1989) we have shown that a synthetic iron-oxide exhibits a  $ZPC_{pH}$  in the range of 6.5 to 7 while the  $ZPC_{pH}$  of Al<sub>2</sub>O<sub>3</sub> is known to be around 9 and the  $ZPC_{pH}$  of SiO<sub>2</sub> is known to be around pH 2 (Stumm and Morgan, 1970). Moreover, when minerals are made of chemical mixtures  $ZPC_{pH}$  changes. For example, if instead of Fe<sub>2</sub>O<sub>3</sub> we have a chemical mixture of Fe<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> the  $ZPC_{pH}$  of this oxide will need to be determined experimentally (Stumm and Morgan, 1970). This means that the pH at which these mixed-surfaces act as metal cation adsorbers or oxyanion adsorbers is not known. Figure 9 demonstrates protonation and dissociation intrinsic constants for one of the fly ash samples. They are in the range of intrinsic constants of As/Fe/Si-oxides reported in the literature.

### Long-term Water Equilibration

Long-term water equilibrations were conducted in our laboratory using 50:950 fly ash:water suspensions by weight in 1000 ml plastic Erlenmeyer flasks under various  $pCO_2$  levels. Accompanied by vigorous stirring, half of the fly ash suspensions were bubbled for one hour per day with pure nitrogen gas (simulating zero  $pCO_2$ ), and the other half of the fly ash suspensions were bubbled with pure carbon dioxide @ $CO_2 = 1$ . Conductivity and pH of the suspensions were measured after each bubbling, and six samples were collected at intervals throughout the duration of the experiment. After a 45-day equilibration, all fly-ash suspensions were equilibrated with atmospheric air @ $CO_2 = 0.0003$ ) and sampled. Chemical composition of two fly ash samples are given in Table 8. With regard to boron, of the two ashes in question, the ash which was originally high in pH released more boron (Figure 10) as the pH went down in response to  $pCO_2$ . The low pH ash did not respond to  $pCO_2$  with respect to change in pH and boron release (Figure 11). With regard to nickel, neither the originally high nor low pH fly ash released nickel differently with respect to partial pressure of CO<sub>2</sub> (Figures 12 and 13). Although the long-term equilibration experiment lasted for 62 days, the first sampling was only one hour after the start of the experiment, most of the release was complete by then. The breakthrough data in Figure 14 show the relatively rapid release of boron when fly ash is leached.

When fresh fly ash is exposed to the open environment (H<sub>2</sub>O and CO<sub>2</sub> gas) two chemical pathways can be hypothesized with respect to the fate of heavy metals or oxyanions. If CO<sub>2</sub> gas is introduced to a fly ash slurry most metals will precipitate as metal carbonates and the oxyanions are expected to be adsorbed by the oxide surfaces, depending on  $ZPC_{pH}$ . Therefore, release of heavy metals to water is expected to be dependent greatly on the partial pressure of CO<sub>2</sub> ( $pCO_2$ ). In the absence of excess  $pCO_2$ , a smaller fraction of the metals is expected to precipitate as carbonates and a larger fraction of heavy metals and oxyanions is expected to interact with each other and the surfaces of the oxides. If the oxide surfaces are physically blocked by the various precipitates, or the total quantity of the oxides available for metal cation and/or oxyanion surface adsorption is low, then both metal cations and oxyanions will be released to the water and may remain soluble or coprecipitate depending on types of minerals that can be formed, e.g. Ba(AsO<sub>4</sub>)<sub>2</sub> a very insoluble mineral ( $K_{sp} = 8.0 \times 10^{-51}$ ). Some bituminous coal fly ashes do not contain metal oxides such as CaO and are quite acidic. In such fly ashes, oxide-surface  $ZPC_{pH}$  and surface charge behavior with respect to pH would be a major controlling factor in metal and/or oxyanion release.

## Metal Adsorption Isotherms

The data in Figures 15 and 16 show the potential of the 'alkaline fly ash' and 'acid fly ash', respectively, to adsorb nickel. These two figures clearly show that the adsorption of nickel by fly ash is strongly pH dependent as one would expect due to variable charge surfaces of the fly ash metal oxides. It is also quite clear from these data that the acid fly ash exhibits a greater potential for nickel adsorption at the two highest pH values tested. The data show that in the case of the 'alkaline fly ash' adsorption maxima at around pH 7 is only obtained for the 2 ppm nickel level (Figure 15). On the other hand, in the case of 'acid fly ash' nickel adsorption maxima was attained nearly by all solution nickel concentrations tested (Figure 16). These data clearly demonstrate that the acid fly ash exhibits greater potential than the alkaline ash to adsorb heavy metals at the higher pH values.

### **Environmental Effects**

Because fly ash contains toxic elements, disposal sites should be monitored for excessive buildup of heavy metals, salts and alkalinity. Potential heavy metal problems with power plant wastes are greatly reduced by the pronounced liming effects of the wastes.

A problem that some consider an environmental issue is the movement of heavy metals from fly ash in ponds or landfills to drainage waters. Levels of heavy metals or metalloids, e.g., selenium, chromium, boron, and in some instances, mercury and barium, exceeded EPA's public water supply guidelines. Passage of the leachates through soil columns removed most of the dissolved elements. Thus, passage of pond effluents through soil was found to provide significant protection against ground water contamination (Terman, 1978 and references therein). An important consideration is that soils that receive fly ash or ash disposal sites should always have the pH maintained at above 6 in order to keep most heavy metals immobile.

### **Agricultural Uses**

Fly ash contains numerous elements found in coal and when fresh it is toxic as a plant substrate due to boron (B) and high alkalinity. About 20% of the fly ash produced in the U.S. is used in the construction industry as fill material or in concrete products; to minimize costs, most must be disposed of at nearby sites, largely in impoundments or in old mines.

Numerous studies have been carried out which demonstrate that fly ash could be used as source of K, P, Ca, Mg, S and many of the micronutrients (Adriano et al., 1980). Other agricultural uses of fly ash include liming, improving soil moisture holding capacity and the reclamation of surface mined lands. However, it has been demonstrated that some crops growing under fly ash-amended soil conditions may bioaccumulate heavy metals at concentrations greater than normal ranges. This is highly dependent on the type of fly ash used.

Some fly ashes may also introduce toxicity to plants due to the high boron content and high alkalinity. For this reason, when fly ash is to be used for any agricultural purposes it should be first allowed to age to some degree. Aging has two potential effects. One effect is carbonation which converts alkaline oxides to carbonates and the second effect is leaching, thus removing portion of the alkalinity as well as boron, selenate and some of the heavy metals (Adriano et al., 1980).

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Table 1. Variations in coal ash composition (Terman, 1980)

Rank	Composition, %									
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	CaO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	Ash
<i>Crandall (1972)</i>										
Anthracite	48-68	25-44	2-10	1.0-2	0.2-4	0.2-1	—	—	0.1-1	4-19
Bituminous	7-68	4-39	2-44	0.5-4	1.0-36	0.1-4	0.2-3	0.2-4	0.1-323	32
Subbituminous	17-58	4-35	3-19	0.6-2	2.0-52	0.5-8	—	—	3.0-163	16
Lignite	6-40	4-26	1-34	0.0-0.8	12.0-52	2.8-140	28	0.1-1.38	3-324	19
<i>Meikle (1975)</i>										
							Na <sub>2</sub> O + K <sub>2</sub> O			
Bituminous	30-55	10-35	10-40	1.0-3	0.0-15	0.0-5	1.0-5	0.0-3	—	—
Lignite	20-41	10-18	7-16	1.0-3	20.0-40	2.0-11	0.5-0	0.5-0	—	—
<i>Endell (1958)</i>										
Lignite (Fortuna)	4-40	2-4	14-16	—	49.0-55	9.0-15	—	—	8.0-12	—

Table 2. Partial chemical and physical composition of limestone scrubber sludge (Terman, 1978 and references therein)

Element	Elemental composition,		
	A	% of dry solids	
		B	C
SiO <sub>2</sub>	31.6	4.9	0.58
Al <sub>2</sub> O <sub>3</sub>	18.3	3.4	1.21
Fe <sub>2</sub> O <sub>3</sub>	4.3	0.6	0.39
CaO	18.1	43.2	43.4
MgO	2.4	0.2	0.01
Total S	7.2	18.9	20.0
Component	D	E	F
CaSO <sub>4</sub> ·2H <sub>2</sub> O	22.0	15.0	6.0
CaSO <sub>3</sub> ·0.5H <sub>2</sub> O	18.0	21.0	49.0
CaCO <sub>3</sub>	39.0	20.0	3.0
MgSO <sub>4</sub> ·6H <sub>2</sub> O	5.0	4.0	2.0
Fly ash	20.0	41.0	40.0

A - Eastern Power Plant-19% ash; 1.9% sulfur; sample taken upstream of fly ash collection device.

B - Same as "A" except sludge from scrubber located downstream of fly ash collector.

C - Western Power Plant-Scrubber located downstream of ash collector.

D - TVA Shawnee Stream Plant, 2/1/73

E - Same, 7/12/73

F - Same, 3/19/94

Source: Ray and Parker, 1977

Table 3. Composition of 12 fluidized bed waste samples<sup>1</sup> (Terman, 1978 and references therein)

Macro elements			Micro Elements		
Element	Avg. %	Range, %	Element	Avg. ppm	Range ppm
Ca	27.2	21.0-34.0	B	136	110-240
S	9.1	7.0-13.0	Cu	62	57-75
Mg	0.96	0.8-1.2	Mn	190	178-196
Al	1.8	1.5-2.5	Zn	147	123-222
Fe	2.8	2.0-5.0	Ni	53	43-67
Na	0.17	0.14-0.19	Sr	164	132-193
K	0.38	0.24-0.52	Cd	-7	6-9
P	0.03	0.02-0.04	Cr	75	35-115
			Pb	74	63-85

<sup>a</sup> Analyses made by USDA, Morgantown, West Virginia

Table 4. Partial elemental composition of various fly ash sources<sup>a</sup> (Terman, 1978 and references therein)

Power plant	Location	Elemental composition							Neutralizing value, meq. H <sub>3</sub> O <sup>+</sup> /g
		K	Ca	Mg	P	B	Zn	Mo	
				%			ppm		
Big Sandy	Louisa, KY	3.10	0.72	0.53	0.04	319	51	7.4	0.12
Clinch River	Cleveland, VA	2.69	2.52	0.74	0.08	342	55	9.2	1.23
Glen Lynn	Glen Lynn, VA	2.41	0.58	0.23	0.05	307	36	6.8	0.09
Kanawha River	Glasgow, WV	3.19	0.67	0.27	0.03	391	46	5.6	0.09
Muskingum River (1)	Beverly, OH	2.33	0.45	0.84	0.06	301	115	11.8	Acidic
Muskingum River (2)	Beverly, OH	1.97	0.82	0.49	—	340	—	9.3	—
Phillip Sporn	New Haven, WV	2.51	0.65	0.09	0.05	340	88	11.1	0.05
Mount Storm	Mount Storm, WV	2.29	0.90	0.11	0.07	278	378	16.9	Acidic
Albright	Albright, WV	2.50	0.31	0.22	0.04	264	30	6.2	0.04
Rivesville	Fairmont, WV	2.45	0.65	0.26	0.07	236	13	7.8	Acidic
Fort Martin	Maidsville, WV	2.25	2.44	0.82	0.17	415	88	15.5	0.58
Crawford Edison	Chicago, IL	2.42	3.27	0.80	0.10	613	363	39.3	1.33
John Sevier	Rogersville, TN	3.14	0.61	0.46	0.05	323	74	9.4	0.01
E.C. Gaston (1)	Wilsonville, AL	2.70	0.71	0.82	0.15	428	186	24.4	0.25
E.C. Gaston (2)	Wilsonville, AL	2.65	0.97	0.30	—	367	—	24.8	—
Hoot Lake	Fergus Falls, MN	0.65	12.30	5.99	0.21	618	86	5.7	3.05
Lewis and Clark	Sidney, MT	1.07	12.56	6.02	0.28	414	132	7.5	3.73
Kansas Power and Light	Lawrence, Ks	—	—	—	0.06	48	353	—	1.87

<sup>a</sup> Martens *et al.* (1970), Martens (1971), Mulford and Martens (1971), and Doran and Martens (1972).

Table 5. Ranges and average chemical composition of fly ash<sup>†</sup> (Roy and Griffin, 1982)

Constituent	Range	No. of data	Avg.
	%		%
SiO <sub>2</sub>	2.19–68.1	58	44
TiO <sub>2</sub>	0.5–2.55	39	1.3
Al <sub>2</sub> O <sub>3</sub>	3.39–39.4	60	23
Fe <sub>2</sub> O <sub>3</sub>	3.60–29.2	58	11
CaO	0.2–31.0	58	8.2
MgO	0.4–12.8	58	2.7
Na <sub>2</sub> O	0.2–8.0	50	1.8
K <sub>2</sub> O	0.2–8.1	49	2.0
C	0.1–25.7	21	5.0
SO <sub>2</sub>	0.1–7.28	48	1.6

<sup>†</sup> Data from the literature and unpublished data from Illinois State logical survey files.

Table 6. Fly ash groups (Roy and Griffin, 1982)

Group	Sialic component ( $\Sigma$ SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + TiO <sub>2</sub> )	Calcic component ( $\Sigma$ CaO + MgO + Na <sub>2</sub> O + K <sub>2</sub> O)	Ferric component ( $\Sigma$ Fe <sub>2</sub> O <sub>3</sub> + SO <sub>2</sub> )
	----- % -----		
1. Sialic (essentially Si + Al)	>88	0–12	0–12
2. Fersic (Fe + sic from sialic)	48–77	0–29	23–52
3. Calsialic (Ca + sialic)	48–<71	>29–52	0–23
4. Modic (from modal concept)	>48–88	0–29	0–<23
5. Ferric (Fe)	<48	0–29	>23
6. Calcic (Ca)	<48	>29	0–23
7. Fercalsic (Fe + Ca)	<48	>29–77	23–71

Table 7. Summary of nomenclature and examples (Roy and Griffin, 1982)

Group	pH character (prefix to group name)	Special compositional properties and texture (examples)
Sialic	acid neutral alkaline	Acid C-Sialic silt Neutral Ba, C-Sialic Alkaline B, Ba, C-Sialic
Modic	acid neutral alkaline	Acid Ba, ZnModic loam Neutral B, Zn-Modic Alkaline C-Modic
Fersic	acid neutral alkaline	Acid B-Fersic silt loam
Calsialic	acid neutral alkaline	Alkaline Zn-Calsialic
Ferric	acid neutral alkaline	Acid Cd-Ferric silt loam
Calcic	acid neutral alkaline	Acid Ba, Cu, Zn-Calcic silt
Fercalsic	acid neutral alkaline	Neutral C, Ba, Cu-Fercalsic

Table 8. Chemical analysis of aqueous samples taken during the long-term equilibration, and some elemental analyses of decomposed solid

	Aqueous analysis for long-term equilibration samples								Elemental Analysis of solid	
	Ash 3				Ash 6				Ash 3	Ash 6
	N <sub>2</sub>	CO <sub>2</sub>	Atm	Av	N <sub>2</sub>	CO <sub>2</sub>	Atm	Av		
pH	3.6	3.8	3.9	3.8	11.4	6.0	7.1	8.2		
Conductivity, (mmhos cm <sup>-1</sup> )	1.6	1.6	1.6	1.6	3.4	1.9	7.8	2.0		
	ppm				ppm					
Aluminum	*	*	-	*	*	*	-	*	12 %	6 %
Arsenic	-	-	-	-	-	-	-	-	39 ppm	67 ppm
Boron	2.0	2.2	2.0	2.1	2.3	12.8	8.0	7.7	34 ppm	227 ppm
Cadmium	*	*	-	*	*	*	-	*	7 ppm	10 ppm
Calcium	68	75	-	72	16	133	-	75		
Chloride	2.3	1.8	-	2.0	2.0	1.5	-	1.8		
Iron	-	-	-	-	-	-	-	-	15.8 %	16.3 %
Lead	*	*	-	*	*	*	-	*		
Nickel	0.8	0.8	0.8	0.8	0	0	0	0	242 ppm	123 ppm
Potassium	176	178	-	177	24	24	-	24		
Silicon	12.7	13.6	22.2	16.2	1.2	13.	7.9	7.4		
Sodium	18	16	-	17	6	6	6	6		
Sulfate	129	130	157	139	19	14	93	85		
- Not analyzed										
* Values below detection limits										

Figure 1. Initial pH values of various Kentucky fly ashes.

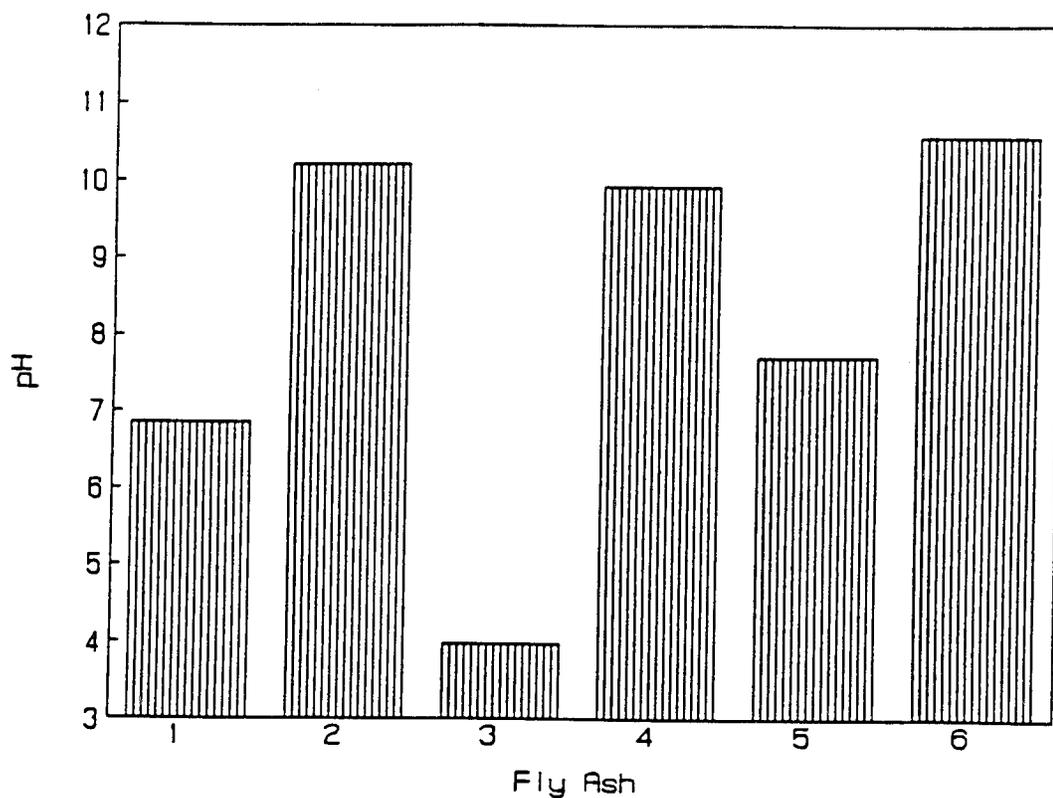


Figure 2. Scanning Electron Microscope photo of Kentucky fly ash.



Figure 3. Scanning electron microscope photo of a Kentucky fly ash sphere containing numerous smaller ash spheres

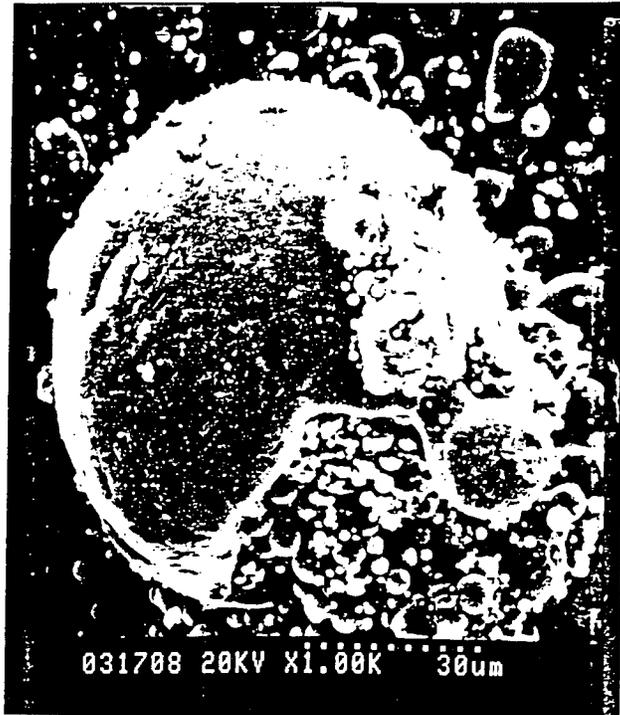


Figure 4. Scanning electron microscope photo of a broken Kentucky fly ash sphere.



Figure 5. Titrations of two Kentucky fly ashes

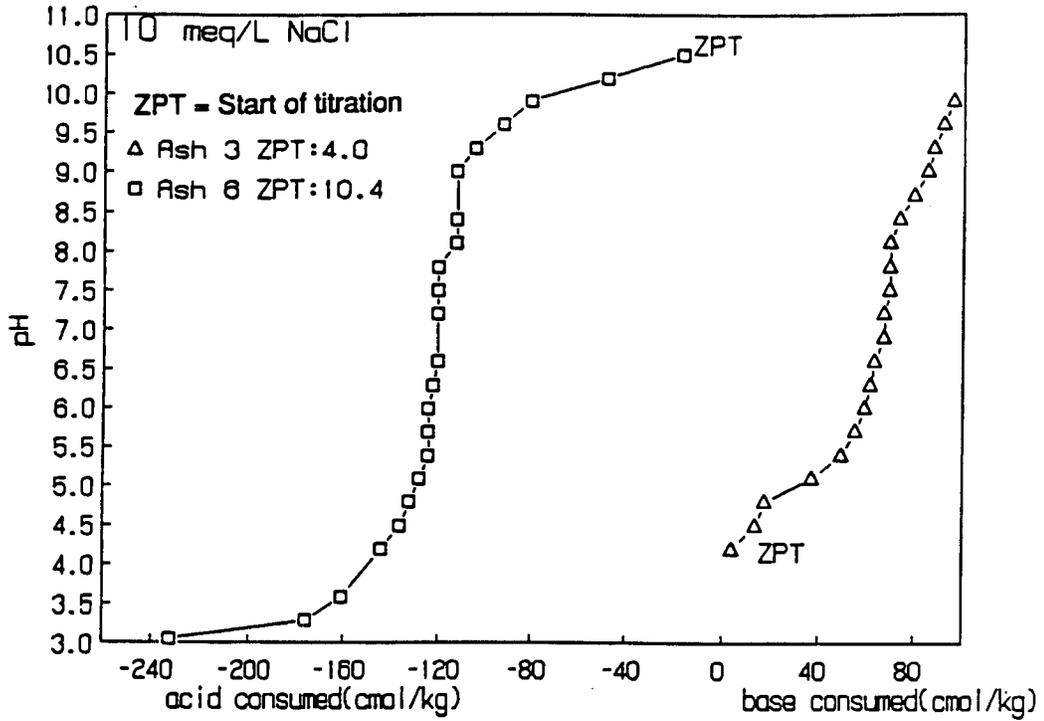


Figure 6. Potentiometric titrations of fly ash and NaOH with and without CO<sub>2</sub>

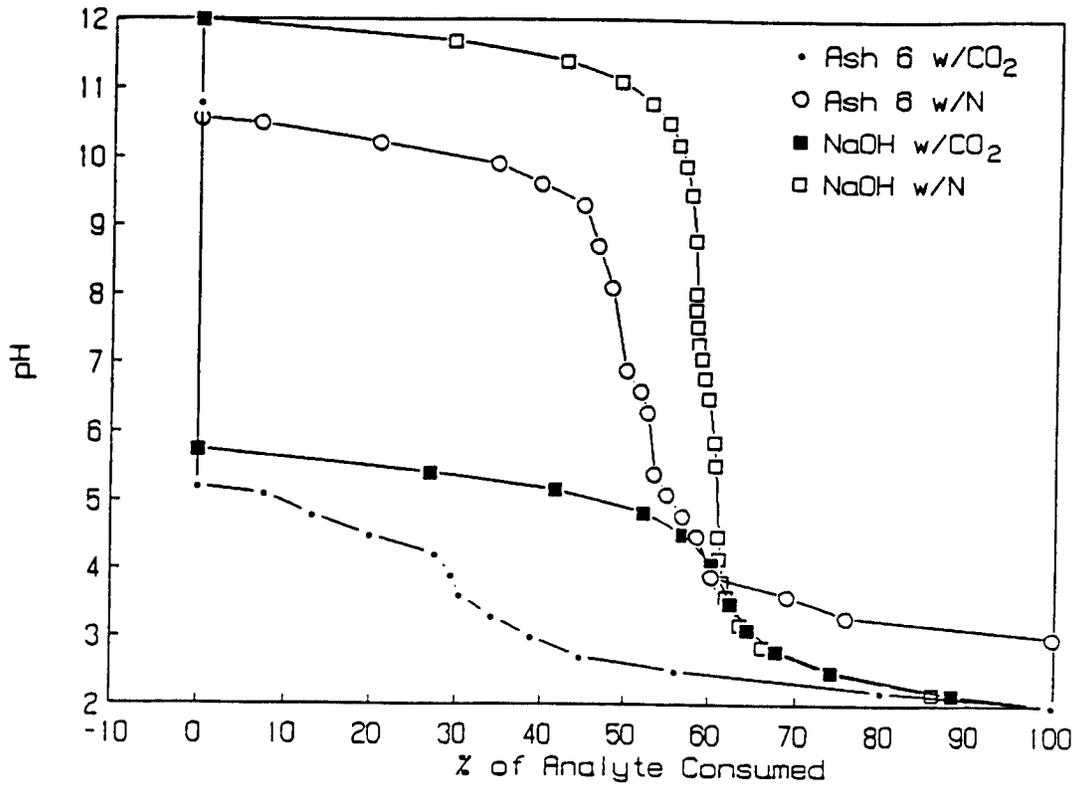


Figure 7. Potentiometric titrations of fly ash and  $Al(OH)_3$

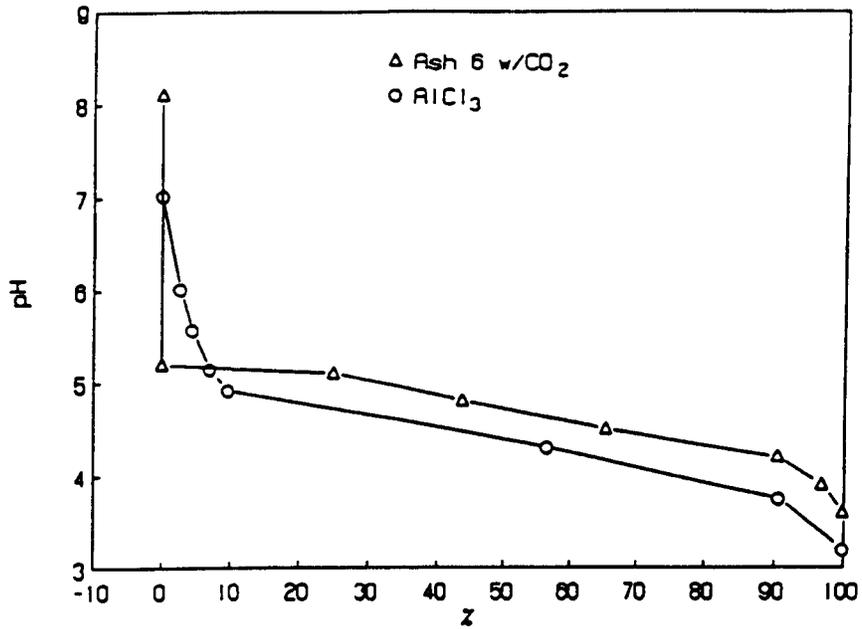


Figure 8. Potentiometric titration of fly ash demonstrating the "salt effect"

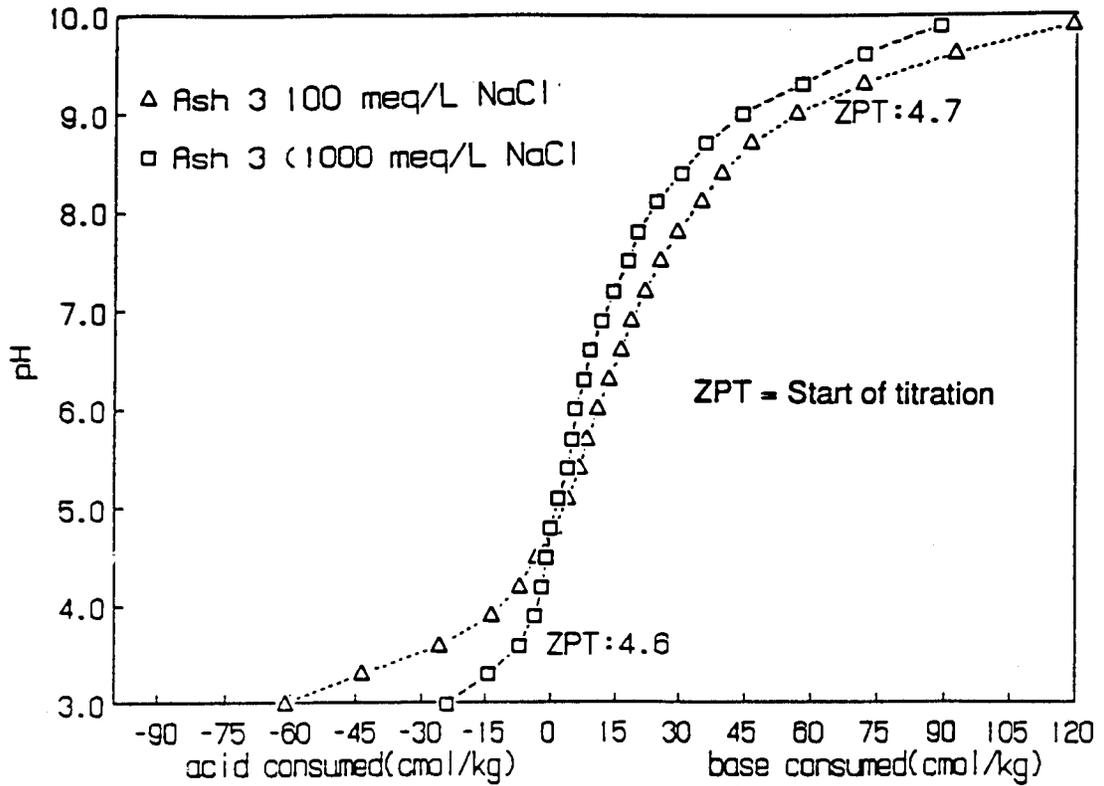


Figure 9. Protonation/deprotonation constants ( $K_a$ ) of fly ash as determined by potentiometric titrations

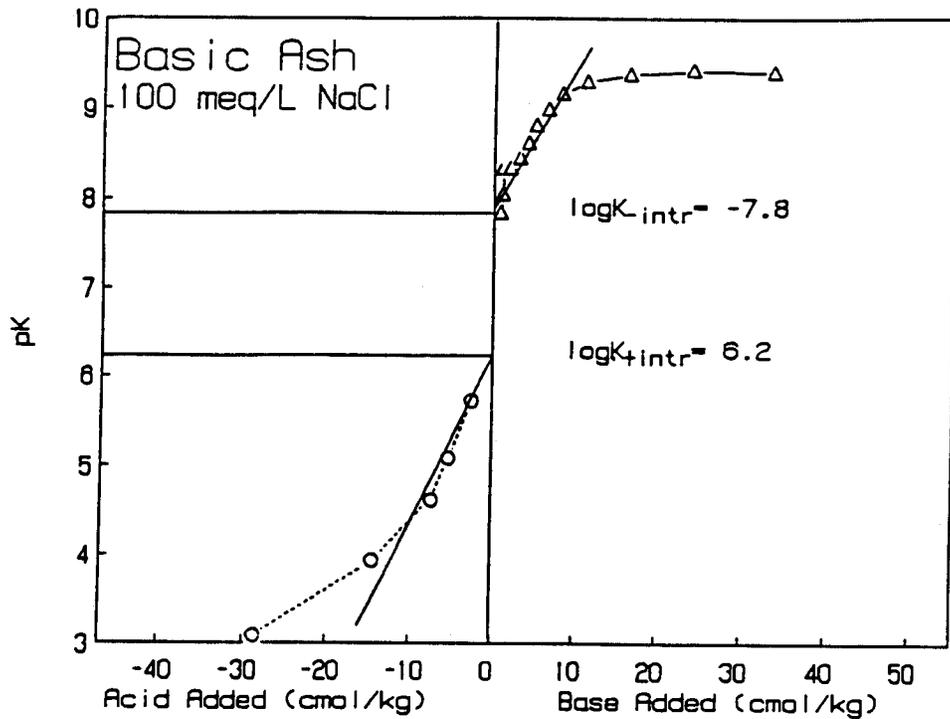


Figure 10. Boron release as a function of pH and partial pressure of  $CO_2$  for an initially high pH fly ash (Data for  $CO_2=0\%$ , and  $CO_2=100\%$  are averages of six data points each. Value for  $CO_2=0.03\%$  is from a single sampling.)

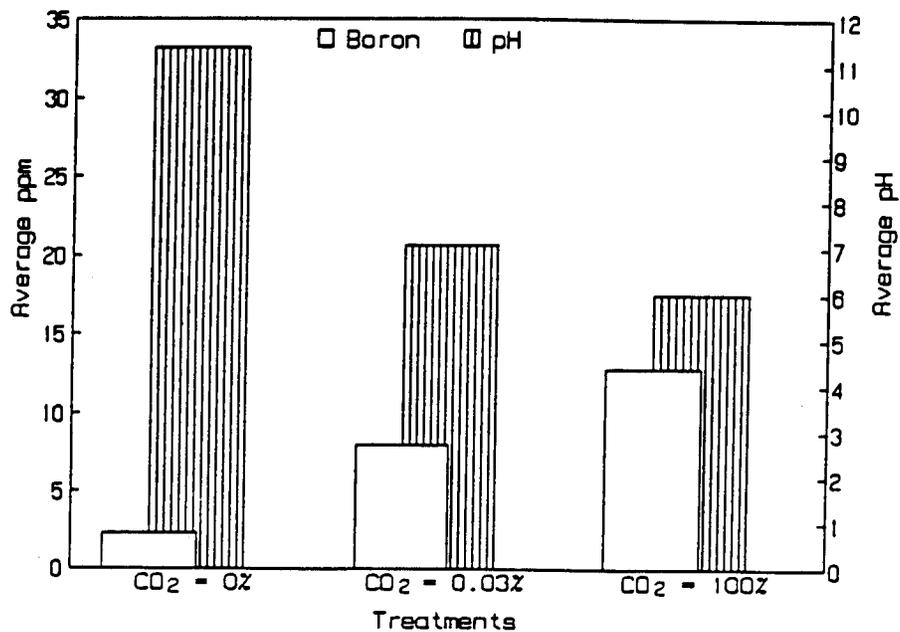


Figure 11. Boron release as a function of pH and partial pressure of CO<sub>2</sub> for an initially low pH fly ash (Data for CO<sub>2</sub>=0%, and CO<sub>2</sub>=100% are averages of six data points each. Value for CO<sub>2</sub>=0.03% is from a single sampling.)

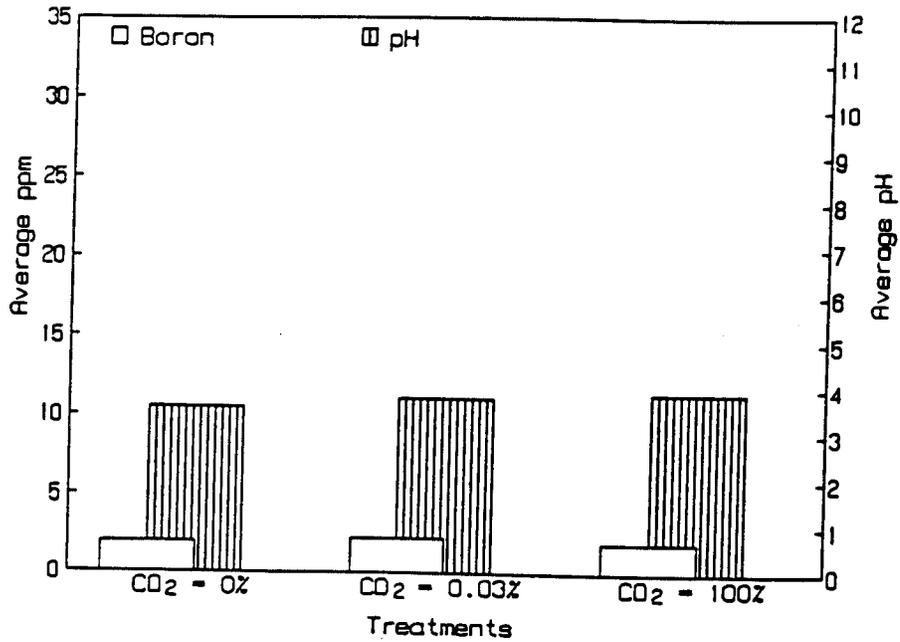


Figure 12. Nickel release as a function of pH and partial pressure of CO<sub>2</sub> for an initially low pH fly ash (Data for CO<sub>2</sub>=0%, and CO<sub>2</sub>=100% are averages of six data points each. Value for CO<sub>2</sub>=0.03% is from a single sampling.)

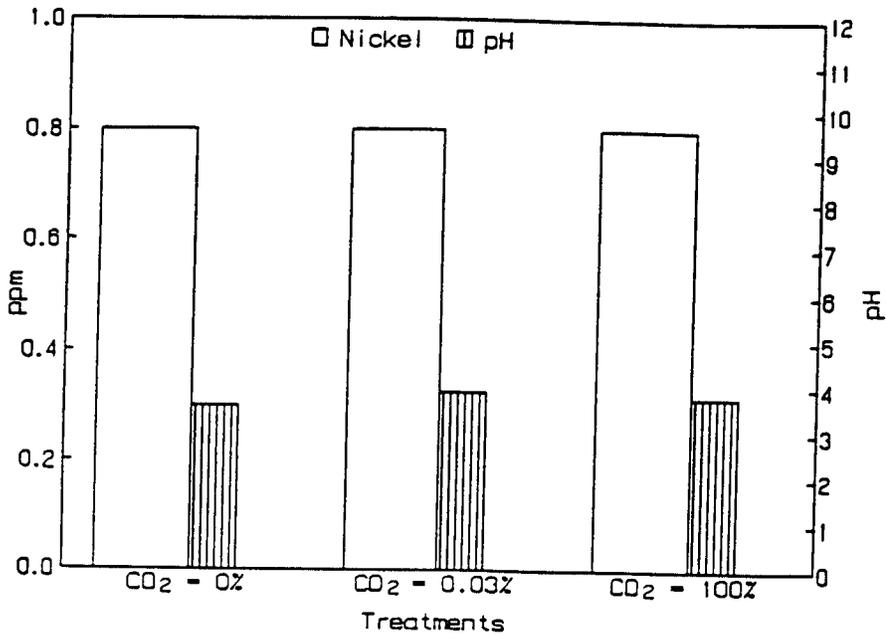


Figure 13. Nickel release as a function of pH and partial pressure of CO<sub>2</sub> for an initially high pH fly ash (Data for CO<sub>2</sub>=0%, and CO<sub>2</sub>=100% are averages of six data points each. Value for CO<sub>2</sub>=0.03% is from a single sampling.)

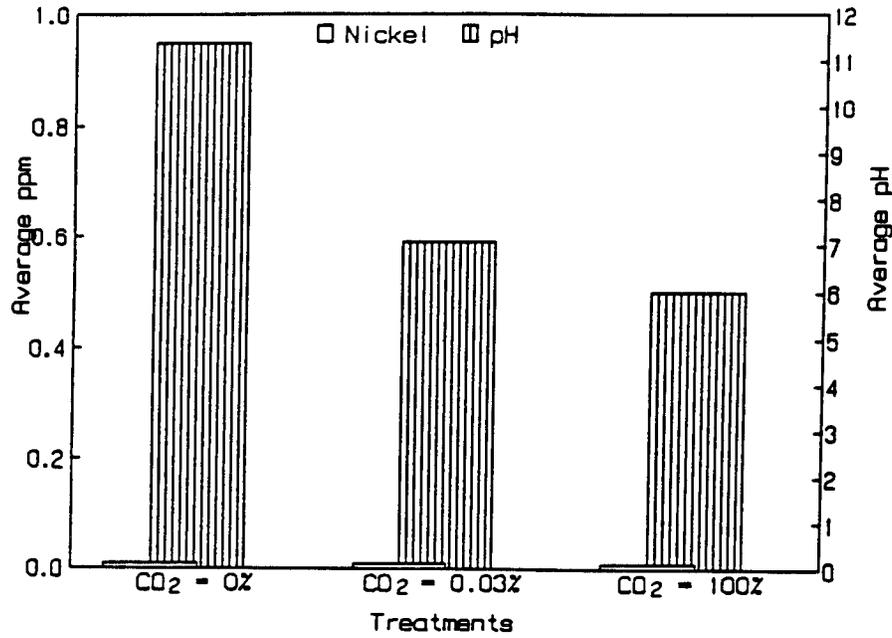


Figure 14. Breakthrough column data for boron in the presence of air with atmospheric composition

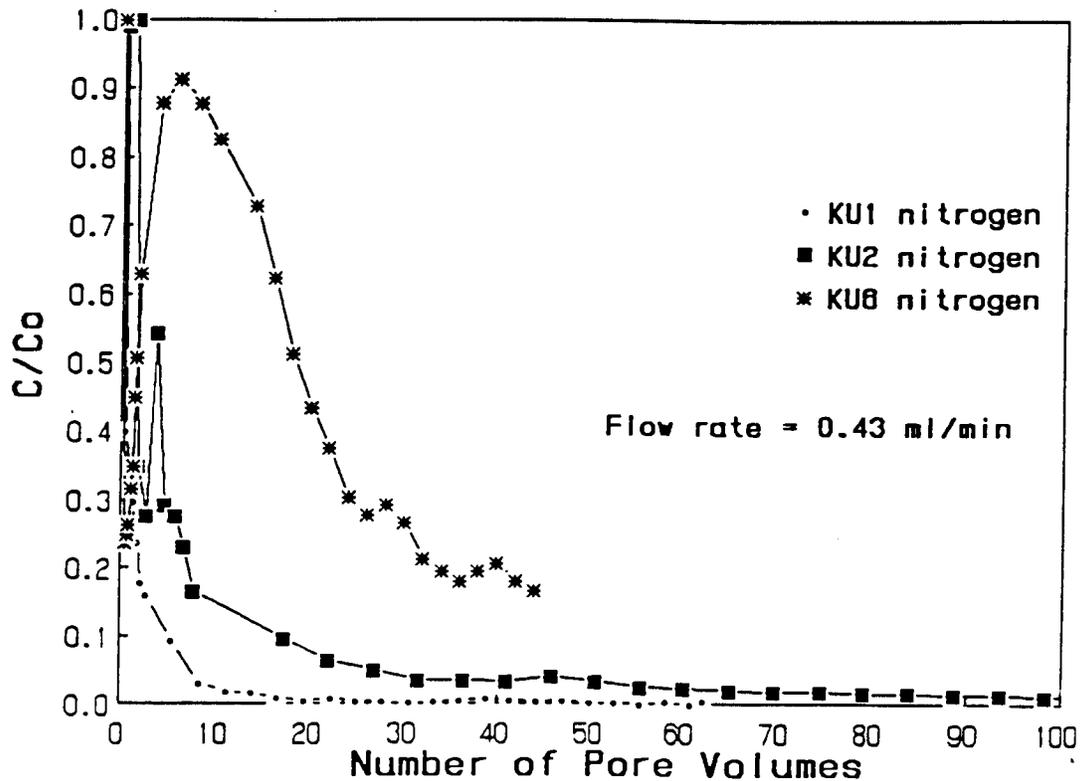


Figure 15. Relationship between percent adsorbed nickel relative to maximum adsorbed by the “alkaline fly ash” and suspension pH (Maximum adsorbed nickel was that obtained at the highest pH tested and at the highest total nickel solution concentration) ( Dark squares suggest that the nickel is weakly adsorbed)

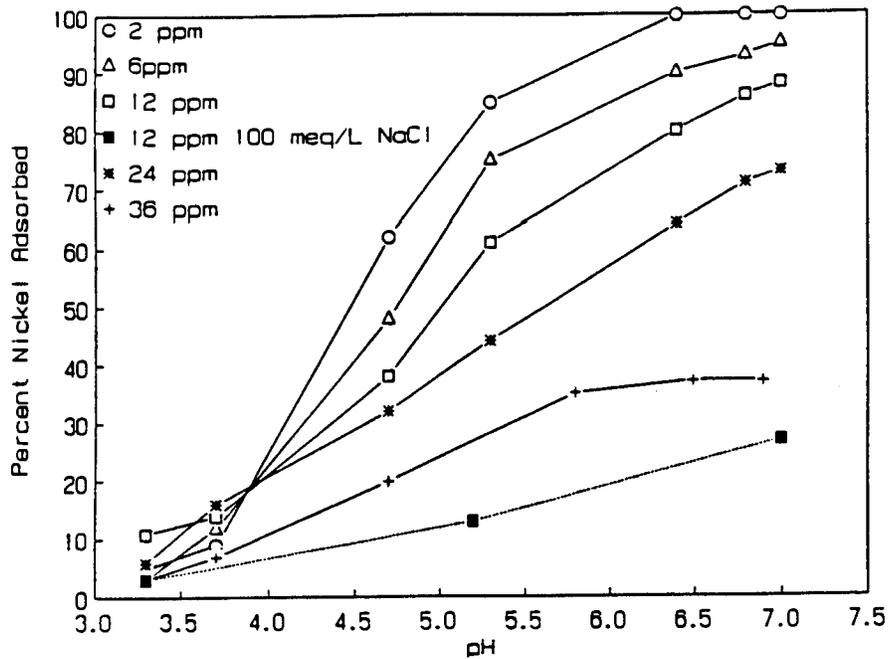


Figure 16. Relationship between percent adsorbed nickel relative to maximum adsorbed by the “acid fly ash” and suspension pH (Maximum adsorbed nickel was that obtained at the highest pH tested and at the highest total nickel solution concentration) ( Dark squares suggest that the nickel is weakly adsorbed)

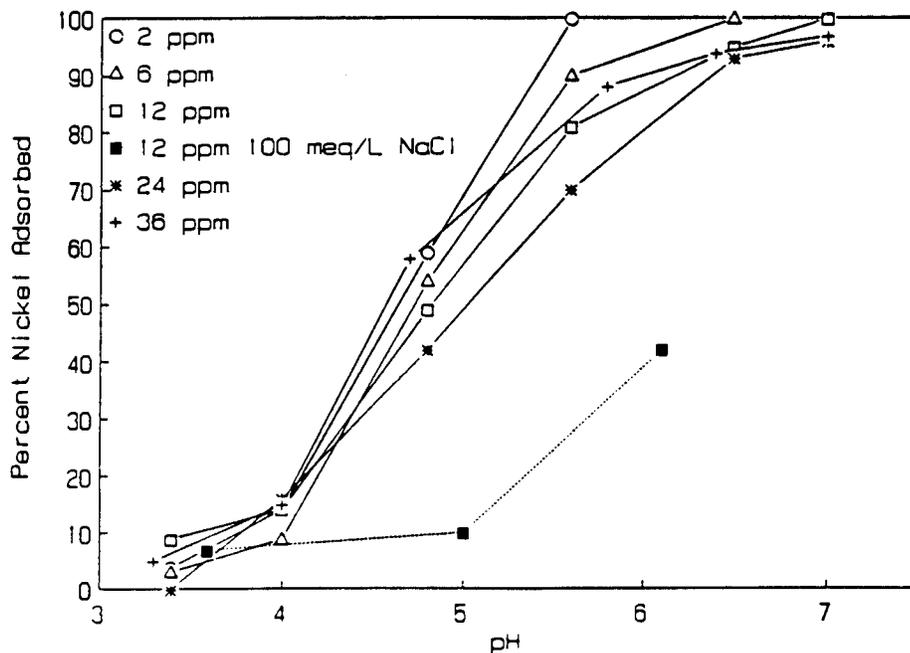


Table 1. Variations in coal ash composition (Terman, 1980)

Rank	Composition, %									
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	CaO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	Ash
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Lignite	6-40	4-26	1-34	0.0-0.8	12.0-52	2.8-140	28	0.1-1.38	3-324	19
<i>Meikle (1975)</i>										
							Na <sub>2</sub> O + K <sub>2</sub> O			
Bituminous	30-55	10-35	10-40	1.0-3	0.0-15	0.0-5	1.0-5	0.0-3	—	—
Lignite	20-41	10-18	7-16	1.0-3	20.0-40	2.0-11	0.5-0	0.5-0	—	—
<i>Endell (1958)</i>										
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CaCO <sub>3</sub>	39.0	20.0	3.0
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E.C. Gaston (1)	Wilsonville, AL	2.70	0.71	0.82	0.15	428	186	24.4	0.25
E.C. Gaston (2)	Wilsonville, AL	2.65	0.97	0.30	—	367	—	24.8	—
Hoot Lake	Fergus Falls, MN	0.65	12.30	5.99	0.21	618	86	5.7	3.05
Lewis and Clark	Sidney, MT	1.07	12.56	6.02	0.28	414	132	7.5	3.73
Kansas Power and Light	Lawrence, Ks	—	—	—	0.06	48	353	—	1.87

<sup>a</sup> Martens *et al.* (1970), Martens (1971), Mulford and Martens (1971), and Doran and Martens (1972).

Table 5. Ranges and average chemical composition of fly ash<sup>†</sup> (Roy and Griffin, 1982)

Constituent	Range	No. of data	Avg.
	%		%
SiO <sub>2</sub>	2.19–68.1	58	44
TiO <sub>2</sub>	0.5–2.55	39	1.3
Al <sub>2</sub> O <sub>3</sub>	3.39–39.4	60	23
Fe <sub>2</sub> O <sub>3</sub>	3.60–29.2	58	11
CaO	0.2–31.0	58	8.2
MgO	0.4–12.8	58	2.7
Na <sub>2</sub> O	0.2–8.0	50	1.8
K <sub>2</sub> O	0.2–8.1	49	2.0
C	0.1–25.7	21	5.0
SO <sub>2</sub>	0.1–7.28	48	1.6

<sup>†</sup> Data from the literature and unpublished data from Illinois State logical survey files.

Table 6. Fly ash groups (Roy and Griffin, 1982)

Group	Sialic component ( $\Sigma$ SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + TiO <sub>2</sub> )	Calcic component ( $\Sigma$ CaO + MgO + Na <sub>2</sub> O + K <sub>2</sub> O)	Ferric component ( $\Sigma$ Fe <sub>2</sub> O <sub>3</sub> + SO <sub>2</sub> )
	----- % -----		
1. Sialic (essentially Si + Al)	>88	0–12	0–12
2. Fersic (Fe + sic from sialic)	48–77	0–29	23–52
3. Calsialic (Ca + sialic)	48–<71	>29–52	0–23
4. Modic (from modal concept)	>48–88	0–29	0–<23
5. Ferric (Fe)	<48	0–29	>23
6. Calcic (Ca)	<48	>29	0–23
7. Fercalsic (Fe + Ca)	<48	>29–77	23–71

Table 7. Summary of nomenclature and examples (Roy and Griffin, 1982)

Group	pH character (prefix to group name)	Special compositional properties and texture (examples)
Sialic	acid neutral alkaline	Acid C-Sialic silt Neutral Ba, C-Sialic Alkaline B, Ba, C-Sialic
Modic	acid neutral alkaline	Acid Ba, ZnModic loam Neutral B, Zn-Modic Alkaline C-Modic
Fersic	acid neutral alkaline	Acid B-Fersic silt loam
Calsialic	acid neutral alkaline	Alkaline Zn-Calsialic
Ferric	acid neutral alkaline	Acid Cd-Ferric silt loam
Calcic	acid neutral alkaline	Acid Ba, Cu, Zn-Calcic silt
Fercalsic	acid neutral alkaline	Neutral C, Ba, Cu-Fercalsic

Table 8. Chemical analysis of aqueous samples taken during the long-term equilibration, and some elemental analyses of decomposed solid

	Aqueous analysis for long-term equilibration samples								Elemental Analysis of solid	
	Ash 3				Ash 6				Ash 3	Ash 6
	N <sub>2</sub>	CO <sub>2</sub>	Atm	Av	N <sub>2</sub>	CO <sub>2</sub>	Atm	Av		
pH	3.6	3.8	3.9	3.8	11.4	6.0	7.1	8.2		
Conductivity, (mmhos cm <sup>-1</sup> )	1.6	1.6	1.6	1.6	3.4	1.9	7.8	2.0		
	ppm				ppm					
Aluminum	*	*	-	*	*	*	-	*	12 %	6 %
Arsenic	-	-	-	-	-	-	-	-	39 ppm	67 ppm
Boron	2.0	2.2	2.0	2.1	2.3	12.8	8.0	7.7	34 ppm	227 ppm
Cadmium	*	*	-	*	*	*	-	*	7 ppm	10 ppm
Calcium	68	75	-	72	16	133	-	75		
Chloride	2.3	1.8	-	2.0	2.0	1.5	-	1.8		
Iron	-	-	-	-	-	-	-	-	15.8 %	16.3 %
Lead	*	*	-	*	*	*	-	*		
Nickel	0.8	0.8	0.8	0.8	0	0	0	0	242 ppm	123 ppm
Potassium	176	178	-	177	24	24	-	24		
Silicon	12.7	13.6	22.2	16.2	1.2	13.	7.9	7.4		
Sodium	18	16	-	17	6	6	6	6		
Sulfate	129	130	157	139	19	14	93	85		
- Not analyzed										
* Values below detection limits										

Figure 1. Initial pH values of various Kentucky fly ashes.

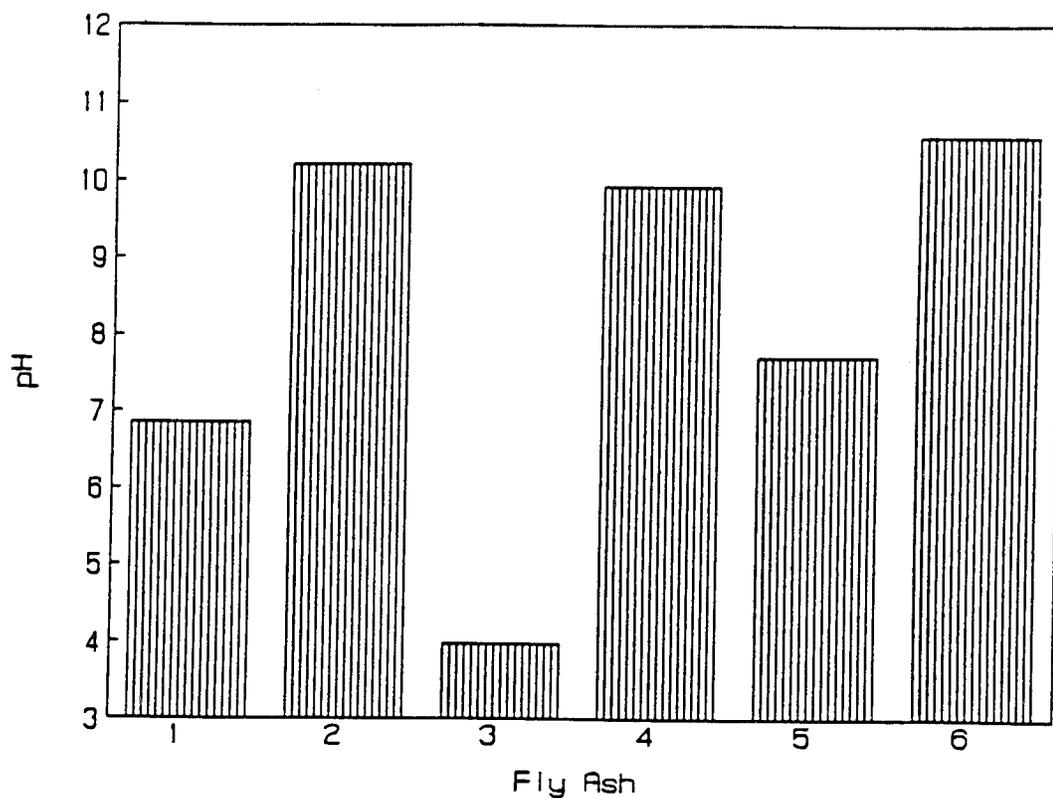


Figure 2. Scanning Electron Microscope photo of Kentucky fly ash.



Figure 3. Scanning electron microscope photo of a Kentucky fly ash sphere containing numerous smaller ash spheres



Figure 4. Scanning electron microscope photo of a broken Kentucky fly ash sphere.



Figure 5. Titrations of two Kentucky fly ashes

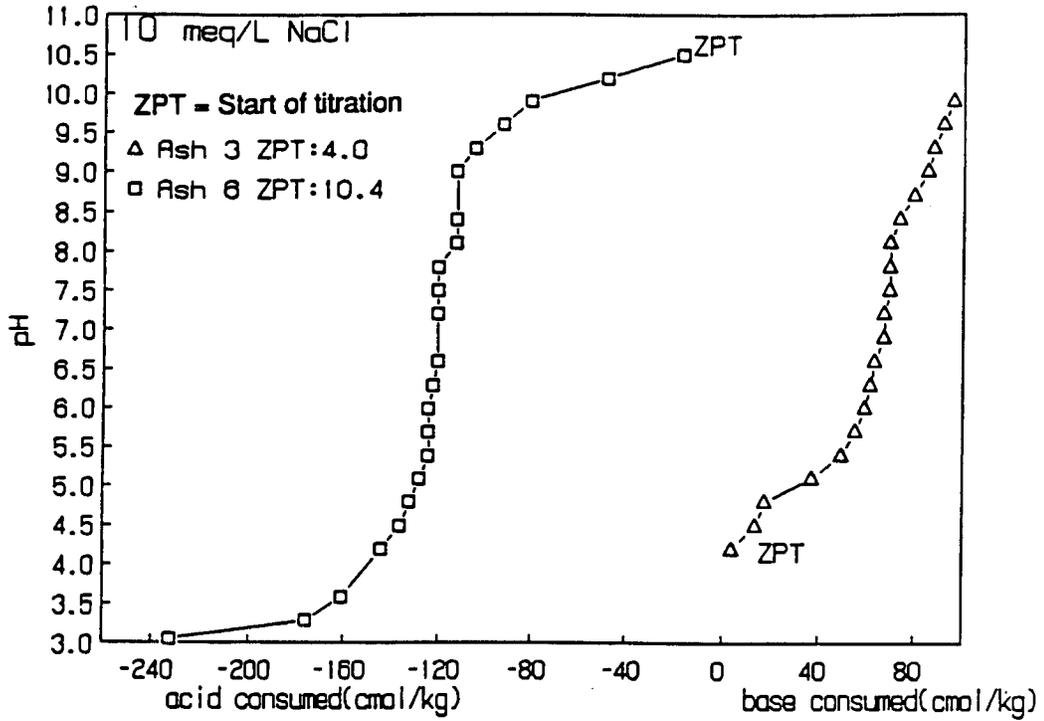


Figure 6. Potentiometric titrations of fly ash and NaOH with and without CO<sub>2</sub>

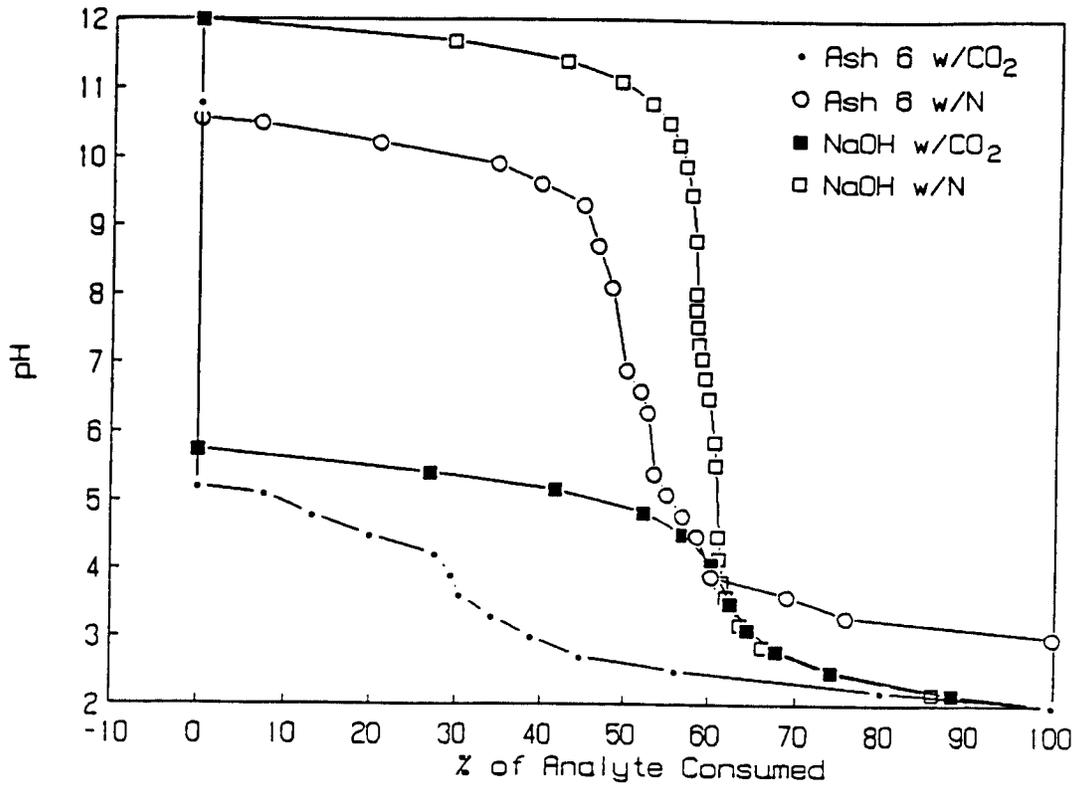


Figure 7. Potentiometric titrations of fly ash and  $Al(OH)_3$

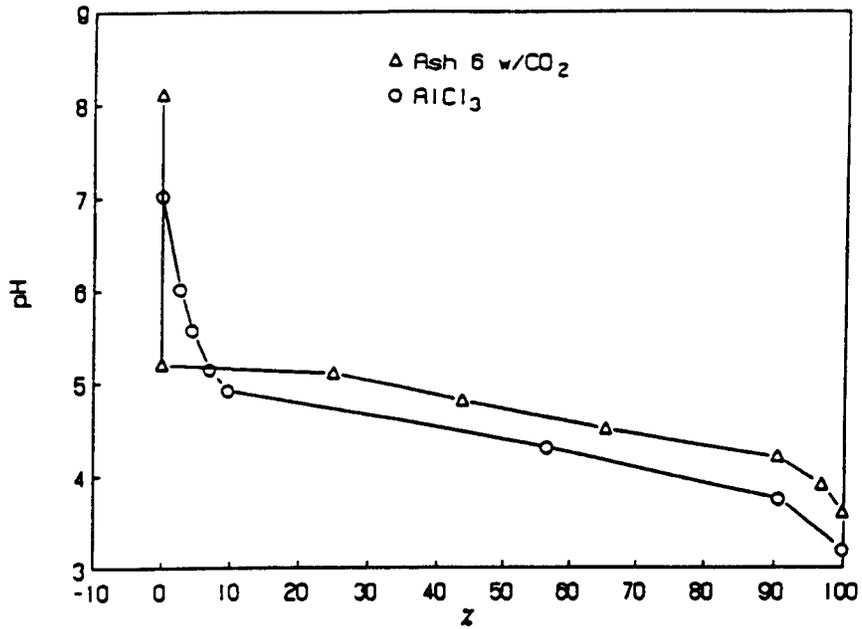


Figure 8. Potentiometric titration of fly ash demonstrating the "salt effect"

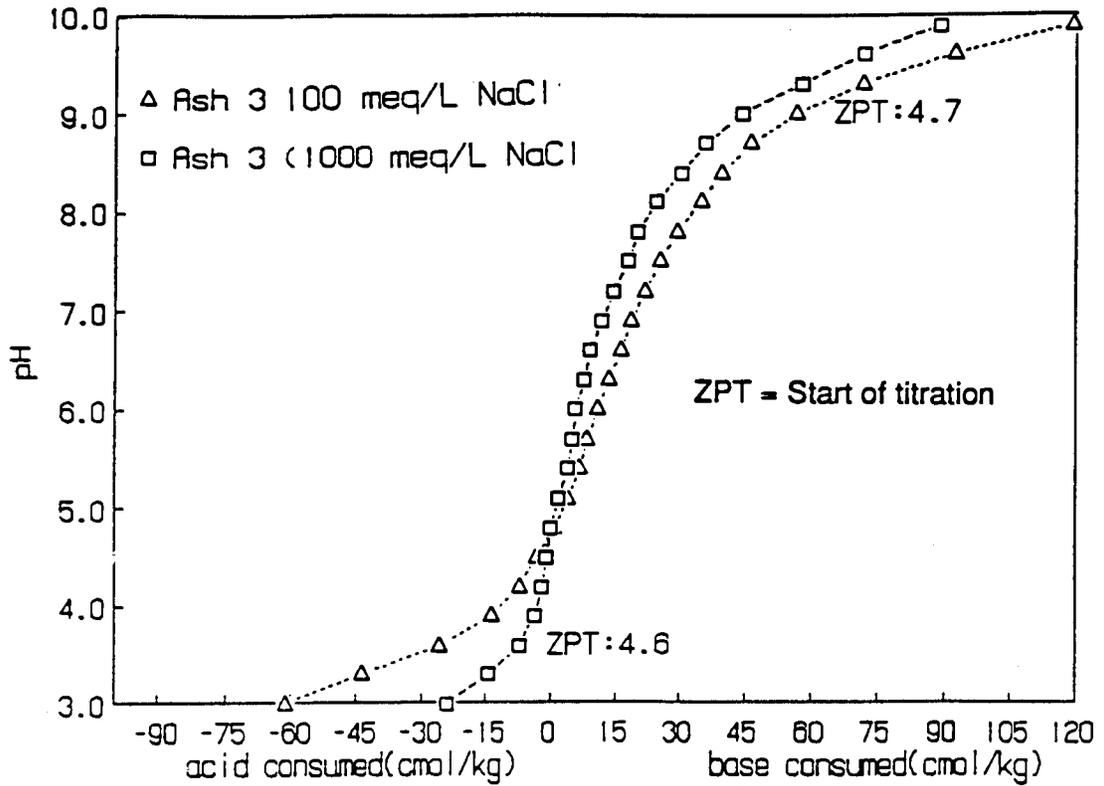


Figure 9. Protonation/deprotonation constants ( $K_a$ ) of fly ash as determined by potentiometric titrations

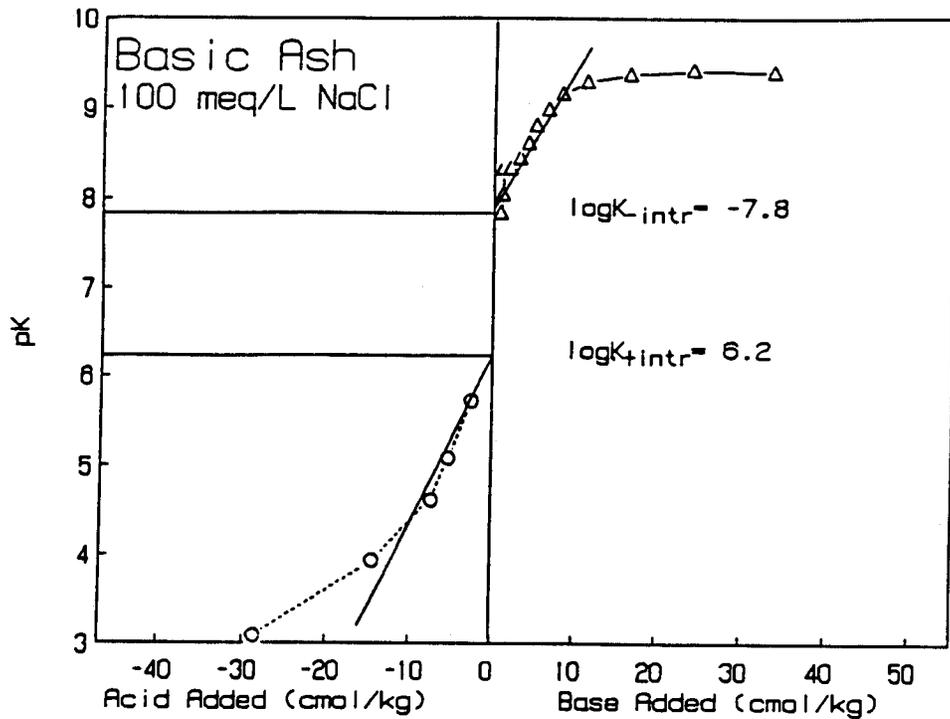


Figure 10. Boron release as a function of pH and partial pressure of  $CO_2$  for an initially high pH fly ash (Data for  $CO_2=0\%$ , and  $CO_2=100\%$  are averages of six data points each. Value for  $CO_2=0.03\%$  is from a single sampling.)

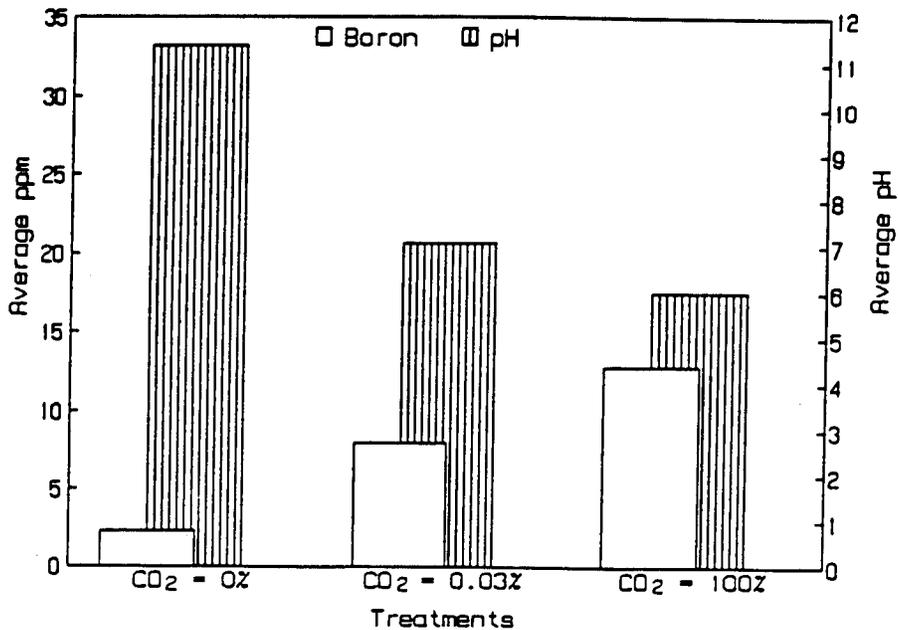


Figure 11. Boron release as a function of pH and partial pressure of CO<sub>2</sub> for an initially low pH fly ash (Data for CO<sub>2</sub>=0%, and CO<sub>2</sub>=100% are averages of six data points each. Value for CO<sub>2</sub>=0.03% is from a single sampling.)

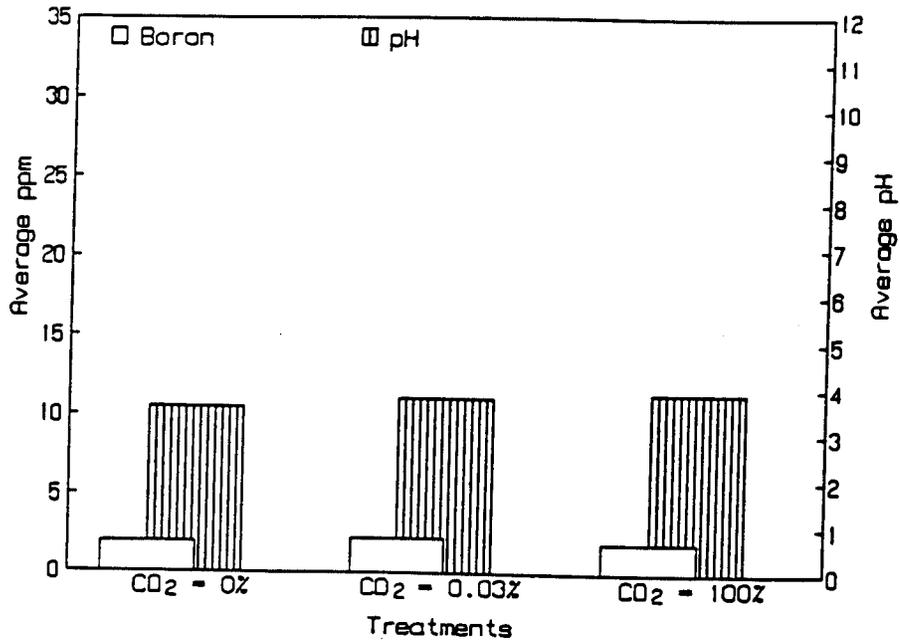


Figure 12. Nickel release as a function of pH and partial pressure of CO<sub>2</sub> for an initially low pH fly ash (Data for CO<sub>2</sub>=0%, and CO<sub>2</sub>=100% are averages of six data points each. Value for CO<sub>2</sub>=0.03% is from a single sampling.)

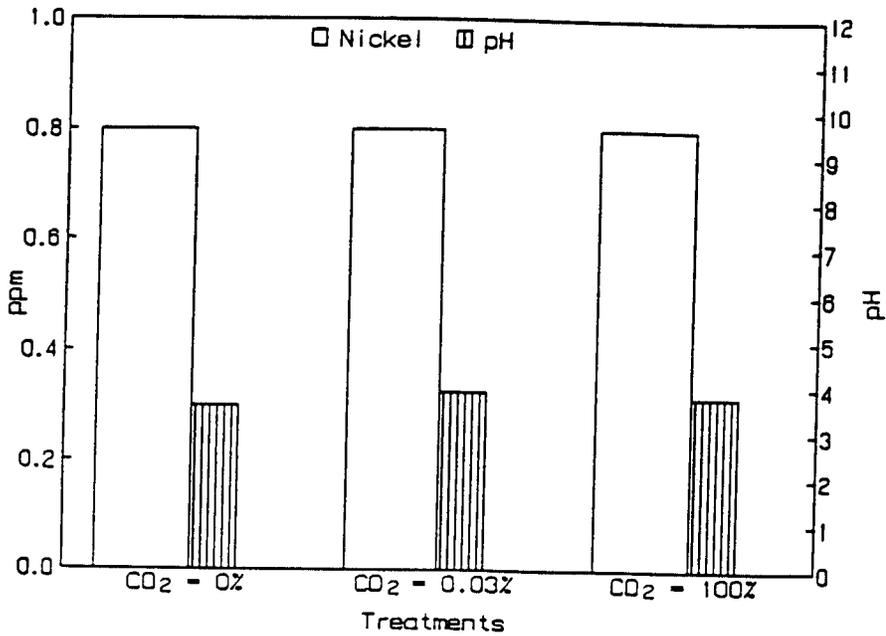


Figure 13. Nickel release as a function of pH and partial pressure of CO<sub>2</sub> for an initially high pH fly ash (Data for CO<sub>2</sub>=0%, and CO<sub>2</sub>=100% are averages of six data points each. Value for CO<sub>2</sub>=0.03% is from a single sampling.)

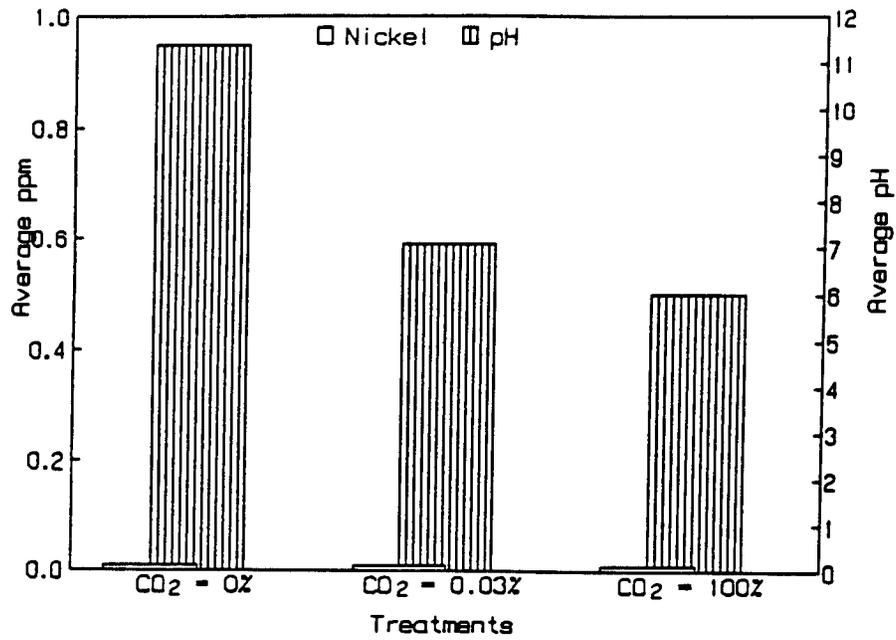


Figure 14. Breakthrough column data for boron in the presence of air with atmospheric composition

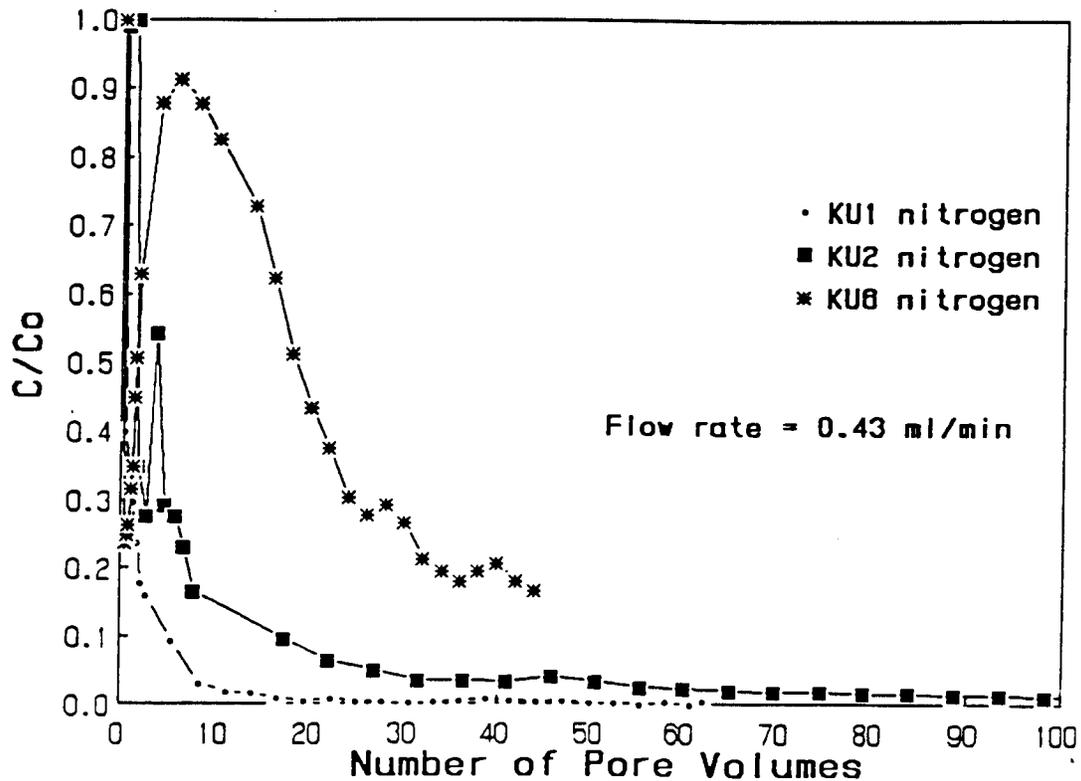


Figure 15. Relationship between percent adsorbed nickel relative to maximum adsorbed by the “alkaline fly ash” and suspension pH (Maximum adsorbed nickel was that obtained at the highest pH tested and at the highest total nickel solution concentration) ( Dark squares suggest that the nickel is weakly adsorbed)

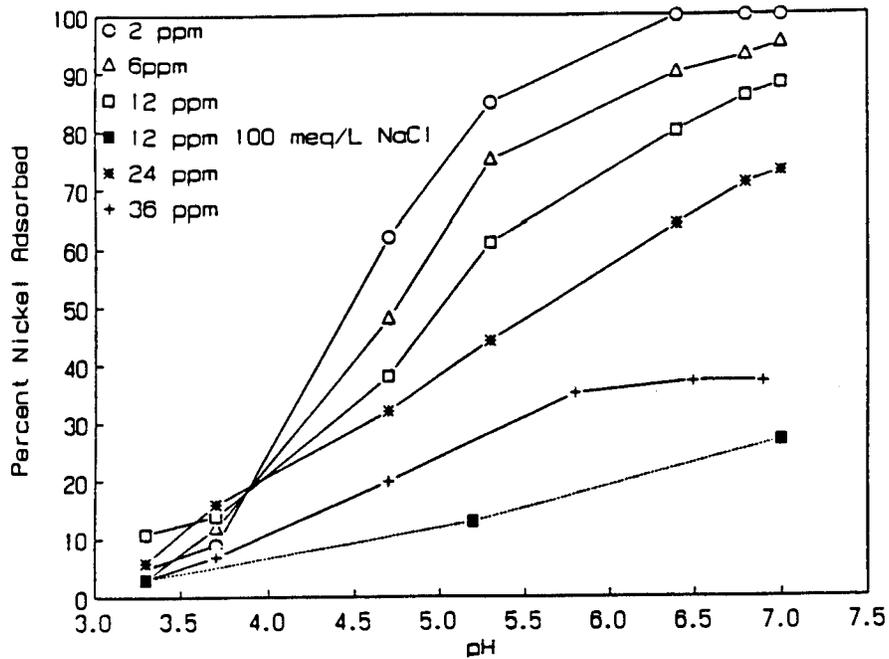
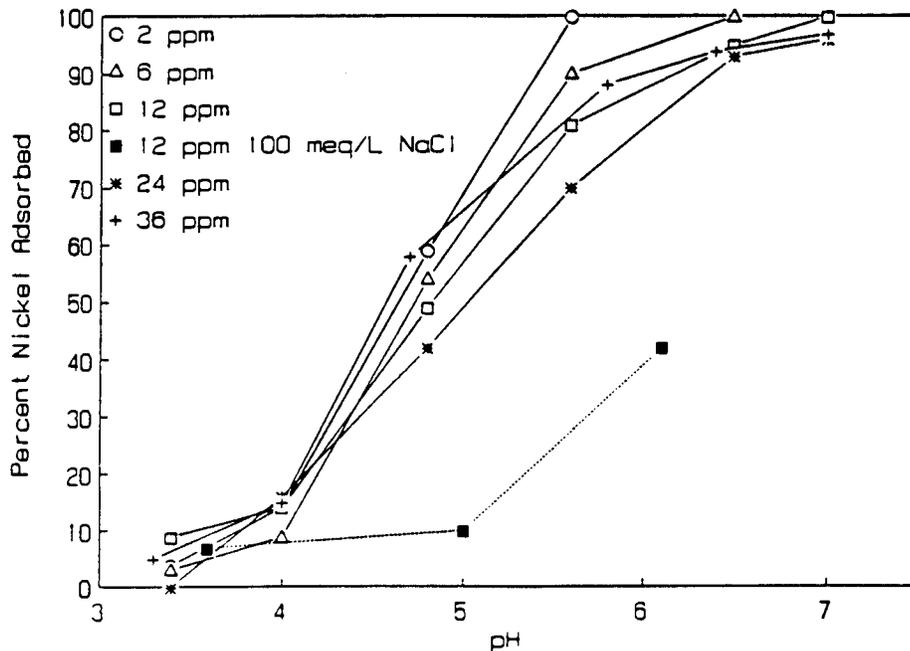


Figure 16. Relationship between percent adsorbed nickel relative to maximum adsorbed by the “acid fly ash” and suspension pH (Maximum adsorbed nickel was that obtained at the highest pH tested and at the highest total nickel solution concentration) ( Dark squares suggest that the nickel is weakly adsorbed)



## **USE OF COAL COMBUSTION BY-PRODUCTS FOR RECLAMATION: ENVIRONMENTAL IMPLICATIONS**

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### **Abstract**

Coal combustion byproducts are made of incombustible materials contained in the coal or added to the boiler or stack gas streams. They are available in large quantities and in many cases are now hauled back to mine sites to be land-filled at their source. These materials have significant potential as bulk reagents, fills, and chemicals in mine reclamation. Many of the materials are alkaline and can be used for water neutralization, pH balance adjustments to Gob, and alkaline recharges. Some materials are cementitious and can be used to strengthen soils and Gobs at mine sites or to produce impermeable caps. Still other materials are valuable fertilizers.

Combustion residues have been looked upon as dangerous waste products prone to degrade the ground and surface waters, cast dangerous dust clouds into the air, or create sterile organic free piles for anemic plant growth. Large field scale pilot projects that have followed laboratory tests suggest that most of these fears are unwarranted. A 50,000 ton scrubber sludge backfill in a final strip cut was instrumented with monitoring wells and cleans heavy metals from the groundwater. One hundred and fifty tons of FBC fly ash were used to neutralize an acid lake and heavy and toxic metals concentrations all dropped, even where the ash was expected to leach toxic metals that would not precipitate with changing pH. A 1,000 ton test bed of FBC fly ash and Gob was instrumented with a 15 by 20 foot lysimeter catchment basin beneath to determine if the leachate carried heavy metals or other toxics. The bed is so impermeable that in 2 years it is not possible to get a 10 ml water sample for analysis. A 7 acre cap made of FBC ash and spoil has yielded no leachate to sample. Run-off from the cap area has slight elevation in potassium and sodium concentrations but no indication of heavy or toxic metals. There are no adverse impacts detectable in the adjacent stream. Engineered mixes of coal combustion residues and mine wastes seem to bind even mobile elements like boron. Open frame-less dump trailers filled with dry FBC fly ash have been unloaded in the field with practically no dust emissions. Much of the dust in handling can be avoided with attention to minor details in construction sequences. Experiments are under way to design mobile field systems that will render FBC fly ash non-dusty while retaining its dry fine granular characteristics. A power plant in Illinois produces a force oxidized synthetic gypsum from scrubbing operations that is more pure than the natural product and enhances plant growth. The low cost, high volumes, and excellent properties of combustion residues make suitable for beneficial use in the mines they are hauled back to.

### **Introduction**

Reclamation of coal mines involves large amounts of material and requires significant input of bulk reagents or fills. The U.S. produces around 1 billion tons of coal annually, most of it by surface methods with stripping ratios in the range of two yards to over twenty cubic yards of overburden per ton of coal produced. In some locations the broken overburden rock can become susceptible to accelerated weathering which releases acidity or salt over a shorter space of time than would have occurred naturally. Since incombustible soils and rocks settled in ancient swamps along with plant material, the resulting coal today contains impurities. These impurities range between about 6 and 35 percent of the total coal

tonnage removed from a mine in the U.S. The impurities can be removed by coal preparation plants, but with waste product tonnages averaging around 20% of the raw tonnage. Frequently these coal washing products are at least partially acid producing.

The alternative to coal washing is to transport worthless impurities with the coal to power plants to become an unwanted byproduct at that location. Ultimately, rock not removed from the coal will be fired in the boiler and either carried up the stack as tiny fly ash particles to electrostatic precipitators for collection, or fused into slags or larger particles that must be mechanically removed from the bottom of the boiler as boiler slag or bottom ash. Acid forming pyrite in coal, if not removed by coal preparation, will report to the boiler and form sulfur dioxide gas (SO<sub>2</sub>) for which strict emission limits now exist. Wet scrubbers use lime or limestone slurries as sorbants to remove the SO<sub>2</sub> from the stack gasses. Fluidized Bed Combustors (FBC) inject limestone into the boiler with the coal to capture the SO<sub>2</sub> as it forms. Of coarse injecting incombustible rock into the boiler usually doubles the volume of fly ash and bottom ash (called spent bed for FBC units) that must be dealt with, just as wet scrubbers form a similar amount of excess byproduct called "scrubber sludge".

By-products of coal mining, preparation, and combustion find a variety of potential uses, but unsuitable specifications and vast tonnages still leave hundreds of millions of tons of altered natural materials each year to become waste products. High carbon F type fly ashes and byproducts of SO<sub>2</sub> control are especially likely to be wasted, since they have not found a place in regular concrete and shingles like other coal combustion ashes. To consume finite and expensive landfill space as a depository for rocks is becoming increasingly difficult to justify. Some states now allow combustion byproducts to be returned to the mine site, rationalizing that this new source of landfill space is in fact where the rock came from in the first place. But should combustion byproduct be land-filled at all?

#### Mine Site Uses of Combustion By-Products

Each independent handling operation is an additional cost to the use of coal. Returning combustion byproducts to mine sites for disposal still leaves the cost of landfill handling as a hidden cost to the consumer. If onsite handling of combustion byproducts returned to the mine site could be combined with other operations, cost savings may be achieved. Concurrent reclamation is a requirement of modern coal mining and a special tax on all coal mined now funds reclamation of long abandoned mined lands. Coal combustion byproducts have properties that make them suitable bulk materials and chemicals for land reclamation.

The most useful properties of coal combustion byproducts are alkalinity, cementitiousness and pozzolanic activity. Of course there are mine reclamation applications where a simple fill is required. In the case of the old Forsythe Energy #5 mine, near Marion Illinois, an unstable final cut strip-pit was located within 50 feet of a major road and airport. The unstable highwall was slumping and threatened to engulf the road and several accidents had involved motorists losing control and plunging as much as 40 feet into the lake at the bottom of the pit. There were concerns too about accidents that could occur with planes making emergency landings at the nearby airfield. Available soil to fill the pit was scarce and would have to be trucked significant distances around the mine site. A local power plant had large quantities of wet sulfite rich limestone scrubber sludge and an agreement was reached for the utility to truck the material to the site and place it by the edge of the pit for use as a fill. The utility saved money on land-filling costs while the States reclamation division saved money on the handling of the fill materials.

Cementitious properties of FBC ash were used in another project to steepen the embankments used around slurry impoundments at mines. Coarse gob was amended with about 25% FBC fly ash to yield a mixture with several hundred psi of strength that could stand steeper and higher than ordinary berms. The ash was disked into the Gob in the field. Limited disk penetration indicated that lifts should be built only 1 foot at a time, which many mine operators would find unacceptable. Mixing the ash with the GOB before haulage or use of more penetrating "gator" tillers are alternatives.

GOB materials amended with FBC ash are as impermeable as a clay liner with hydraulic conductivities in the  $10^{-7}$  to  $10^{-9}$  cm/sec range. One test bed built at the Burning Star #1 mine in 1994 was equipped with a 15 by 20 plastic lined sand-tiled catchment basin beneath it. A monitoring well was drilled through the bed and set in the sand. In two years the giant lysimeter-like structure has yet to capture enough water to allow a sample to be taken from a 2 inch diameter well.

A larger application of FBC ash amended regular mine soil, spoil material, and GOB at the Thunderbird mine site with about 35% FBC to create a cap over a 7 acre area. Acid producing Gobs were buried in a final cut strip pit and then covered with a one foot cap and two feet of soil cover. The cap was placed in two lifts with 10,000 tons of FBC ash disked into three types of loose mine material with the mix compacted by conventional roller. Lysimeters placed under the cap have failed to detect water percolating through the cap and monuments anchored into the cap have not detected heaving or swell that could threaten the liner integrity. The cost of the cap was about 1/2 the cost of a cap using clay imported to the site. Ash handling operations for placement, spreading, disking, and rolling came to \$5/ton of ash.

The cementitious properties of FBC ash involve entringite formation as opposed to alkali reaction complexes with aluminosilicate glass pozzolans like conventional concrete. If more conventional cement reactions are desired, conventional F type fly ashes from PCC boilers can be used with the lime in FBC fly ashes used as an activator. In a cooperative demonstration with the U.S. Department of Energy, PCC fly ash provides the pozzolon for a low grade cement made of scrubber gypsum (a setting retardant) and lime from a venturi scrubber on an industrial boiler. The material is pumped as a paste, bleed-water free backfill to stabilize underground mine openings against subsidence. Where soft floor conditions drive subsidence in places like Illinois it is not necessary to fill the opening to control the subsidence. The ability to custom design a cement has many uses in mine reclamation or even operation. In another project, high carbon (6% plus LOI) F type fly ash is activated with FBC fly ash to make fiber reinforced crib members with lower cost, similar weight, and greater strength than wood. Like wood, the members can be sawed and nailed. Blocks for sealing mine workings have been similarly prepared. Obviously preparation plant wastes can be amended with a wide range of combustion residue cements and used to construct semi-permanent enhanced earth structures around the mine. Caution should be exercised in use of FBC ash for preparation of surface road pavements as some highway tests have suffered from material degradation and delayed swelling. A test by SIU-C researchers suggests that appropriately formulated rolled concrete does not have this limitation. Any application of combustion residues as a structural cement should be approached with careful attention to formulation as most mixes in a random array of tests produced useless materials and potentially unpleasant behavioral surprises.

The alkalinity in combustion residues from SO<sub>2</sub> control is useful as a bulk chemical. A two million gallon pond of highly acidic water was neutralized before discharge using FBC fly ash with a calcium carbonate equivalent (CCE) value of 71%. FBC spent bed has a texture of agricultural lime and 76% CCE. It releases a much more powerful burst of alkalinity (around pH 12.5) on initial hydration than does agricultural lime, while stabilizing to the same long term pH values around 8. For spreading in alkaline recharges where an acid mine drainage problem already exists, the powerful burst of alkalinity would be far more effective in precipitating the ferric oxidant than limestone. While code H lime also has this property, it is much more expensive and has problems with caustic dust. The user should be cautioned that FBC spent bed will self cement, unlike agricultural limestone.

Sulfite rich limestone and dual alkali scrubber sludges (CCE 30% and 54% respectively) can also be used for alkaline recharges where a damp more soil-like material is desired for handling reasons. At the Harco mine site a 35 acre area of acid producing Gobs and coal slurries was capped with sulfite rich limestone scrubber sludge. The material was handled like soil. It was picked up and put down with scrapers, leveled with a dozer and roller compacted to limit permeability. Field hydraulic conductivities for unrolled sulfite rich limestone scrubber sludge were in the lower  $10^{-5}$  cm/sec range so near clay like hydraulic conductivities are expected at Harco. If scrubber sludges compete against borrow clay for

capping applications they would have the advantage of a significant alkali reserve that would make seepage more like an alkaline recharge. A problem with clays from some Illinois basin and Eastern mine sites is that native clays near the coal seam are highly acid producing and may become the source of the problem they were intended to solve. Dual alkali scrubber sludges have a strong initial alkali burst, while wet limestone scrubber sludges have pH values around 8. Initial pH and permeability can be chosen by the reclamation engineer.

Combustion residues can also assist and enhance revegetation. Synthetic gypsum from force oxidized limestone scrubbers is a natural sulfate fertilizer. It helps to restore structure to mine soils that have been over-compacted by the equipment used for reclamation. It easily leaches to carry calcium into soil zones that are normally accessible only with expensive deep tillage equipment. There the calcium reduces problems with aluminum toxicity and enhances root penetration. In experiments carried out by SIU-C investigators the gypsum was delivered by frame-less dump truck, loaded into a lime spreader with a tractor, and spread on the ground with an agricultural limestone spreader. FBC spent bed has been applied to agricultural lands in Illinois using lime spreaders. FBC fly ash is too fine and dusty for a lime spreader, but if it is left outdoors for a season it will clump into a weak cement mass that can be broken with a loader and ground to make a coarse granular product which can be spread with a lime spreader. FBC byproducts have both strong alkali potential and sulfate fertilization. When they are loose in the upper soil the byproducts can degrade and alter into gypsum which will then aide in reducing aluminum toxicity. Of coarse it takes several seasons to create gypsum from FBC ash and then it will not help the soil texture.

#### **Environmental Issues for Coal Combustion By-Products in Reclamation**

Coal combustion byproducts can be chemicals, alkaline recharges, caps, and custom structural materials in mine reclamation. Unfortunately there are environmental issues with their use. coal combustion residues are most commonly classed as a special waste, though some states regulate under RCRA subtitle D, and some expect FBC ashes to receive mandatory subtitle D or even subtitle C requirements when the Bellville amendment exemption runs out. The mentality that combustion residues are a sinister waste product from an industrial plant has caused a presumption of environmental liability and a general neglect of environmental enhancement potential. Much regulation and concern centers around the notion that industrial waste products release dangerous leachate into the water supply. Fugitive dust concerns are receiving more attention as companies move to dry disposal alternatives. Finally a last concern with coal combustion byproducts, noticed most frequently by mine reclamationists, is the general lack of organic material to spur plant growth.

Many of the field scale pilot projects in which SIU-C has participated have been heavily monitored to determine if leachates were detrimental to ground or surface waters. For a year before the final strip pit at Forsythe Energy #5 was filled, laboratory column leaching experiments were run on the scrubber byproduct proposed for the fill. Monitoring wells were located within 15 meters of the area to be filled and groundwater quality was followed for about a year before filling. Water from the upgradient monitor well was used as the leaching medium for the column experiments. Before any fill was placed in the field, a channel was dug at the bottom of the pit and perforated well pipe was laid in silica sand. The "drain" was piped to the surface as the pit was filled. This allowed leachate from the fill to be collected before significant attenuation in the environment. By knowing the source concentration and the down-gradient concentrations in the monitoring wells it is possible to calibrate the dispersivity in groundwater flow and contaminant transport models.

The water at the Forsythe site was of poor quality, though the pH of 6.7 could hardly be called acidic. TDS values were high. Iron ranged between about 100 and 350 ppm and manganese values were around 35 ppm. Other heavy metals were above class I water standards and many were above class II standards as well. One would suspect that the water quality had been degraded by the loose spoil material broken up by mining, though pre-mining groundwater quality is not known. and Southern Illinois groundwaters are often of poor quality with no human intervention. The column experiments

indicated calcium, potassium, sodium, boron, and molybdenum could potentially leach out of the material. Dissolved solids changed only slightly due to ion exchange since less mobile alkali metals like magnesium were removed from the water.

Contrary to popular fears of heavy metal contamination, the scrubber byproduct removed most of the iron and manganese from solution and a significant part of the trace metals such as lead, cadmium, and nickel, bringing most of these parameters into compliance with class I or class II groundwater limits. The slight increase in pH might be argued as a possible cause of iron removal by precipitation, but pH values around 8 could never have precipitated the manganese from solution. For manganese, and many of the other heavy metals, the removal is much more consistent with surface adsorption or incorporation into secondary mineral phases. Removal of manganese from degraded mine waters is difficult using conventional technologies. Manganese can only be precipitated out of solution by raising the pH to 10, but pH values above 9 constitute alkaline mine drainage. One cannot meet one standard without violating the other. The sulfite rich scrubber sludge at Forsythe appears capable both of cleaning manganese in both laboratory columns and in the field, where the results of the column experiments were mirrored almost exactly on all 24 elements analyzed.

The heavy metals cleaning potential of the scrubber sludge raises an interesting question in environmental values because the boron release from the material is significant and reached a high of 100 ppm in the field drain before falling off. Computer models indicate a leachate plume of around 100 acres that exceeded the 2 ppm class I groundwater standard for 20 years after the fill. Most boron concentrations are too low to cause salt damage to grasses commonly used in reclamation, but more sensitive cultivated plant species might suffer ill effects if the water from the plume was used for irrigation. Shake tests using pure water indicate that enough calcium can dissolve to cause hard water. One might certainly have reasons to avoid placing the scrubber byproduct in communication with high quality potable aquifers, but in mine settings with high TDS waters were toxic and heavy metals drainage is a problem a case could be made that the environmental enhancements far outweigh the risks.

In another experiment, 150 tons of FBC fly ash was introduced into a 2 million gallon pond of pH 2 mine water. Ordinarily, such an action would not be permitted since the conditions would be expected to release toxic and heavy metals from fly ash surfaces. The pond was carefully monitored during and following introduction of the ash. Obviously iron and aluminum precipitated as the pH rose, but the heavy and toxic metals concentrations fell around an order of magnitude. No heavy or toxic metals contamination was detected. The same result was observed for arsenic which can be mobilized by acidic conditions but solubility for arsenic reduces very little as water is neutralized. One might still hesitate to use FBC fly ash as an additive to ones daily cup of coffee but the experiment suggests that, for acidified mine waters that already contain heavy and toxic metals, the metals release by fly ash (if it exists at all) will be overpowered by effects related to neutralization of the water.

If combustion byproducts are used as a capping material there may not be enough leachate to create a groundwater plume. The well placed beneath the test embankment at Burning Star was intended to provide leachate source concentrations just like the drain at Forsythe. No such data has been obtained because there is too little water in the well to take a sample, even by lowering about a weighted 10 ml cup into the well. Lysimeters placed beneath the 7 acre cap at Thunderbird also have not been able to collect any leachate from the cap. It was possible to get a sample of infiltrating run-off water from an ash pile storage area during the winter. This sample had slightly elevated sodium and potassium levels, but no heavy or toxic metals could be detected. A network of sampling stations on a surface stream adjacent to the Thunderbird cap has been monitored for a year now with no detection of any contaminants, not even the sodium and potassium identified in infiltrating run-off. Some data collected in ongoing projects suggests that even boron, which leaches from many fly ashes, may be immobilized by cementitious reactions in designed mixes of combustion residue and mine material.

Fugitive dust may also be an issue in the use of some combustion residues, especially dry collected fly ash. For FBC fly ash, which is useful as an alkali chemical and as a soil cement, the fact

that the dust is caustic poses a special risk to individuals in close proximity. Similar risks are routinely accepted in mine reclamation or construction work involving code H lime and dry cement. For FBC fly ash, conventional dust control techniques like spraying with water tend to be ineffective. At the Thunderbird site, where the 7 acre cap was constructed, the highest dust levels resulted from water trucks spraying the ash to prevent dusting. Observations and dust measurements at Thunderbird indicate that significant reductions in fugitive dust can be achieved simply by arranging the order of construction operations to avoid tire contact with loose fly ash. A tarping method tested at Thunderbird resulted in essentially complete elimination of the dust cloud from frame-less dump unloading of fly ash. A practical field unloading system is being developed in an ICC1 research project this year. The project is also following through on methods of rendering fly ash non-dusty. Originally the system was intended for installation at the ash source, but large cost reductions may be possible by making this a mobile system for use in the field as well.

Finally, there are the concerns about lack of organic material in combustion residues. This concern would be most valid if combustion residues were used as a growth medium for plants. Most of the applications cited in this paper do not require the bulk material or chemical used to be a plant growth medium. Work done by the National Mined Land Reclamation Centers used sewerage sludge and fly ash as a plant growth medium without heavy metals uptake problems. Certainly other mixes of mine preparation wastes and combustion residues might be tailored and augmented to be suitable plant growth mediums if this were needed. Gypsum from force oxidized scrubbers is already a valuable plant nutrient, even though it is not organic. A force oxidized scrubber in Illinois produces a gypsum that is far more pure and free of trace metals than any commercially available natural gypsum.

### **Conclusions**

The existing practice of hauling coal combustion residues back to the mine site can be significantly enhanced to provide cost savings and environmental advantages both to boiler operators and to mines. Handling of combustion residues can be made a part of mine reclamation or even active mining operations reducing the need for separate land-filling operations and their associated costs. When combustion residues are hauled back to the mine they become a free delivered source of bulk chemicals that would be difficult for conventional manufactured reagents to challenge. Indeed, there are many times when Gob treatment or capping would be beneficial to the environment, but would be cost prohibitive if such quantities of manufactured reagents were purchased. In applications, such as FBC ash used in alkaline recharges, combustion residues are more effective than the conventional reagents commonly used. The environmental risks of water contamination or fugitive dust are either over-rated or manageable and are eclipsed by the environmental benefits that can be realized in most mine settings.

## COAL COMBUSTION RESIDUES AS SOIL AMENDMENTS: SURFACE COAL MINING

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### **Abstract**

Coal combustion by-products have received increased attention as possible soil amendments and/or as substitutes for normal agricultural amendments such as limestone and gypsum. However, there remain a number of concerns with their widespread use. These concerns include elevated trace element loadings to soils, especially for arsenic (As), selenium (Se), molybdenum (Mo), boron (B), and increases in soil soluble salts. Several issues such as determination of application rates, long term effects of induced calcium (Ca):magnesium (Mg) imbalances from application of high Ca by-products, and clarification of beneficial utilization versus disposal, need to be understood. This report will examine these current concerns and issues in regards to the use of conventional fly ashes, oxidized flue gas desulfurization (FGD) residues, and fluidized bed combustion (FBC) residues. The concept of co-utilization of by-products will be introduced and discussed as well as the need to consider cropping systems and site management in reclamation of surface mined areas.

### **Introduction**

This report addresses a number of topics important for the utilization of FGD, conventional fly ash, or FBC residues applied to soils with emphasis on surface mined areas. There are a number of review articles that detail the potential utilization and effects of coal combustion residue applications on the terrestrial ecosystem, [Adriano, et al. (1980) and El-Mogazi et al. (1988)], agriculture and horticulture, [Korcak (1995)], the environment in general, [Page et al. (1979), and Carlson and Adriano (1993)], and use in mine land reclamation [Haering and Daniels (1991)].

Unlike most agricultural soils, the extremely acidic nature of mined lands, resulting from oxidation of sulfur and sulfide, requires additions of alkaline materials to bring pH into the range where plants can grow and where trace element availability is controlled. Consequently the use of coal-fired power plant by-products, many of which are basic (FBC residues and Class C fly ash), can assist in moderating pH to the desired levels to reduce trace element availability. However, the use of alkaline fly ash and other coal combustion by-products with the addition of an organic material may provide a better environment for long-term revegetation of mined lands.

Since more is known about the potential use of coal combustion by-products on agricultural soils than surface mined lands, information is drawn from the agricultural utilization literature to help highlight problem areas and potential solutions.

### **Residue Characteristics Important for Land Use**

The soil/plant system requires a balanced nutritional media for revegetation. Coal combustion by-products can be a supplier of many of the nutrient needs of plants, either in whole or in part, with the exception of nitrogen and usually P. However, nutritional imbalances and excesses can occur. Regardless of whether by-products are being used for amendment of agricultural soils or for reclamation of mined lands, a number of by-products properties should be taken in account.

#### Ca:Mg Ratio

Application of FGD or FBC by-products, which usually originate from facilities using a

Ca-based sorbent, can create a Ca:Mg imbalance. This imbalance may induce a Mg deficiency in the plant species being established. Therefore, before an application is made, care must be taken to monitor both the Ca:Mg ratio of the material applied and of the unamended soil. Fortunately, Mg deficiency is usually easily corrected by a soil application of magnesium sulfate (Epsom salts) or by application of dolomitic limestone. Currently, research in Ohio and West Virginia is exploring the use of a Ca-rich FGD by-product plus a MgOH by-product (personal communication, R. Stehouwer and Dale Ritchey). This type of Ca and Mg mixture should help to alleviate the occurrence of Ca-induced imbalances.

Plant available potassium (K) may likewise be lowered due to the high soil Ca status after coal combustion by-product addition to soils.

The high levels of Ca, Fe (iron), and Al (aluminum) in some coal combustion by-products (including most ashes from western coals) may combine with soil phosphorous (P) to form insoluble complexes. These complexes reduce the availability of P to plants, which may result in an induced P deficiency. However, there may be situations where the formation of insoluble Ca-P (or Fe-P, or Al-P) complexes is desirable. For example, one of the limitations on land utilization of animal manures is the potential for P pollution of surface and sub-surface water supplies. The co-utilization of FBC ash (high in Ca) and animal manures is currently being examined (R. F. Korcak and W. L. Stout, unpublished data).

### Solution I

A program of yearly tissue monitoring should be established to assist in identifying plant nutrient imbalances. In the short-term, Ca:Mg imbalances may be of less concern (and can usually be easily corrected) in the revegetation of surface mined soils since the overwhelming problem is soil pH control and maintenance.

#### pH Effects

Because of the alkaline nature of many coal combustion by-products, a number of studies have examined their effect on modifying soil chemistry, primarily pH. The basic property used to quantify the effects of these by-products on soil pH is the  $\text{CaCO}_3$  equivalence of the materials. The neutralizing effect of pure  $\text{CaCO}_3$  is 100 percent and that of coal combustion by-products usually ranges from near 0 to 60 percent. Therefore, if a coal combustion by-product has a  $\text{CaCO}_3$  equivalence of 50 percent, twice as much coal combustion by-product as  $\text{CaCO}_3$  is needed to neutralize the same amount of soil acidity. FBC residues will most likely provide the highest amount of acid neutralizing power due to un-reacted sorbent while FGD materials, by their nature, will have very little, if any, neutralizing power. For fly ashes, Haering and Daniels (1991) provide a rule of thumb for determining their alkalinity: if the ratio of amorphous Fe to water-soluble Ca in a given ash is less than three, the ash will be alkaline.

A computerized automatic rapid weathering apparatus which predicts actual potential acidity and lime application rates for reclamation of coal wastes has been developed and tested (Gitt and Dollhopf, 1991). The use of this type of predictive model for calculating basic coal combustion residue application rates has not been reported.

Since successful modification of soil pH has been demonstrated with a wide range of coal combustion by-products, future agricultural applications of alkaline by-products will probably be based on soil pH modification. The situation with acid surface-mined soils is more complex. A one-time application of an alkaline by-product, at typical agricultural application rates (1 to 10 tons per acre), may not be effective in environments where pyrite is continuously oxidized.

Repeated application of FBC residue (about 3 tons per acre per year for 3 years) to reclaimed surfaced mined pastures resulted in no deleterious effects to forages or grazing lambs (Cochran et al., 1959). In controlled greenhouse studies, Stehouwer and Sutton (1992) amended acid (pH about 3.0) spoil

and underclay materials with alkaline Lime Injection Multi-Stage Burner FGD or pressurized FBC materials (pH range from 10 to 12) at rates up to 24% (by weight) and found increased plant survival and growth and successfully modified media pH. Similar studies in the field on acid mine spoils are currently underway in Ohio (personal communication, R. Stehouwer).

Plass and Capp (1974) amended an acid spoil with 150 tons per acre of an alkaline fly ash which raised the media pH from about 3 to 6 and increased available P. At such rates significant soil physical effects were noted, including higher subsurface water retention resulting from increased infiltration, soil porosity and percolation to a depth of 4 feet.

High application rates of coal combustion by-products can increase media pH, as noted above, and have positive effects on soil physical parameters; however, there are examples where excessive applications rates have been detrimental.

## **Solution II**

Formulas exist for predicting the amount of aglime to be applied to reclamation sites. However, with the exception of basing FBC application rates on calcium carbonate equivalency, these formulas have not been tried with basic coal combustion residues. Due to site variations, trial plots should be established to identify appropriate rates. One of the adverse reactions to high application rates of coal combustion by-products is elevation of soluble salts which can limit or narrow the choices for appropriate vegetation to be established.

### Soluble Salts

One of the major concerns with the agricultural or reclamation use of coal combustion by-products is the high soluble salt content of many materials. Most agricultural or reclamation application methods homogenize the applied ash into the surface which results in maximal seed contact. At high application rates, salt injury can occur to germinating seeds or established plants. The problem of high soluble salts may be alleviated in a number of ways. First, selection of by-products with low soluble salt contents. Because subbituminous and lignite coals tend to produce ashes with higher salt contents, they should be avoided.

There are a number of methodologies which may lessen the impact of soluble salts on revegetation. Surface application of coal combustion by-products followed by plowing or mixing may allow seed germination due to a dilution of the salts within the plow layer. A novel technique was used by Jacobs et al. (1991) where ash was banded into the soil at a 45° angle to the surface. These application methods tend to isolate the applied material from initial root contact. Additionally, the timing of application can have a significant impact on avoiding initial problems with soluble salts. Applying residues in the fall prior to plant establishment in the spring allows time for leaching a portion of the salts out of the root zone.

The occurrence of soluble salt problems can also be lessened if by-products are stockpiled and weathered before application rather than applied fresh. During weathering a substantial portion of the soluble salts are removed by percolation, and some of the oxides and hydroxides are stabilized by carbonation. Martens and Beahm, (1976) found that weathered ash could be used on corn at rates of up to about 70 tons per acre whereas salt-related problems with fresh ash occurred at about 45 tons per acre. Also the incidence of B toxicity (often related to the soluble salt problem) was lower with weathered ash because a relatively high percentage of the B in ash is usually soluble. Therefore, smaller amounts of water-soluble B will be applied to soils with weathered ash. The use of weathered materials also decreases the dust hazard associated with applying fresh, dry, coal combustion by-products because bonding and recrystallization during moist weathering reduces the proportion of small-size particles.

Soluble salt problems can also be circumvented by using FBC residues as a soil 'cap' wherein a

thick (5-cm) layer of FBC residue is surface-applied around the plant or within tree rows and not plowed or mixed with the soil (Korcak, 1988). Since the entire soil surface is not amended when this method is used for horticultural or forestry crops, it provides either sufficient soil mass for the roots to avoid contact with the initial flush of soluble salt or reduces this initial flush to levels that can be tolerated by crops. The 'cap' remains porous and acts as a one-way valve, allowing water to infiltrate, but decreasing evaporation from the surface.

The potential value of FBC soil 'caps' as well as selection of salt tolerant plant species will be discussed later in this report.

### Solution III

If required application rates will produce soluble salt problems, the easiest remedy is to use weathered materials or apply materials as far in advance of plant establishment as possible. As noted, one of the associated problems with soluble salts is B. Boron is one of several trace elements that have received attention as being either potentially phytotoxic or of concern due to bioaccumulation.

#### Trace Elements

Most reports on the use of coal combustion by-products in agriculture conclude that the most serious potential hazards stem from Se, As, Mo and B accumulation in soils and plants. However, coal combustion by-products, at times, can act as a supplementary source of Ca, S, B, Mo, Se, and other nutrient elements when soil concentrations are deficient for adequate plant growth. Determining the best rates for applying ash as a nutrient supplement is very site specific.

Selenium is not an essential element for higher plant growth, although it has been shown to be a required element for some lower plant species. However, Se is an essential element for animal growth. One problem with Se in animal nutrition is that it is needed only in very low concentrations; slightly higher concentrations cause Se toxicity. Recommended food and feed concentrations to provide adequate animal Se range from 0.1 to 1 mg Se kg<sup>-1</sup> plant material. Food and feed Se concentrations above 5 mg kg<sup>-1</sup> can cause animal Se toxicity (Mengel and Kirkby, 1987). It is estimated that one-third of the forage and grain crops in the United States contain below-optimal levels of Se for animal nutrition (Mengel and Kirkby, 1987). Mbagwu (1983) showed that fly ash could be used as a soil amendment to increase forage Se concentration on low-Se soils. Increased Se in corn from seleniferous fly ash in New York (Combs et al., 1980) was used to replace supplemental Se added to poultry feed diets.

Arsenic is not essential to either plants or animals. Arsenic in the oxidized form (arsenate) may be bound by the soil clay fraction or with iron oxides. There also exists a strong soil/plant As-P interaction. Added P interferes with As uptake at the plant root and P may aid in moving As downward in the soil profile. Generally, As has not been included in the analytical data presented by many researchers in the past. It appears that As will gain added attention as an environmental contaminant in the near future.

Molybdenum is an essential element for both plants and animals and its availability in soils increases with soil pH. As with Se, the concern with Mo is that the optimal concentration range in animals is narrow and any substantial increase in plants may result in imbalances or toxicities in animals. Plant tissue Mo concentration ranges of 10 to 20 mg kg<sup>-1</sup> (dry weight basis) have been associated with adverse effects on animals therefore monitoring of plant tissue Mo should be included in any management plan (Elsewji and Page, 1984).

Boron, like Mo, is an essential element for plants and animals. Plant species vary in their ability to tolerate high levels of available soil B. In some regions, such as the dairy farm areas of New York, B is added to commercial fertilizer for use on high-B requiring crops like alfalfa.

As noted, coal combustion by-product can be used in agriculture to supplement crops and soils low in Se, Mo, Cu, Zn or B (Adriano et al., 1980 and El-Mogazi et al., 1988). The application of by-products should be based on crop needs and current soil levels of the particular nutrient. Additional studies are needed to define mineralogy, solubilities, chemical speciation, uptake rates, and plant responses in order to calculate optimum application rates for soil application of ashes.

#### Solution IV

There are many reports in the literature that do not provide soil, plant or environment assessments of these four (Se, As, Mo, B) potentially hazardous elements. It is strongly recommended that any revegetation plan include analytical determinations of these elements to assess bioaccumulation potential.

#### Ca-Sulfate vs. Ca-Sulfite

Gypsum has been an agricultural soil amendment for over 200 years and the list of benefits to soils and plants is lengthy (Shainberg et al., 1989; Wallace, 1994). In the past, flue gas desulfurization sludges have received little attention as agricultural or reclamation amendments. However, our knowledge of FGD-derived  $\text{CaSO}_4$  and  $\text{CaSO}_3$  is increasing due primarily to the research being performed in Ohio (e.g. Stehouwer and Sutton, 1992) and West Virginia (e.g. Ritchey et al. 1994 and Clark et al. 1995).

Among the agricultural benefits of FGD- $\text{CaCO}_3$  application to soils is the potential for decreasing problems associated with subsurface soil acidity and increasing plant rooting depth and drought tolerance. These are equally important effects for the reclamation of surface mined soils. Additionally, the application of gypsum to mined areas may aid in reducing phytotoxic effects of Al under acidic conditions as well as aid in reducing plant uptake of ash-derived Se (Arthur et al., 1993). The effect appears to be due to a competitive interaction between Se and S.

Unoxidized FGD scrubber sludges, predominantly  $\text{CaSO}_3$ , will require more careful monitoring. When mixed with acid soils,  $\text{CaSO}_3$  decomposes to form  $\text{SO}_2$  (toxic to plants) and oxidizes to  $\text{CaSO}_4$  (Ritchey et al. 1995). Sulfur dioxide formation is favored at low soil pH. Since conversion to  $\text{CaSO}_4$  can be relatively rapid, FGD-derived  $\text{CaSO}_3$  may be applied to lands in advance of plant establishment to avoid any phytotoxic responses (e.g. fall or winter application followed by plant establishment in the spring).

Some scrubber sludges contain significant amounts of fly ash, which is often added at the end of the waste stream to aid in stabilization of the slurry (Terman 1978). Under these conditions, the amount and composition of the added ash should be determined prior to utilizing the scrubber sludge.

Gissel-Nielsen and Bertelsen (1988) evaluated a number of FGD products in trials with barley. One of these contained 10 percent sulfite, 24 percent sulfate, 8 percent fly ash, and 0.5 percent nitrate. Although not noted, the high amount of sulfate present apparently indicated some oxidation of the material. Plant Se concentrations were increased from 0.05 mg  $\text{kg}^{-1}$  (the level of the control) to 0.18 mg  $\text{kg}^{-1}$  at the highest application rate. Plant Se at the highest FGD rate (0.5 percent by weight) should provide an adequate level of Se for animal nutrition.

Ransome and Dowdy (1987) used scrubber sludge containing 4.1 g B  $\text{kg}^{-1}$  as a B source to correct a B deficiency on a loamy sand soil. Although soybean yields were decreased during the first application year from rates of about 5, 10, and 20 tons per acre because of elevated salt content, yields were enhanced by scrubber sludge at all rates by the third year. Adequate soil B for soybean growth was achieved with the 10 tons per acre application rate. The type of scrubber sludge, whether oxidized or not, was not indicated.

Gypsum has also been used for the correction of sodic (high sodium) soil problems. The many benefits of gypsum for both soil chemical and physical improvement indicate that significantly more gypsum can be used to assist in revegetation of surface mined lands.

### Solution V

The use of FGD-CaSO<sub>4</sub> in the reclamation of surface mined spoils will probably increase as research findings showing beneficial effects on revegetation establishment and longevity accumulate.

#### Auulication Criteria

*Beneficial Use vs Disposal:* To justify its use, any amendment to the soil- plant system must clearly benefit the environment (soil, water or air) and the plant. These benefits must exceed the costs and potential hazards whether one is applying fertilizer, organic mulch, irrigation, or an industrial by-product. Potential benefits and hazards from the agricultural or reclamation use of various coal combustion by-products have been noted above. If the application of a particular by-product enhances plant establishment or growth a beneficial use can be established. Lacking an identifiable beneficial use, application of materials to lands is disposal.

*Application Rates:* For the agricultural utilization of FBC residues, a manual for determining application rates is available (Stout et al., 1988). Although this manual does not include reclamation of surface mined lands, it should prove useful as a starting point. The manual is modeled after the USEPA guidelines for sewage sludge application to agricultural soils. A schematic flow diagram allows the user to determine how much FBC should be surface applied for a given soil.

However, there are no known manuals or tables that can be referenced as guides for determining land application rates for any other coal combustion residue, including gypsiferous FGD. Where needed, gypsum is usually applied to agricultural soils at rates not exceeding 10 tons per acre. However, a number of 'quick' tests and laboratory procedures for determining responses from the application of gypsiferous materials are under investigation (personal communication, K. Ritchey).

### Solution VI

When considering coal combustion residues, it is suggested that a flow diagram similar to that in the above cited FBC manual (Stout et al., 1988) be followed. Additionally, the chemical composition, inclusive of trace element assays, pH, total salts, and lime equivalency, of the residue to be applied and the recipient soils should be determined. These types of analytical results will work well when a single residue is applied. However, if more than one type of material is to be used for remediation purposes, other parameters have to be considered.

#### The Future

*The Concept of Co- Utilization:* Co-utilization is the composting, blending or mixing of two or more waste products in order to produce a new by-product that has enhanced economic value or fulfills a predetermined need (e.g. designed to correct a known nutrient deficiency or aid in remediating a potential phytotoxicity). An example of co-utilization is the work reported by Beeghly et al. (1992). They successfully mixed sewage sludge and LIMB ash to produce a soil-like product. The LIMB ash was used successfully as the alkaline reagent to pasteurize and dewater sewage sludge. Similarly, Logan (1992) reported that a soil product made from sewage sludge and cement kiln dust was as effective as lime and fertilizer when applied to acidic mine spoils.

Additionally, there have been reports on applying coal combustion by-products and sewage sludges, but not necessarily as a premixed product (Korcak, 1980; Stehouwer and Sutton, 1992). Others have found beneficial responses in crops grown on soils from amending manure or sewage sludge

compost with fly ash (Adriano et al., 1982; Garau et al., 1991; Menon et al., 1992; Ghuman et al., 1994) and amending bottom ash with compost made from grape marc and cattle manure (Chen et al., 1991).

Pietz et al. (1989) studied the use of lime and sewage sludge for amending acidic coal refuse materials. They suggest that for long-term revegetation (greater than 5 years) rates of about 300 tons per acre of sewage sludge and about 50 tons per acre lime should be initially applied. Lower initial application rates usually require additional applications over time. However, these types of high application rates need to be considered in relation to plant N requirement to avoid elevating nitrate leaching.

It should be noted that sewage sludges are usually lacking in sufficient plant K particularly for long-term plant establishment. Supplemental K should be provided either from a synthetic fertilizer source or from the incorporation of an additional by-product (e.g. waste rice hulls contain a high level of K and have been used as a K-supplement).

One of the benefits of blending an organic material with an alkaline material such as fly ash or FBC is the maintenance of a higher pH with concomitant reduction in heavy metal availability. This effect was noted by Pietz et al. (1989) from adding sewage sludge and lime to acidic coal refuse material.

Beaver (1995) recently reported on the co-composting of separated cow manure with up to 32% fly ash (calculated on a dry weight basis). The initial pH of the ash was 11.6. However, the final composted product had a pH of about 8.6, which is normal for most composted materials.

Another benefit of co-utilization of coal combustion by-products with an organic material is the addition of N and P to the revegetation area. More importantly, the N applied is in a more stable (slow-release) form.

Co-utilization, by definition, should result in products that can assist in meeting the nutritional requirements of plants as well as alleviate the adverse growing conditions present at reclamation sites.

*Cropping Systems and Site Management:* Crop selection can have a significant effect on the success of revegetation activities. Sims et al. (1993) screened several crop species for revegetation of fly ash landfills. Hairy vetch, red clover, and tall fescue performed the best, however, when the ash was amended with a co-compost made from municipal refuse and sewage sludge, lespedeza and a fescue-lespedeza mixture showed better early growth. Similarly, Carlson and Adriano (1991) recommended planting a number of tree species on abandoned ash basins to be able to assess metal toxicities or deficiencies for a particular site.

It is difficult to predetermine the type of vegetation to recommend for a particular revegetation site. Two of the most important initial factors will probably be matching salt tolerance of the plant species to be planted with the by-product and meeting nutritional needs of the plant while avoiding weed competition. Carlson and Adriano (1993) note a number of plant species that are salt tolerant and local extension personnel will probably also be helpful in recommending specific cultivars to be established.

The other persistent problem particularly with tree establishment is competition from weeds. One option to eliminate herbicide use would be to utilize FBC residues as a post-planting 'cap' around the tree. This may help to eliminate or reduce weed competition for up to 2 to 3 years.

### **Summary and Recommendations**

Potential benefits from coal combustion by-products include alleviation of soil trace elemental deficiencies, modification of soil pH, and improvement of calcium and sulfur, infiltration rates, depth of rooting, and drought tolerance. Flue gas desulfurization products and residues from fluidized bed combustion which contain appreciable amounts of gypsum appear to have particularly high potentials for improving water use efficiency, product quality and productivity of soil-crop systems.

The existing literature on utilization of coal combustion by-products needs to be expanded to include data from long-term exposure of these materials in the soil environment. Potential sites for examination exist. Additionally, researchers should evaluate the potential utilization of by-products resulting from new Clean Air technologies as they are developed. These studies should also address innovative strategies for application and clear documentation of potential benefits.

Documentation of hazards involved and benefits derived, especially from field studies, will be required to reduce present regulatory barriers to utilization of coal combustion by-products either used alone or co-utilized with other wastes. On-site disposal may result in environmentally hazardous concentrations of certain elements in water supplies and the food chain.

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**PUBLIC CONCERNS  
REGARDING THE MANAGEMENT OF COAL COMBUSTION WASTES**

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**Introduction**

Your perspective is changed when you are the landowner next to an operation that is proposing to dispose of coal combustion waste, or you are a person who will be drinking ground water that may be affected by disposal practices. The disposal of coal combustion wastes at surface coal mines is a serious issue for **90** percent of Kentuckians who live in rural areas and rely on ground water as their sole source of drinking water. This is an issue that needs to be approached in a serious and judicious manner. It needs to address the concerns of neighbors in a compassionate, understanding, and responsible manner. This is not a responsibility that is framed by the 2 year post closure care period that typically attends special waste landfills, or one that is framed by the 5 year liability period of surface mining performance bonds. Rather, it should be a responsibility that understands that our knowledge of the fate, partitioning, and transport of metals in the environment over the long term is limited. We need to thoroughly understand what it is we intend to do with these wastes, before we dispose of them in the environment where they will remain a potential concern long after the persons responsible for the disposal will be gone.

I will be speaking as a representative of neighbors. There are significant concerns that have been voiced in Kentucky regarding the disposal of coal combustion wastes. We have not had a lot of disposal of coal combustion wastes at mine sites. The reason for this is that the utilities in Kentucky will not release their ash to be managed by any third party. They understand that there are liabilities associated with the management of these wastes. They do not want it mixed with other wastes or disposed of at mine sites where they do not have the ultimate control over the management of that disposal process resulting in an open ended disposal liability. This is not the case, however, for utilities from other States. Representatives of the coal industry have sought changes in the Kentucky law during the 1994 legislative session which would facilitate the disposal of wastes at mine sites. This was done to create a competitive advantage so that they could provide a full service of hauling coal to the utilities and returning with the waste.

**Specific Concerns**

Why are we concerned about coal combustion wastes? You look at the literature and it indicates that the wastes do not typically leach metals at hazardous concentrations. If you understand the definition of hazardous under the Resource Conservation and Recovery Act (RCRA), you see that there is a range of potential concern. The range is from the innocuous, completely inert, or insoluble wastes to wastes that leach metals at 100 times the public drinking water standard. The waste becomes hazardous if it exceeds 100 times the drinking water standard. I think that any of us would be concerned if we were drinking water that contained heavy metals at concentrations up to 100 times the drinking water standard. What we should be looking for, when we dispose of these wastes, is to insure that there is no leaching of any constituents of concern, be they organics or heavy metals into the ground water where they may contaminate someone's drinking water.

The question of how to manage coal combustion wastes (CCW) under the Surface Mining Reclamation and Control Act of 1977 (SMCRA) is an open question. It is open because, in large part, the Office of Surface Mining has not historically addressed such issues with the specificity that such an issue deserves. The fact that we are all here talking about the issue is a statement that there are concerns about proper management and beneficial use of coal combustion wastes. I would suggest that the Office of

Surface Mining has a responsibility to move forward in establishing some basic benchmarks in how we manage these wastes on surface coal mines.

Why are we concerned about these wastes? The US EPA assessment of coal combustion wastes in its report to Congress under RCRA stated that these wastes did not need to be managed as hazardous wastes provided that they were properly managed as solid or special wastes. This disposal should be mitigated as appropriate with the installation of liners, leachate collection systems, ground water monitoring, and corrective actions as necessary to clean up the ground water.

A study of CCW in Indiana (Boulding, 1991) indicated that CCW does contain high enough concentrations of leachable toxic elements to create environmental concern. Characterization of the wastes is extremely important. Significant findings of the report by Boulding were that: (1) neither TCLP nor extraction procedure provide a complete assessment of the leaching potential of the wastes. Long term leaching tests, conducted until equilibrium has been achieved for each element of concern, using a leaching solution that simulates natural groundwater, would give a more accurate depiction of potential groundwater contamination; (2) there are 17 potentially toxic elements have been found in CCW including: aluminum; antimony; arsenic; barium; beryllium; boron; cadmium; chromium; copper; lead; manganese; mercury; molybdenum; nickel; selenium; vanadium; and zinc; (3) fluidized bed combustion wastes retain volatile and semi-volatile elements in the bottom ash to a greater extent than conventional CCW, thus enhancing the leachability of these elements; (4) leachates from CCW typically exceed drinking water standards, but by less than hazardous levels. CCW leachate typically exceed the standard by 1.1 to 10 times and often by more than 10 times for one or more element; (5) disposal of CCW in coal mines may be of particular concern, due to the increase in surface area available for leaching elements resulting from the fracturing of layers of overburden. There is also the potential for the higher total dissolved solids in mine spoils to compete for sorption sites with toxic elements released by CCW.

The US EPA report and the Boulding study indicate that the management of special wastes must be attuned to the specific concentrations of potentially toxic elements in CCW, the specific characteristics of the disposal site, and the specific type of CCW. Other reports indicate a concern with enhanced levels of radio nuclides, including radium-226 and other daughters of uranium and thorium, that could pose significant long term management challenges. A summary of studies on ground water contamination potentially associated with CCW disposal is provided at the end of this report.

### **Principles For Responsible CCW Management**

A principle that should apply to the management of disposal of these materials is that it is irresponsible to place these materials where ground or surface water can be contaminated by leachate from the wastes. There is a great variability in the geohydrology across the coal fields. In eastern Kentucky, we have a ground water regime that is characterized by secondary permeability or fracture flow such that any contaminants would be leached into the shallow ground water system where most people get their drinking water. In western Kentucky, there is an isolation from mining areas and ground water used as a source of drinking water. These have different management concerns related to disposal sites.

The standards governing management of CCW should differentiate at least three categories of CCW that will be managed under greater scrutiny, including individual permits for any disposal or reuse. These categories include: (1) FBC waste which, as noted in the Boulding report, presents a higher potential for leaching elements of concern; (2) CCW generated through the firing of hazardous waste fuels and waste oils; and (3) CCW co-fired with waste tires and refuse-derived fuels. Each of these categories adds constituents to the combustion which may significantly increase the hazards of improper disposal, including a range of products of incomplete combustion of chlorinated and other synthetic organic compounds that warrant extensive analysis and careful management beyond that necessary with CCW alone.

Clarification should be provided that CCW should not include utility wastes such as metal and boiler cleaning waste nor other wastes generated at power plants beyond those directly resulting from combustion and control of emissions from the combustion process.

CCW will potentially be of concern for far longer than the post closure liability period for the disposal area. Long term fate, transport, and partitioning of the wastes need to be understood in the planning and characterization process.

The potentially affected landowners need to be notified and involved in the decision making process. The rights of landowners and users of water in these areas are paramount.

### **Potential Radioactivity**

There is an Oak Ridge National Laboratory report that addressed the issue of radio nuclides in terms of emissions from utilities and in the resulting ash. This needs to be assessed in the waste characterization and management process. We tend to manage radioactivity in a very uneven fashion depending upon its source. Radioactive materials need to be properly managed and disposed of, if it is a concern. It is especially important that we do not contaminate soil materials with radioactive wastes.

All CCW should be screened for radio nuclides and managed as low-level radioactive wastes in accordance with the applicable State and Federal laws, where such wastes exhibit activity that is above background. Protocols for the characterization of CCW for elevated radio nuclides and management of wastes with enhanced radioactivity must recognize the inadequacy of traditional solid waste management tools for disposal. Protocols that should be adopted by agencies for evaluation of applications for disposal of CCW that contain elevated radio nuclides (and are properly classified as technologically-enhanced low-level radioactive waste) include: (1) complete characterization of waste composition and chemistry based on actual samples measured for Ra 226 and daughters (i.e. Lead 210), specific radium analysis, and gamma spectroscopy. Leachate analysis should use actual leachate from the proposed facility where possible, and TCLP or other appropriate leaching tests; (2) a fate and transport analysis including a multi-path risk assessment; (3) a "cap" on the radioactivity of waste allowed for disposal at other than a commercial LLRW disposal facility, with an upper-bound limit on activity associated with the material established, as necessary, to satisfy the most restrictive pathway (which will likely be the drinking water at 4 mrem/yr) and which in no instance should exceed 15 mrem (consistent with NRC proposed standards); (4) the measurement of activity must be based on representative sampling, with higher activity wastes and hot spots managed separately. No dilution of clean waste or soil to lower the activity levels prior to disposal should be allowed; (5) management of wastes with lower volumes and higher activity, such as scale, or equipment, should be handled through licensed low-level radioactive waste storage/disposal facilities. Any equipment with micro R readings above twice the background level should be sent to a licensed commercial facility; (6) wastes to be disposed of at a solid waste landfill or mine-site should first be stabilized and containerized in order to minimize air emissions during handling and to provide a primary barrier allowing some decay of the material prior to loss of primary containment; (7) disposal in a solid waste landfill must be in a separate constructed cell with secondary containment, grouted in place, and controlled with separate leachate collection system; (8) long term cap maintenance and groundwater monitoring after the end of post-closure monitoring and care period (30 year plus corrective action period for landfills, 5 years after reclamation for minesites) through perpetual care, funded by owner/operator/disposer, and managed by the State and local government; (9) approval by the landowner and local government for disposal of the material. A public comment period should be provided with a requirement for approval for any new waste stream from a particular facility. All proposals should be subject to major modification review.

## **The Role of the Office of Surface Mining**

OSM has a responsibility to do more than has been done in assuring that these wastes will be properly characterized and managed For potential environmental concerns. Currently, the disposal of non-coal mine waste is required to be placed in a controlled manner and isolated from water. Beyond that there has been an absence of Federal guidance. This has resulted in increased conflict in enforcement related to disposal activities. It produces one downs-man-ship that the States have engaged in concerning environmental quality and the regulation of coal mining. This was the pattern that characterized the early 1960s and 1970s before the Federal law was passed. In Kentucky, during the 1994 legislative session, we were faced with an argument that Kentucky should take a minimalist approach to CCW because other States had done so. Because of the significant concern by the Kentucky legislature, we were able to avoid that type of approach. I feel that we have a very responsible approach in Kentucky that characterizes the waste and collects extensive background data in order to determine if there are changes in the prevailing hydrologic balance. Additional requirements concern the design and placement of CCW in the disposal facility in order to isolate them from potential leachate contact with water.

### **Conclusion**

In conclusion, I would like to take a quote from Dr. Hassett, in the context of testing CCW, and apply it to the entire management of CCWs. He said, "disposal is forever, and if scientifically valid conclusions are to be made concerning the potential for environmental impact of disposed materials, then valid tests must be performed." I would simply add that once valid tests are performed, responsible measured should be developed to address whatever concerns arise from that valid testing. Responsibility for the disposal should be commensurate with the potential risks posed by the material.

DOCUMENTED CASES OF GROUND-WATER CONTAMINATION FROM DISPOSAL OF  
COAL COMBUSTION WASTE

Arthur D. Little, Inc. 1985. Full-Scale Field Evaluation of Waste disposal From Coal-Fired Electric Generating Plants. EPA-600-7-85-028 (EPA Contract #68-02-3167). [Summary information obtained from Appendix E to U.S. EPA, 1968]

Evaluation of coal ash and flue gas desulfurization (FGD) waste disposal practices at 6 power plants:

1. The Allen Plant in North Carolina shows elevated levels of trace elements in ground water downgradient for unlined ash disposal ponds. Arsenic (up to 31 times) and cadmium (up to 5 times) exceeded primary drinking water standards (PDWS) in the ash ponds. Water samples obtained from under the active pond exceeded secondary drinking water standards (SDWS) for iron and manganese (up to 90 and 280 times respectively) whereas ponds liquor samples did not indicating that pond leachate was mobilizing iron and manganese from the soil beneath. Downgradient monitoring wells exceeded PDWS for iron and manganese up to 82 and 102 times. Downgradient contamination had not reached steady-state concentrations with respect to mixing of leachate generated by the ponds and ground-water and it was expected that further degradation would in downgradient wells.
2. The Elrama plant in western Pennsylvania disposes of a fixed FGD sludge-fly ash mixture on coal mine spoils and river alluvium. Leachate collected beneath and within the wastes found that arsenic exceeded PDWS by 3 to 5 times. Cadmium exceeded PDWS by up to 20 times in both water in and under the waste and in downgradient monitoring wells. It was difficult to separate effects of contamination from acid mine drainage and ash disposal, but the cadmium contamination was considered to probably be from the ash. Again, steady state concentrations from ash leachate did not appear to have been reached at the monitoring wells so the effects from the leachate were expected to increase with time.
3. The Dave Johnston plant in Wyoming disposes of ash in two unlined landfills. Cadmium exceeded PDWS, and molybdenum and sulfate exceeded SDWS in ground water beneath the waste and in pond liquors. Concentrations of boron were also elevated. Chemical attenuation by soils at the site was found to be low for trace metals such as arsenic. Actual impacts on groundwater were difficult to determine because of the presence of other waste disposal sites and naturally high mineralization in the ground water.
4. The Sherbourne County Plant in central Minnesota disposed of fly ash and FGD waste in one day-lined pond and bottom ash in an adjacent clay-lined pond. Pond liquors contained chromium up to 16 times the PDWS and downgradient ground-water exceeded the PDWS by 1.2, whereas upgradient samples did not. Sulfate and boron had apparently migrated from the waste into ground-water, but did not exceed SDWS. Steady state conditions had not been achieved between the leachate and the ground water so continued increase in trace element concentrations was expected. The surrounding soils did not effectively attenuate selenium and exceedance of PDWS for this element was considered possible when steady state conditions were achieved.
5. The Powerton Plant disposed fly ash, bottom ash and slag in a landfill, part of which was underlain by a liner consisting of ash and lime. Downgradient wells exceeded PDWS for cadmium up to 3 times, and SDWS for iron, manganese, and sulfate. Concentrations of these elements in downgradient wells was significantly higher than in upgradient wells. Dilution and chemical attenuation may have prevented significant downgradient concentrations of arsenic and selenium.

6. The Lansing Smith plant in southern Florida disposed of a mixture of fly ash and bottom ash in an unlined disposal pond located in a coastal area. Cadmium (up to 5 times PDWS) and chromium (up to 4 times PDWS) were measured in the downgradient groundwater. The impact on groundwater quality was considered to be measurable, but since the leachate migrates into a shallow, unused tidal aquifer health risks were considered to be minimal.

Boulding, J.R. 1992. Disposal of Coal Combustion Waste in Indiana: An Analysis of Technical and Regulatory Issues. Final Report March 31, 1992, Prepared for Hoosier Environmental Council. Indianapolis, IN, 104 pp. [Summarized from Appendix C.3]

Downgradient monitoring well data from the Peabody Universal Mine in Indiana where coal fly ash was being backfilled without a liner showed that average concentrations exceeded PDWS for selenium by almost a factor of 2, and that average concentrations of arsenic, cadmium, and lead were right at PDWS. Average concentration of total dissolved solids, molybdenum and nickel, and possibly barium exceeded SDWS. This contamination was coming from ash that was relatively benign based on analysis of laboratory leaching test on 50 samples of coal combustion waste from coal mined in Indiana.

Cherkauer, D.S. 1980. The Effect of Fly Ash Disposal on a Shallow Ground-Water System. Ground Water 18(6):544-550.

The Cedarsauk site, a fly ash landfill in southwestern Wisconsin is located in an abandoned sand and gravel pit. After eight years of disposal the contaminant plume apparently stabilized about 200 meters downgradient of the disposal site. No exceedance of RDWS were observed, but SDWS were exceeded for iron, manganese, total dissolved solids and sulfates. Neutralization of the acidic ash probably served to precipitate many of the trace metals in the leachate.

Dames and Moore. 1982. Review of Existing Literature and Published Data to Determine if Proven Documented Cases of Danger to Human Health and the Environment Exist as a Result of Disposal of Fossil Fuel Combustion Waste. In: Report and Technical Studies on the Disposal and Utilization of Fossil Fuel By-Products. Utility Solid Wastes Activities Group, Appendix II. [Cited in U.S. EPA, 1988]

Leaching from two fly ash disposal ponds at the Michigan City site in northern Indiana near Lake Michigan, resulted in downgradient concentrations of arsenic exceeding PDWS with one observation by more than 100 times the standard. Lead also was observed to exceed PDWS downgradient by as much as 7 times, but upgradient wells also exceeded the PDWS for lead by as much as 3 times. A steel slurry wall installed between the site and Lake Michigan was intended to keep contaminated groundwater from reaching the lake.

Environosphere. 1979. Environmental Effects of Utility Solid Waste Disposal. Prepared for Utility Solid Waste Activities Group and Edison Electric Institute. [Cited in U.S. EPA, 1988]

Environosphere (1982) analyzed paired upgradient-downgradient ground-water observations at 25 disposal sites in the U.S. Out of 4079 total observations, 128 downgradient observations (3.1%) exceeded PDWS when the upgradient well did not. In addition 122 downgradient observations (3.0%) exceeded PDWS while at the same time upgradient observations also exceeded PDWS. Apparently no attempt was made to analyze the extent to which downgradient concentrations were higher than upgradient but still below PDWS, which is the typical situation judging from the more detailed site specific studies by A.D. Little, Inc. (1985). Furthermore, apparently no attempt was made to distinguish between observations where both upgradient and downgradient concentrations exceeded the PDWS but the downgradient was still higher than the upgradient concentration. Cadmium most frequently exceeded PDWS (10% of observations) followed by lead (5%) and chromium (3%). It is interesting that the combined percentage

of downgradient wells exceeding PDWS (6.1%) is not far from the 7.4% in the Franklin Associates (1984) study. This indicates the perhaps half of the observations in the study could be considered to be definitely caused by ash leachate with the other half possibly caused, but less certain.

A similar analysis of SDWS constituents found that downgradient wells exceeded the standards in 681 out of 4728 observations (14.4%) and an additional 875 observations indicated exceedance both upgradient and downgradient (185%). Downgradient, manganese most frequently exceeded the SDWS when the upgradient did not (32% of observations), followed by sulfate (28%), and total dissolved solids (18%).

Given the observations in the ADL study (Arthur D. Little, 1985) that steady-state conditions had not been achieved at any of the sites studied, it would appear that in the long run the frequency of observed exceedance of drinking water standards will be higher than indicated by this study.

Also at an unspecified location in Indiana, leaching from two large, unlined ash disposal ponds resulted in downgradient concentrations of arsenic and lead about 2 times PDWS and about 4 times PDWS for selenium.

Franklin Associates, Ltd. 1984. Survey of Groundwater Contamination Cases at Coal Combustion Waste Disposal Sites. Prepared for U.S. Environmental Protection Agency. [Cited in U.S. EPA, 1988; no document number given]

This study analyzed water quality data from 4700 wells in the vicinity of ash disposal sites at 66 sites in 13 states. PDWS were exceeded in 1129 cases out of 15,000 observations (7.4% of total). Ninety two percent of the exceedances were less than 10 times the PDWS and 8 exceedances were more than 100 times the PDWS (cadmium, lead, mercury and selenium). There were 5952 exceedances of SDWS (29.9%). Unfortunately this study made no attempt to distinguish between upgradient and downgradient wells. It only makes sense, however, that an undetermined number of the exceedances can be attributed to contamination from ash disposal.

Given the observations in the ADL study (Arthur D. Little, 1985) that steady-state conditions had not been achieved at any of the sites studied, it would appear that in the long run the frequency of observed exceedance of drinking water standards will be higher than indicated by this study.

Groenewold, G.E. and B.W. Rehm. 1981. Applicability of Column Leaching Data to the Design of Fly Ash and FCD Waste Disposal Silts in Surface-Mined Areas. In: Proceedings of the Low-Rank Coal Technology Development Workshop. DOE/ET/17086-1932 CONF-81006235, pp. 3-79 to 3-95.

This study reports on monitoring of the ash disposed at the Center site in North Dakota. Natural background levels of sulfate, iron and manganese all may exceed SDWS at the site. No PDWS constituents were exceeded in natural background levels. Groundwater samples in the area influenced by the ash disposal showed concentrations of arsenic as much as 12 times PDWS and of selenium as much as 80 times the PDWS. While natural sulfate levels exceeded SDWS by a factor of 2 to 4, in the vicinity of the ash disposal the concentrations ranged from 22 to 211 times the SDWS. The maximum concentration of iron near the disposal site was 8.6 times the SDWS (compared to a natural maximum exceedance of 43 times. Maximum exceedance of SDWS by manganese increased from 55 times SDWS (natural) to 130 times near the ash disposal site. The chemistry of lignite ash, and spoils in North Dakota are very different from coal ash and spoils in Indiana, so the results are not directly relevant. However, it is not encouraging that the one study where good data are available on the ground-water impacts of ash disposal at a coal mine indicate clear evidence of significant deterioration of ground-water quality.

Gschwend, P.M., DA. Backhus, J.K. MacFarlane, and A.L. Page. 1990. Mobilization of Colloids in Groundwater Due to Infiltration of Water at a Coal Ash Disposal Site. J. Contaminant Hydrology 63-7-320.

This study reports a significant discovery while studying a plant ash disposal site in the western U.S. They found that silicate colloid particles in ground-water samples taken from near the ash disposal site had been released by the dissolution of secondary carbonate minerals by water percolating through the ash. These particles are small enough to move in suspension through pore spaces in the aquifer and may serve as a means to transport toxic elements that are sorbed to the particle surfaces. Normally suspended colloids are filtered out before ground-water samples are analyzed, because they are assumed to be local aquifer material. There is no way of knowing how commonly the phenomena observed by Gschwend et al. (1990) exists, but conventional ground-water sampling methods will fail to detect contaminants that move through aquifers by this mechanism.

Hardy, M.A. 1981. Effects of Coal Fly-Ash Disposal on Water Quality in and Around the Indiana Dunes National Lakeshore, Indiana. U.S. Geological Survey Water-Resources Investigations Report 81-16. [Cited in U.S. EPA, 1988]

At the Baily site, near Indiana Dunes National Lakeshore, fly ash is slurried into interim settling ponds which are periodically drained and the drained ash disposed in an on-site pit. Maximum downgradient concentrations of arsenic was 4.6 times PDWS, whereas arsenic never exceeded PDWS in upgradient wells. Aluminum, boron, iron, manganese, molybdenum, nickel, strontium and zinc all increased in concentration downgradient from the disposal area, but not in levels exceeding PDWS.

Rai, D. and J.M. Zachara. 1989. Field Investigation of a Flue Gas Desulfurization (FGD) Sludge Disposal Site. EPRI U-5923. Electric Power Research Institute, Palo Alto, CA.

This study provides detailed data on the chemistry of pore water (pH range 6.7 to 8.2) in a FGD sludge basin at an unspecified disposal site in the Midwest. Concentrations of boron, manganese, and sulfate exceeded SDWS in pore waters. Only boron was stated in the study to have penetrated to a maximum depth of 1.5 meters into the soil below the basin. However, data in the report indicates that manganese and sulfate had also migrated into the soil pore waters. This study notes that reducing conditions in the sludge basin immobilized many toxic metals through sulfide precipitation reactions, but that these might be remobilized if drying should create oxidizing conditions in the future.

U.S. Environmental Protection Agency (EPA). 1988. Report to Congress: Waste from the Combustion of Coal by Electric Utility Power Plants. EPA/530-SW-88-002.

Where indicated, information on reports summarized above are derived from this report

**Session VI:**  
**MONITORING AND EVALUATION**

**Session Chairs:**

**Dr. Steve Esling**  
**Department of Geology**  
**Southern Illinois University at Carbondale**

**Bill Joseph**  
**Office of Surface Mining**  
**Alton, Illinois**

**Panelist:**

**Jeffery Stant**  
**Hoosier Environmental Council**  
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# COAL COMBUSTION BY-PRODUCTS AND CONTAMINANT TRANSPORT IN GROUNDWATER

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## Abstract

Leachate from coal combustion by-products can contain elevated concentrations of boron, sulfate, trace metals, and other inorganic constituents. Contaminant transport modeling can be used to evaluate the impact of these constituents on groundwater quality. To properly evaluate the potential impact of coal combustion by-products disposal on groundwater quality, the physical and chemical properties of coal combustion by-products, transport processes in groundwater, and the solution techniques of mathematical models must be understood. Physical and chemical properties of coal combustion by-products and transport processes in groundwater are reviewed. To highlight differences in model input and output, an analytical (MYGRT) and a numerical (MODFLOW/MT3D) contaminant transport model were used to predict the transport of boron from a landfill. The concentrations predicted by the two models are slightly different 50 m downgradient from the landfill because the models handle the contaminant input differently and allow the solute to be mixed over different aquifer thicknesses.

## Introduction

During the combustion of coal, bottom ash, fly ash, flue gas desulfurization (FGD) waste, and fluidized bed boiler waste may be produced. While some of these wastes are used in building materials and as structural fill material, the majority is disposed in landfills and surface impoundments. The potential for groundwater contamination from leachate originating from these landfills and surface impoundments represents the greatest environmental concern for disposal of coal combustion by-products (USEPA, 1988). To determine the environmental impact of the leachate from coal combustion by-products in landfills and surface impoundments, modeling can be used to estimate the leachate transport via groundwater. The objective of this paper is to describe and discuss different types of models used to estimate the transport of coal combustion by-products leachate in groundwater. In this paper, we also discuss the physical and chemical characteristics of coal combustion by-products, transport processes important for coal combustion by-products, and analytical and numerical modeling of contaminant transport in groundwater. Two different models were used to model a single case history. Differences in model input and output will be highlighted.

The significance of various transport processes depends on the leachate constituents. To focus this discussion about transport processes, the characteristics of leachate generated from coal combustion by-products will be reviewed. The three most common coal combustion by-products are fly ash, bottom ash, and flue gas desulfurization (FGD) waste. Carlson and Adriano (1993) reviewed the literature on the environmental impact of fly ash, bottom ash, and FGD waste, and noted that information on the environmental impact of FGD waste was much more limited than fly and bottom ashes. Another source of data on coal combustion by-products including FGD waste is Ainsworth and Rai (1987).

## Description of Coal Combustion By-Products

The physical, chemical, and mineralogical characteristics of fly and bottom ashes depend upon several factors including the composition of the parent coal, combustion conditions, the efficiency and type of emissions control devices, and the method of ash disposal (Carlson and Adriano, 1993). Although ash characteristics are variable, certain generalizations can be made. Fly ash is composed predominantly

of silt-sized, glassy, sometimes hollow particles with specific gravities of 2.1 to 2.6. Compared with fly ash, bottom ash has a greater percentage of coarse-grained particles and has a greater specific gravity (Carlson and Adriano, 1993). Fly ash is generally considered a ferro-aluminosilicate mineral with Al, Si, Fe, Ca, K, and Na as the predominant elements. In addition, fly ash contains all naturally occurring elements and is substantially enriched in trace elements compared with the parent coal. The concentrations of major elements (Al, Ba, Fe, K, Mg, and Si) are similar in fly ash and bottom ash (Ainsworth and Rai, 1987). Fly and bottom ashes are also generally enriched in the trace elements, As, B, Ca, Mo, S, Se, and Sr. Many of these trace elements are concentrated in the smaller ash particles. Ash pH depends on the S content of the parent coal. Eastern coals produce acidic ashes because these coals generally contain higher concentrations of S. Ainsworth and Rai (1987) noted that several trace elements including As, Mo, and Zn, are more concentrated in the fly ash of bituminous coal than subbituminous or lignite coal.

Flue gas desulfurization involves the removal of SO<sub>2</sub> from the flue gas, usually by the addition of a limestone slurry to the flue gas at the smokestack (USEPA, 1988). Lime, sodium hydroxide, and sodium sulfate are also used to absorb sulfur dioxide from the flue gas (USCOTA, 1992). FGD waste is generally a combination of fly ash, Ca-S salts, and CaCO<sub>3</sub> (Carlson and Adriano, 1993). FGD waste typically contains higher concentrations of Br, Cl, and S than fly and bottom ashes (Ainsworth and Rai, 1987). Because of its higher concentrations of sulfur and other contaminants, FGD sludge may be of greater environmental concern than fly and bottom ashes (USCOTA, 1992).

#### Disposal of Coal Combustion By-Products

The two predominant methods for the disposal of fly ash, bottom ash, and FGD sludge are settling ponds and landfills (USEPA, 1988). Surface impoundments receive ash in slurry form. In these ponds, the ash particles settle to the bottom of the pond. The effluent water is then pumped back to the power station for reuse or is discharged to a stream or lake. Many impoundments are unlined, sometimes allowing a significant portion of the slurry water to leach through the bottom. Landfills receive dewatered ash from settling ponds and/or dry ash directly from the power plant. Landfills are currently considered the favored disposal method, although settling ponds were previously favored because of the lower cost and operational simplicity (USEPA, 1988).

The potential for groundwater contamination due to leachate from coal combustion by-products disposal sites was identified by USEPA (1988) as the primary concern, based on the elevated concentrations of soluble salts and potentially toxic trace elements including As, Ba, Cd, Cr, Pb, and Se present in coal combustion by-products. The geochemistry of As, B, Ba, Cd, Cr, Se, and SO<sub>4</sub><sup>2-</sup> in groundwater was summarized by Summers et al. (1989). A limited number of field investigations has shown that the effects of ash disposal on groundwater quality depend on the physical and chemical characteristics of the ash and the hydrogeologic conditions and climate of the disposal site (Carlson and Adriano, 1993). Groundwater contamination downgradient from ash landfills and surface impoundments has been reported, but rapid attenuation limited the extent of groundwater contamination (Carlson and Adriano, 1993; USEPA, 1988). Leachate from coal combustion by-products disposal sites is generally characterized by relatively high soluble salt concentrations with Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> usually the dominant cation and anion, respectively. Leachate pH varies with the ash composition (Carlson and Adriano, 1993).

#### Transport processes in groundwater

Leachate from disposal sites containing combustion by-products from Illinois coal will generally have an alkaline pH (Roy et al., 1981) and contain elevated concentrations of cations and anions. The important transport processes in groundwater for this type of leachate are advection, hydrodynamic dispersion, and several types of chemical reactions such as acid/base, reduction/oxidation (redox), adsorption/desorption, and precipitation/dissolution. Advection is defined as the transport of a solute with the movement of groundwater. Hydrodynamic dispersion includes mechanical dispersion and

diffusion. Mechanical dispersion is the transport of a solute resulting from minor differences in groundwater velocity as it flows through nonhomogeneous porous media. Diffusion describes the movement of a solute from an area of higher concentration to lower concentration, and is an important transport mechanism in geologic materials with low hydraulic conductivity. Advection and hydrodynamic dispersion simply redistribute the mass within the geologic material. Neither process changes the amount of solute mass in groundwater. However, chemical processes can alter the mass of solute by transforming the solute to another form or moving the solute from the liquid (groundwater) to solid phase (aquifer material).

Several processes including adsorption/desorption, redox, and precipitation/dissolution can change the solute mass in the groundwater. Adsorption is a general term and includes all processes where the solute bonds to a solid phase (Fetter, 1993). Adsorption includes ion exchange, which refers to the exchange of solutes (generally cations but may include some anions) with charged surfaces, such as clay minerals, due to electrostatic forces. Precipitation describes the process where solutes in the groundwater react to form a solid, while dissolution is the process where a solid dissolves in the groundwater. Adsorption, precipitation, and dissolution of inorganic solutes are controlled by pH, redox conditions, temperature, and solute concentration. These processes may be reversible if these controlling conditions change over time. Additional details on contaminant hydrogeology can be found in Fetter (1993).

### Modeling of Contaminant Transport

Modeling involves three initial considerations-- model selection, solution technique, and input data. Model selection involves selection of the type of processes to be studied and included in the mathematical statement. Different solution techniques are available to solve the chosen mathematical model. Finally, input data for the model must be gathered from a literature review, field investigations, and/or laboratory studies. This discussion about modeling is limited to contaminant transport in groundwater, assuming that the leachate mixes completely with groundwater and does not change the density and/or temperature of the groundwater. This discussion also will be limited to transport through saturated, porous media. Transport through unsaturated or fractured media is beyond the scope of this introductory discussion.

#### Model Selection

A mathematical model of any complex natural process such as contaminant transport in groundwater may not be able to completely reproduce field observations, but a good model should reproduce the more significant field observations. Deterministic and stochastic models are used to model contaminant transport. Deterministic models provide a single result based on single input parameters. Stochastic models use statistical descriptions as input parameters and thus yield statistical descriptions as results. Because deterministic models are more widely used, this discussion will focus solely on these models.

The following differential equation describes one-dimensional, advective-dispersive transport (Fetter, 1993) and is simply a statement of one of the basic scientific principles, conservation of mass. The derivation of this equation can be found in Freeze and Cherry (1979, Appendix X).

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x} - \frac{B_d K_d}{\theta} \frac{\partial C}{\partial t} + \left( \frac{\partial C}{\partial t} \right)_{rxn} \quad [1]$$

The first term describes the rate of change of a solute concentration, C, over time, t. The second term accounts for the dispersion of the solute, where D is the dispersion coefficient in the direction of flow. The third term accounts for the advection of the solute, where the average linear groundwater velocity is denoted by v. The fourth term accounts for solute adsorption, where  $B_d$  is the bulk density of the aquifer, q is the porosity of the aquifer, and  $K_d$  is the distribution coefficient.  $K_d$  accounts for the solute that adsorbs to the solid and assumes a linear and reversible adsorption model. Fetter (1993) noted that a

linear adsorption model is not always accurate because it does not limit the amount of solute that can adsorb onto the solid. However, its use allows [1] to be solved easily and is an example of the compromises made in mathematical models. The final term accounts for any solute added to or removed from solution due to any reactions. If the only type of reaction the solute experiences is radioactive decay, the final term in [1] can be replaced by  $\lambda C$ , where  $\lambda$  is the radioactive decay constant. As a matter of convenience, [1] is sometimes rewritten in a slightly simpler form (Javandel et al., 1984):

$$\frac{\partial C}{\partial t} = \frac{D}{R} \frac{\partial^2 C}{\partial x^2} - \frac{v}{R} \frac{\partial C}{\partial x} - \lambda RC \quad [2]$$

The retardation factor, R, equals  $1 + B \cdot K_d / q$ . This equation is suitable for modeling the transport of a single solute. Multiple, interacting solutes can be studied using multicomponent modeling, which couples groundwater flow and equilibrium chemistry models. Multicomponent modeling was recently reviewed by Engesgaard and Christensen (1988) and Mangold and Tsang (1991).

### Solution Technique

The solution to [2] requires one initial condition for the derivative with respect to time and two boundary conditions for the derivative with respect to space (x). This equation can be solved analytically or numerically. An analytical solution is given by [3], and is based on the following assumptions:

- The system is initially free of the solute.
- The concentration gradient at a distant boundary does not change over time.
- Solute is added continuously at the concentration  $C_0$  at the near boundary.

Mathematically, these conditions are expressed as follows:

initial condition:  $C(x,t) = 0 \quad \text{for } t = 0$

boundary condition 1:  $\frac{\partial C(x,t)}{\partial x} = 0 \quad \text{for } x = \text{infinity}$

boundary condition 2:  $-D \left( \frac{\partial C(x,t)}{\partial x} + vC \right) = vC_0$

The solution to [2] is (Javandel et al., 1984):

$$\frac{C}{C_0} = \frac{v}{v+U} e^{\left[ \frac{x(v-U)}{2D} \right]} \operatorname{erfc} \left[ \frac{Rx-Ut}{2\sqrt{DRt}} \right] + \frac{v}{v-U} e^{\left[ \frac{x(v+U)}{2D} \right]} \operatorname{erfc} \left[ \frac{Rx+Ut}{2\sqrt{DRt}} \right] + \frac{v^2}{2DR\lambda} e^{\left[ \frac{vx-\lambda t}{D} \right]} \operatorname{erfc} \left[ \frac{Rx+vt}{2\sqrt{DRt}} \right] \quad [3]$$

where  $U = (v^2 + 4DR\lambda)^{1/2}$  and erfc is the complementary error function. This function is a special mathematical function and is tabulated in Fetter (1993, Appendix A). The concentration relative to the input concentration,  $C/C_0$ , at any time and place can be determined using [3] if the variables, D, R, v and  $\lambda$ , are known. These variables are assumed to remain constant over time and space.

Equation [2] also can be solved numerically using finite differences or finite elements. The finite difference method is easier to understand than finite elements, so finite differences will be used to illustrate the numerical solution of [2]. As with all numerical methods, finite differences requires that the porous media under study be divided into small segments. This can be accomplished by laying a rectangular grid over the study area. At the nodes of this grid, the transport equation is solved by approximating the differential equation as a difference or algebraic equation. The difference equation is a mass balance of the solute at a node of the model. The difference equations for all nodes are grouped into a series of linear equations, which can be solved easily using a computer. Additional information on numerical methods can be found in Anderson and Woessner (1992, Chapter 2).

When solving the solute transport equation numerically, the groundwater flow equation must also be solved numerically. The flow and transport equations are linked because the head data from the flow equation are used to compute the velocity term in the transport equation. The velocity term is usually defined by Darcy's Law. A numerical solution offers several advantages over an analytical solution, which justifies the additional effort involved with using numerical methods to solve the transport equation. For numerical models, the input parameters do not have to remain constant over space, but may vary to more accurately reflect the site hydrogeology. Groundwater flow velocities are also allowed to vary over time and space. Also, numerical models allow the modeler to more accurately account for the effects of site boundary conditions, such as rivers.

Finite difference or finite element methods are not the best methods in all situations. Particle tracking is another approach adopted to numerically simulate solute transport and involves tracking imaginary particles through the modeled domain. Particle tracking models use head data from groundwater flow models to compute groundwater velocities, which are then used to determine solute transport. The two most widely used particle tracking methods are particle tracking and random walk (Wen and Gomez-Hernandez, 1996). In particle tracking, hydrodynamic dispersion is not included because transport is assumed to be dominated by advection. The random walk approach accounts for advection and hydrodynamic dispersion. Both methods are free of numerical dispersion and are well suited for determining contaminant arrival times, locations, and concentrations, but large number of particles must be tracked to obtain accurate results (Wen and Gomez-Hernandez, 1996). Numerical dispersion is the artificial spreading of the solute as a result of the numerical methods and is a common problem with finite difference or finite element methods.

### Model input

Model input can be obtained from the literature (e.g., Freeze and Cherry, 1979; Summer et al., 1989), field investigations, and/or laboratory studies. Model input is often considered the most important segment of the modeling process and often dictates the type of model used and the utility of the model results.

## **Case History**

To demonstrate the differences in model input requirements and results, two different models were used to simulate the contaminant transport from a coal combustion by-products disposal site. These models tested were MYGRT and MODFLOW/MT3D.

### Description of Models

MYGRT is a code for modeling transport of inorganic and organic contaminants and includes advection, dispersion, retardation, and decay (Summers et al., 1989). MYGRT can be used to model transport in one or two dimensions. For two-dimensional simulations, the code may be used for either plan (x,y) or profile (x,z) simulations. Output is generated as a function of time and space. MYGRT assumes:

- The geologic materials are homogeneous and isotropic.
- The groundwater flow is uniform over space and time.
- Dispersion is represented by Fick's Law.
- Sorption is represented by linear equilibrium partitioning between the aqueous and solid phases.
- Solutes are not affected by chemical reactions with other solutes during transport.

The differential equation solved by MYGRT has a solution similar to [3] A new version of MYGRT is currently being developed and will allow changes in source concentration over time and changes in transport parameters over space. These changes in MYGRT will enhance modeling of the effects of site closures.

MODFLOW (McDonald and Harbaugh, 1988) is widely used and can simulate one, two or three dimensional, saturated groundwater flow under steady state or transient conditions. Head data generated by MODFLOW are used by transport models such as MT3D (Zheng, 1990) to compute groundwater velocities and contaminant transport throughout the modeled domain. The major assumptions of MODFLOW are:

- Fluid flow is governed by Darcy's law.
- Flow is not affected by thermal, chemical, or density gradients.
- The fluid is slightly compressible and homogeneous.
- The principal components of hydraulic conductivity are aligned with the model axes.

The major assumptions of MT3D are:

- Single species, miscible contaminants are transported by advection and dispersion, and may be affected by simple chemical reactions.
- Chemical reactions are equilibrium controlled, linear and non-linear sorption or first-order, irreversible rate reactions (e.g., radioactive decay and biodegradation).
- The contaminant does not significantly impact the flow field.

#### Description of Coal Combustion By-Products Disposal Site & Model Input

The case study site was an actual unlined coal ash landfill where fly ash and bottom ash was dry-disposed. Because the landfill owner requested anonymity, the site description has been generalized. The landfill covers an area 300 m by 300 m (22 acres). The ash was about 10 meters thick. Ash was disposed in this facility from 1970 to 1995, when it was closed and capped. The facility was located on the floodplain, approximately 100 meters from a major river. Underlying sediments consisted of highly permeable sand and gravel with hydraulic parameters given in Table 1. The data for this case study were obtained from field investigations and the literature. Because boron is an indicator constituent for coal combustion by-products leachate and is mobile in sand and gravel aquifers, it was selected for modeling.

Boron was modeled using an initial relative concentration of 1.0 rather than an absolute concentration. The modeling results can be considered as relative concentration ( $C/C_0$ ) or percent change from the source concentration.

The alluvial aquifer in this case study was relatively homogeneous, with no pumping-well effects near the disposal facility. Furthermore, the river stage was controlled by a nearby lock and dam, so the groundwater gradient did not fluctuate much. Finally, groundwater did not mound beneath the landfill because of the high hydraulic conductivity of the aquifer combined with the relatively low leachate flux from the active landfill.

#### Model Results

*MYGRT simulation:* Because the modeled aquifer was relatively thick, MYGRT was used in the profile mode, which more accurately represents solute concentrations in thick aquifers. Transverse dispersion was ignored in the profile model; however, it had a negligible effect on concentration along the centerline of this plume due to the large width of the facility relative to the short distance to the groundwater discharge point.

MYGRT offers two possible boundary conditions for solute input. One boundary condition allows the user to set the initial concentration in the aquifer. This concentration is evenly distributed throughout the depth of plume penetration. Plume penetration depth is the thickness of the plume at the downgradient edge of the landfill. This depth can be based on monitoring data or estimated using an equation (Summers et al., 1989). If the monitoring data are sufficient to estimate leachate concentration and plume penetration depth, this first boundary condition should be used. The second boundary condition calculates the initial concentration in the aquifer from the concentration of the leachate, the flux rate of leachate into the aquifer, and the velocity of groundwater flow and was the boundary condition used here. The solute concentration is calculated assuming complete mixing throughout the

plume penetration depth.

Model input parameters for MYGRT are listed in Table 1. Because MYGRT does not calculate a groundwater flow field, groundwater velocity ( $v$ ) is input rather than hydraulic conductivity ( $K$ ). Groundwater velocity can be calculated as the product of  $K$  and  $i$  divided by  $n_e$ , where  $i$  is the hydraulic gradient and  $n_e$  is the effective porosity. Rather than total porosity, effective porosity is used. Effective porosity is that portion of the pore space in the aquifer through which groundwater flows. By definition, effective porosity is less than total porosity. In coarse-grained aquifers, it is only slightly less than total porosity; however, it may only be a small fraction of total porosity in clays.

Two MYGRT simulations were used to model transport before and after the landfill was capped. The first simulation assumed a leachate flux rate of 10 cm per year from 1970 through 1995. The second simulation assumed a leachate flux rate of 1.3 cm per year after 1995. The analytical solution allows these results to be added together to simulate a decreasing source term, as illustrated in Figure 1. The model results suggested that concentrations 50 m downgradient from the landfill increase for approximately 15 years and then level off at a relative concentration of approximately 0.23. After the landfill was capped in 1995, the concentration 50 m downgradient from the landfill decreased rapidly from 1998 to 2010.

**MODFLOW/MT3D simulation:** Input for the numerical models MODFLOW and MT3D are listed in Table 1. A two-dimensional profile model was developed using 12 nodes in the  $z$  direction and 50 nodes in the  $x$  direction. The boundary conditions for the flow and transport models are shown on Figure 2. Boron enters the groundwater by recharge from the bottom of the landfill. The concentration of boron in the recharge was 1.0 within the landfill and 0.0 outside the landfill. The capping of the landfill is represented by a decrease in the recharge rate.

Modeling results for MODFLOW/MT3D (Figure 3) were generally similar to the MYGRT results. The concentration 50 m downgradient from the landfill increased from 0 after the landfill was open for 2 years to its peak concentration approximately 2 years after the landfill was capped. The concentration then declined to a new equilibrium concentration. However, the peak concentration estimated by MODFLOW/MT3D was less than the MYGRT-estimated peak concentration, 0.20 and 0.23, respectively. Also, MYGRT predicted that the concentration remained constant at the peak concentration for over 10 years, while the MODFLOW/MT3D concentration did not level off. The models also yielded different concentrations after the landfill was capped. These differences in the predicted concentrations of boron can be explained by examining how the models introduce and mix boron into the aquifer. MYGRT added boron to the aquifer using a line source perpendicular to the direction of flow at the downgradient edge of the landfill ( $x=400$  m, see figure 2). MT3D introduced boron using recharge over the entire area of the landfill ( $x=100$  to 400 m) or along the direction of flow.

Also, MYGRT assumed that the solute was mixed over the plume penetration depth (set at 16.1 m), while in MT3D the solute was transported over the saturated aquifer thickness of 18 m. Both of these factors accounted for the different concentrations observed 50 m downgradient from the landfill.

## Discussion

As with most analytical solutions, MYGRT requires little data input. The transport equation is not a simple expression, but MYGRT solves it in seconds. Simple data structure and presentation of results often make analytical models appealing to regulators who may not have the time or experience to thoroughly review numerical models. Because the limited data input cannot accurately reflect the actual hydrogeologic conditions of most sites, analytical models generally will produce results with a higher degree of uncertainty than results from numerical models. However, ease of application and computational speed of analytical models make it easy to conduct sensitivity tests on model parameters that lead to the high degree of uncertainty in the model results. Analytical models can be considered specialized tools, and are useful to model simple hydrogeologic settings or to provide preliminary estimates of more complicated hydrogeologic settings.

Numerical models are general purpose tools and can be applied to a wide variety of situations. Numerical models are needed where complex groundwater flow or solute transport conditions do not match the simple assumptions incorporated into analytical models, such as uniform groundwater flow. Numerical models may be preferable for cases where calibration is desired to reduce model uncertainty. However, numerical models require much more input data and more time to set up and run. Numerical models also provide other useful data including mass balance data for flow and solute transport. For example, recharge contributed 43 percent of the total flow in the case study. Also, 91 percent of the solute that entered the aquifer was transported out of the downgradient boundary.

### Summary

Contaminant transport modeling of leachate from coal combustion by-product landfills and surface impoundments allows one to assess the environmental impact on groundwater quality. However to properly assess this environmental impact, the modeler must have comprehensive knowledge of the physical and chemical properties of the coal combustion by-products disposed at the site, the significance of groundwater transport processes, and the inherent assumptions of and the solution techniques of the software used for contaminant transport modeling. The case study illustrated differences in the predicted concentration of boron 50 m downgradient from a landfill. While these differences may seem trivial, they could become quite significant in a regulatory setting.

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Table 1. Input data used for the case study

Parameter	Value (units)	Parameter used in the following models		
		MYGRT	MODFLOW	MT3D
<i>Definition of the source</i>				
length	300 m	X	X	X
width	300 m	X	X	X
thickness	10 m			
date opened	1970	X	X	X
date closed	1995	X	X	X
infiltration rate, pre-closure	10 cm/yr	X	X	X
infiltration rate, post-closure	1.3 cm/yr	X	X	X
distance to river	100 m	X	X	X
unsaturated zone thickness	2 m			
<i>Hydrogeology</i>				
aquifer thickness	20 m	X	X	X
hydraulic conductivity	0.010 cm/sec		X	X
hydraulic gradient	0.002		X	X
effective porosity	0.20	X		X
groundwater velocity	31.5 m/yr	X		
bulk density	1.6 g/cm <sup>3</sup>			X
recharge rate	25 cm/yr		X	X
<i>Contaminant transport</i>				
modeled solute	Boron	X	X	X
longitudinal dispersivity	10 m	X		X
vertical dispersivity	0.063 m	X		X
R	2.0	X		X
plume penetration depth	16.1	X		

Figure 1. MYGRT predicted concentrations for boron 50 m downgradient from the landfill

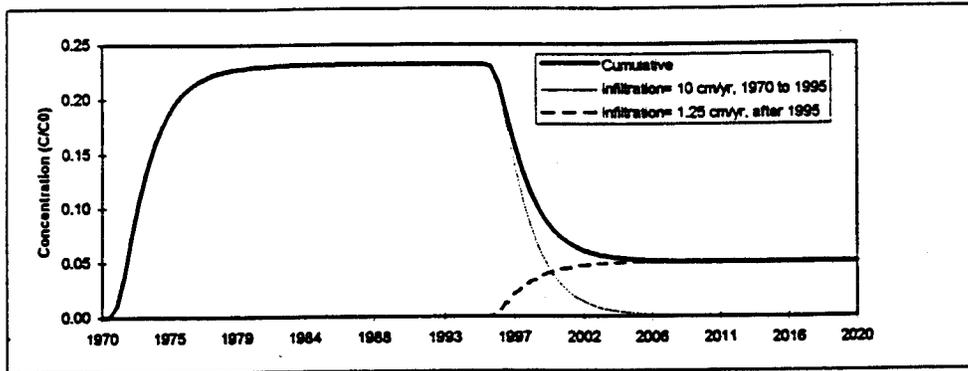


Figure 2. Boundary conditions for MODFLOW and MT3D for the case study

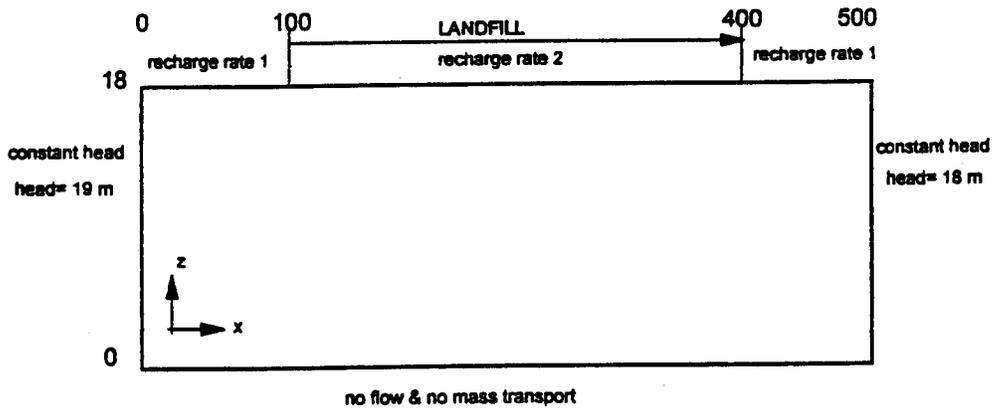
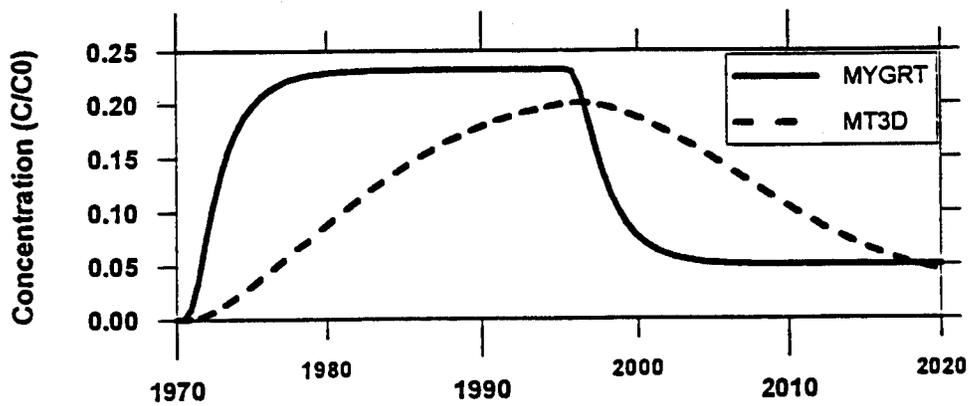


Figure 3. MYGRT and MT3D predicted concentrations for boron 50 m downgradient of the landfill



# ELEMENTS OF COMPUTER-ASSISTED THERMODYNAMIC CHEMICAL EQUILIBRIUM MODELING AS APPLIED TO WASTE TREATMENT AT COAL MINES

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## Abstract

Computer-assisted thermodynamic chemical equilibrium models are useful tools for describing and understanding the reactions that occur in a chemical system. Several models are available either free or at nominal cost. The models presently available generally are designed to compare the ion activity product with the equilibrium constant for a particular reaction. Understanding how models calculate total dissolved activities from solute concentrations and then calculate the activities and concentrations of various aqueous species and solids is essential for selecting the best model for a particular application. Models are limited by the quality of the data in their databases and by the state of theoretical understanding of nonideal solutions. Therefore, results from computer models must be validated through field or laboratory experiments before being accepted and used for making decisions.

## Introduction

Many computerized models have been written over the years but many of these are designed for a narrow purpose. Of the many models developed, only a few are in general use by the scientific community. Acceptance of a chemical thermodynamic equilibrium model seems to be governed by its ease of use, the extensiveness of its thermodynamic database, the breadth of the capabilities of the model, and the ease of modifying the code to suit a particular need (Mattigod, 1995).

## Chemical Fundamentals

Most simply stated, a model is a representation of an object or an event. A chemical equation is a model for a chemical reaction. For example, equations 1-4



represent the dissolution of gaseous carbon dioxide in water.

These equations indicate that (1) carbon dioxide gas will dissolve to some extent in water, (2) an amount of aqueous carbon dioxide will combine with an equimolar amount of water to form an equimolar amount of carbonic acid, (3) carbonic acid will dissociate in water to form hydronium and bicarbonate ions, and (4) bicarbonate ion will further dissociate (equation 4) to form another hydronium ion and carbonate ion. When no additional information is provided, a set of chemical equations is primarily descriptive. These equations tell us what happens when carbon dioxide dissolves in water, but they don't tell us how much of each species will be present.

To determine quantities of species requires additional information, namely, an equilibrium constant for each reaction, that is, the ratio of the mathematical product of each product species activity raised to the power of the coefficient of that species in the chemical equation divided by the mathematical product of each reactant species raised to the power of its coefficient. For example, for the hypothetical reaction



the equilibrium constant is

$$K_{eq} = \frac{[C]^c [D]^d}{[A]^a [B]^b} \quad (6)$$

Equilibrium can be defined as the equality of the rates of opposing reactions. In other words, the rate of production of C and D in equation 5 by the reaction of A and B is equal to the rate of production of A and B by the reaction of C and D.

Another definition of equilibrium can be formulated on the basis of free energy. Any system which is not at equilibrium will change spontaneously with the release of energy. At equilibrium, when the reactants and products are at the same temperature and pressure, the sum of the free energy of the products equals the sum of the free energy of the reactants. Or,

$$\Sigma \Delta G_{\text{prod}} - \Sigma \Delta G_{\text{react}} = 0 \quad (7)$$

The standard free energy of formation of a substance is defined as the free energy change resulting from the formation of one mole of the substance from the stable elements under standard state (25°C and 1 atm) conditions.

The equilibrium constant for a reaction can be calculated from the standard free-energy change of the reaction ( $\Delta G_r^\circ$ ), the difference between the sum of the free energies of formation of the products less the sum of the free energies of formation of the reactants:

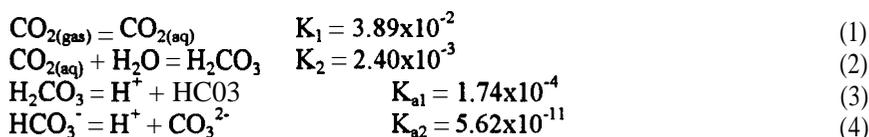
$$\Delta G_r^\circ = \Sigma \Delta G_r^\circ (\text{prod}) - \Sigma \Delta G_r^\circ (\text{react}) \quad (8)$$

At 25°C and 1 atm pressure, the equilibrium constant is related to the standard free-energy change (in kcal) of the reaction by

$$\log K = \frac{-\Delta G_r^\circ}{1.364} \quad (9)$$

One can calculate equilibrium constants from standard free energies of formation, which have been tabulated by several authors.

We are now in a position to calculate the activities of the various species that are formed with the dissolution of carbon dioxide. The equilibrium constants for reactions 1 through 4 are as follows:



By substituting the atmospheric partial pressure of carbon dioxide, 0.0003 atm, into equation 1, and solving the four equations, the concentrations of  $\text{CO}_2$ ,  $\text{H}_2\text{CO}_3$ ,  $\text{HCO}_3^-$ , and  $\text{CO}_3^{2-}$  are found to vary with pH as shown in Figure 1.

These calculations yield activities rather than concentrations. The activity of a species is a

measure of its effective concentration, and is usually smaller than concentration, Activity is related to concentration through the equation

$$act_i = \gamma c_i \quad (10)$$

where  $act_i$  is the activity of the  $i$ th species,  $\gamma$  is the activity coefficient, and  $c_i$  is the concentration of the  $i$ th species. The difference between activity and concentration arises because in a solution, each ion is surrounded by a shell of oppositely charged ions, which decreases the ability of the central ion to enter into chemical reactions.

In an ideal solution, the activity coefficient is equal to 1 and activity equals concentration. Real solutions are not ideal, however, so activity coefficients must be calculated for different solutes. An equation commonly used to calculate activity coefficients is the extended Debye-Hückel equation,

$$-\log \gamma_i = \frac{Az_i^2 \sqrt{I}}{1 + Ba_i \sqrt{I}} \quad (11)$$

where  $A = 1.82 \times 10^6 (\epsilon T)^{-3/2}$ ,  $B = 50.3 (\epsilon T)^{-1/2}$ , and  $\epsilon$  signifies the dielectric constant of the solvent, and  $T$  is the absolute temperature of the solution.

The quantity  $a_i$  is dependent on the “effective diameter” of the ion. Values of  $a_i$  have been determined experimentally and are available in tabulated form. The symbol  $z_i$  is the ionic charge, and  $I$  is the ionic strength of the solution. The ionic strength is calculated from

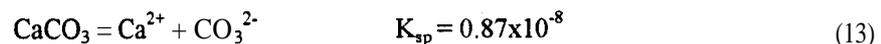
$$I = \frac{1}{2} \sum m_i z_i^2 \quad (12)$$

where  $m_i$  is the molal concentration (mole/kg) of the  $i$ th ion in solution.

The extended Debye-Hückel equation is valid for ionic strengths up to about 0.05m. Other equations, such as the Guntelberg equation or the Davies equation have been developed for higher ionic strengths (Butler, 1964). The Davies equation is useful for ionic strengths up to approximately 0.5m. This ionic strength limit is satisfactory for most environmental work. Figure 2 shows a comparison of activity coefficients calculated from the Debye-Hückel, Guntelberg, and Davies equations with experimental data for several solutes. Figure 2 shows that none of the three equations matches the experimental data entirely adequately. The Pitzer equation (not shown in Figure 2) is useful for calculating activity coefficients in solutions in which the ionic strength is greater than 0.5m.

Typically, in a thermodynamic chemical equilibrium model, the activities of solutes are compared with the solubility of each potential mineral in the database. If the solubility product of some mineral in the model's database is exceeded by the ion activity product (IAP) of the dissolved constituents in the solution being modeled, the model allows the mineral to precipitate until the IAP equals the solubility product. Conversely, if a mineral is present in the solid phase and the IAP of the dissolved constituents in the model solution is less than the solubility product of the mineral, the model allows the mineral to dissolve until the IAP and the solubility product are equal.

For example, the solubility product,  $K_{sp}$ , of calcite at 25°C is  $0.87 \times 10^{-8}$  and is simply an equilibrium constant for the chemical reaction



By definition, the activity of any solid is equal to 1, so the equilibrium constant for the above reaction is

$$K_{sp} = [\text{Ca}^{2+}][\text{CO}_3^{2-}] \quad (14)$$

The IAP is calculated from the activities of the dissolved mineral constituents. The saturation index is defined as  $\log(\text{IAP}/K_{sp})$  for the mineral. If the saturation index is positive, the solution is supersaturated with respect to that mineral, and precipitation of the mineral is allowed by the model. If the saturation index is negative, the solution is undersaturated with respect to that mineral, and dissolution of the mineral is allowed.

Thermodynamic equilibrium models generally are organized around two major approaches. The most common approach is to base the calculations on equilibrium constants (Mattigod, 1995), as illustrated above. The second approach is called the free energy minimization approach. The second approach is not commonly used because the data required are neither as readily available nor as reliable as equilibrium constants. However, the two methods produce mathematically equivalent results.

### **Limitations of Chemical Equilibrium Models**

#### Assumption of Equilibrium

Thermodynamic chemical equilibrium models assume that equilibrium has been attained in the system of interest. This may be the case in a well-stirred solution in a beaker, but it is not necessarily true for a natural system. Natural systems are subject to slow changes in solution composition due to the diffusion of solutes into or out of the system, the diffusion of gases such as oxygen or carbon dioxide into or out of the system, transport of solutes through the system because of groundwater flow, oxidation-reduction reactions, acid-base reactions, microbial activities, adsorption-desorption, and other processes which cause changes in solute concentrations.

#### Limitations of Thermodynamic Data

Models require thermodynamic data such as equilibrium constants, solubility product constants, and enthalpy values, in their calculations, but not all thermodynamic data are of equal accuracy and precision. If a model's developer chose inaccurate thermodynamic data for the database, then the modeling results will also be inaccurate.

If experimentally determined thermodynamic data are not available for each solute of interest, then estimated or indirectly calculated values must be used. However, an equilibrium constant can be calculated for the reaction only when the free energy of formation is known for each desired component in a reaction. Enthalpy data are required in the model to correct equilibrium constants if the modeled solution's temperature differs from the standard state, usually 25°C.

### **Required User Input**

The user of a model must supply chemical information specific to the problem to be modeled. The data required usually include temperature, pH, Eh, and the concentration of each cationic and anionic component in the system to be modeled. Depending on the model, the data must be written to a file with specific formatting requirements or into a preprocessor which writes the properly formatted input file.

Models require that the concentration of some form of inorganic carbon, such as the partial pressure of  $\text{CO}_2^*$ , dissolved inorganic carbon, or the inorganic carbon portion of alkalinity be supplied. None of these is completely straightforward. While the atmospheric partial pressure of carbon dioxide is approximately 0.0003 atm at the earth's surface, the partial pressure of  $\text{CO}_2$  in soils can range up to about 0.01 atm (Hassett and Banwart, 1992), due to microbial respiration. Knowledge of the specific soil  $\text{CO}_2$  content is needed. Dissolved inorganic carbon is the total of all inorganic carbon species in solution, which includes all dissolved species of carbon dioxide plus ion pairs that include carbonate or

bicarbonate. Total dissolved inorganic carbon can be determined by the acidic evolution of  $\text{CO}_2$ .

Generally, the pH and Eh can be fixed in the model or allowed to vary as solution conditions change during the calculation.

If the user wishes to include minerals in the calculation, then data for the concentration of each mineral must be entered in the model. The database will usually include data for end-member compositions only. This is not a problem for minerals such as calcite ( $\text{CaCO}_3$ ) or hematite ( $\text{Fe}_2\text{O}_3$ ) which generally do not enter into solid solution or ionic substitution, but can become a significant source of error for clay minerals, such as smectites and mixed layer clays with variable composition. For example, the smectite mineral beidellite has an ideal composition of  $\text{Ca}_{0.25}\text{Al}_2(\text{Si}_{3.5}\text{Al}_{0.5})\text{O}_{10}(\text{OH})_2 \times n\text{H}_2\text{O}$ . However, in nature, the chemical composition generally will be somewhat more complicated and unpredictable due to polymorphic substitution and inclusion of impurities. A more representative, but less exact chemical formula for beidellite might be  $(\text{Na},\text{K},\text{Ca})_{0.25}(\text{Al},\text{Mg},\text{Fe}^{3+},\text{Fe}^{2+})_2(\text{Si}_{4-x}\text{Al}_x)\text{O}_{10}(\text{OH})_2 \times n\text{H}_2\text{O}$ . It is not possible to determine a general equilibrium constant for real smectites because of the large range of possible compositions.

### Information Available From Models

The information returned by models typically includes the input data set, the charge balance for the initial solution, the distribution of species in solution, the distribution of components in various species, minerals dissolved or precipitated, the mass of each solid phase remaining at equilibrium, the concentrations of solutes at equilibrium, and the saturation indices of all possible solids.

### Available Models

Several models are available free on the Internet or for a fee from the authors. Among the more widely used are MINTEQA2 and its preprocessor, PRODEFA2; ALCHEMI; PHREEQC; and PHRQPITZ. Other available models are C SALT, EQ3/6, GEOCHEM-PC, HYDROGEOCHEM, LEACHM, REACT, SOILCHEM, and SOLMINEQ.

MINTEQA2 (Allison et al., 1991) is a chemical equilibrium model for dilute solutions with ionic strengths up to about 0.5m. The program was originally developed by Battelle Pacific Northwest Laboratory (Felmy et al., 1984) in the mid-80s as MJNTEQ. MINTEQA2 was derived from MINTEQ. MJNTEQA2 has 61 inorganic and 28 organic components available to describe the chemical system. The components are used as reactants in over 900 dissolved species, over 500 solid species, 21 gas species, 42 surface complexation species relevant to adsorption on an amorphous iron oxide surface, and 13 species of complexes of trace elements with dissolved organic matter (Allison and Brown, 1995). MINTEQA2 includes seven options for modeling adsorption-desorption. It also has the ability to conduct "sweeps," or titrations, in which the output data from one execution are used as input for the next execution of the program.

ALCHEMI (Schecher and Driscoll, 1995) is a specialized program that was designed to evaluate the chemistry of Al as it reacts with  $\text{OH}^-$ ,  $\text{F}^-$ ,  $\text{H}_4\text{SiO}_4$ , and  $\text{SO}_4^{2-}$  in natural waters. It can be used to calculate the speciation of Al in water affected by acidic deposition and thereby assess the potential toxicity of Al in the water. ALCHEMI can also be used to calculate the saturation indices of well-defined mineral phases so that the solubility of Al can be evaluated, but is limited in its array of chemical reactions in acidic, low ionic strength waters.

PHREEQC (Parkhurst, 1995) is a program distributed by the U.S. Geological Survey. This program provides for the aqueous speciation of elements, dissolution and precipitation of solid phases, reaction path modeling (in which the progress of a reaction is followed), advective-transport calculations, and so-called inverse modeling. In inverse modeling, the amounts of solids and gases that must be removed from or added to a system to account for specified differences between beginning and final

compositions of a system are calculated. PHREEQC is appropriate for solutions of low ionic strength, but the results must be interpreted with care. The thermodynamic data in the database are not internally consistent because they were taken from various sources and the author did not attempt to determine whether the data were obtained in similar aqueous solutions (Parkhurst, 1995).

PHRQPITZ (Plummer et al., 1988) incorporates the Pitzer virial-coefficient equation to adapt the model PHREEQE, the predecessor of PHREEQC, to use for high ionic strength aqueous solutions. PHRQPITZ is capable of calculating aqueous speciations, mineral saturation indices, mineral solubilities, mixing and titration of aqueous solutions, irreversible reactions, and reaction paths, but PHRQPITZ does not calculate oxidation-reduction reactions.

The capabilities of other generally available geochemical models are listed in Table 1. All can calculate aqueous speciation and dissolution and precipitation of solid phases. Beyond that, the models differ in their other capabilities. REACT (Bethke, 1996) appears to be unique in its ability to integrate simple kinetic rate laws.

### **Application of Thermodynamic Chemical Equilibrium Models**

Chemical equilibrium models can be used to aid our understanding or predict the behavior of a chemical system. For example, Schwab (1995) used the model MINTQA2 to help in understanding which minerals were responsible for controlling aqueous elemental concentrations in leachates from coal combustion residues. Schwab (1995) used analytical data for leachates as input to the model. In initial executions of the program, solids were not allowed to precipitate. In this mode, the speciation of components and the saturation index of each potential solid phase were calculated. In a subsequent execution of the program, solids were allowed to precipitate in order to calculate changes in solution composition upon precipitation of the solids.

The potential solids suggested by the model and the solution analytical data were plotted in activity diagrams (Figure 3) to indicate visually the degree of saturation of the solutions with respect to certain minerals.

The effects of changing parameters in a chemical system can be predicted by using chemical equilibrium modeling. For example, one might wish to know the effect on leachate chemistry when gob is amended with limestone. The user would input leachate chemistry and gob mineralogy to the model. An initial execution would be made to establish equilibrium conditions, then the desired amount of calcium carbonate would be included in the input data, either as the solid or as equivalent amounts of dissolved species. Several executions of the model could be made with varying amounts of calcium carbonate. Other parameters, such as Eh or temperature, can be changed to determine their influence on chemistry and mineralogy.

If one of the models designed for use with solutions of high ionic strength is used, the user can simulate the evaporation of water in a reaction path model. The model will indicate the precipitation of various solids as water is removed from the system.

Another important ability of some models, such as EQ3/6, is that volume changes can be calculated as changes occur in the mineralogy of a deposit. This function could be applied to calculate the potential volume change in an area used for the storage of fluidized-bed combustion (FBC) ash as calcium oxide is hydrated to calcium hydroxide, then as it reacts with carbon dioxide to form calcium carbonate. Other mineralogical changes can occur as the FBC ash weathers. If the overall effect is that the ash will swell on weathering, will it damage a confining structure? A user might want to know whether a material to be disposed of in an impoundment is expected to cause adverse reactions in a liner material. A chemical equilibrium model could serve this purpose. In this type of application, the user could model the reaction of leachate from the disposed material with different minerals in the liner material and check for mineralogical and volumetric changes that could weaken the liner or induce

fractures, that would allow leakage of the leachate.

Other applications might include modeling the solubility of fertilizer components, such as phosphates, under different conditions of mine soil amendment, or calculating the concentration of a particular chemical form in an isolated location.

### **A Note of Caution**

There is a tendency to give more credence than is warranted to almost anything that comes from a computer. Chemical equilibrium models are meant to help our understanding of the chemical processes that occur in a system, not to define them. Each system will define its own chemical processes. The model serves to help us recognize and understand those processes. Models do not predict, future behavior, they merely suggest the reaction paths that are expected for a specified system. Lastly, the results of modeling must be verified by field or laboratory experiments and by observations.

### **Conclusions**

Thermodynamic chemical equilibrium models can be very beneficial for understanding rock-water interactions and “predicting” the effects of on a reaction system of changing chemical parameters. The limitations of models must be recognized. To be accepted as valid, the results of modeling must be verified by laboratory or field observations.

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Table 1. Capabilities of some available thermodynamic chemical equilibrium models

Model name	Low ionic strength	High ionic strength	Aqueous speciation	Dissolution/precipitation	Oxidation-reduction	Surface adsorption	Ion exchange	Titration	Reaction path	Simple kinetics	Saturation index	Solute transport	Inverse modeling	Temperature correction	Gas phase
ALCHEMI	✓		✓	✓		✓					✓				
C SALT	✓	✓	✓	✓										✓	✓
EQ3/6	✓		✓	✓	✓				✓		✓			✓	✓
GEOCHEM-PC	✓		✓	✓	✓										
HYDROGEOCHEM	✓		✓	✓	✓	✓	✓					✓		✓	
MINTEQA2	✓		✓	✓	✓	✓		✓			✓			✓	✓
PHREEQC	✓		✓	✓	✓	✓	✓		✓		✓	✓	✓		✓
PHROPITZ		✓	✓	✓				✓	✓		✓			✓	
REACT	✓		✓	✓	✓	✓		✓	✓	✓	✓			✓	✓
SOILCHEM	✓		✓	✓		✓									
SOLMINEO		✓	✓	✓	✓	✓	✓	✓			✓			✓	✓

Figure 1. Carbonate species in aqueous solutions as a function of pH

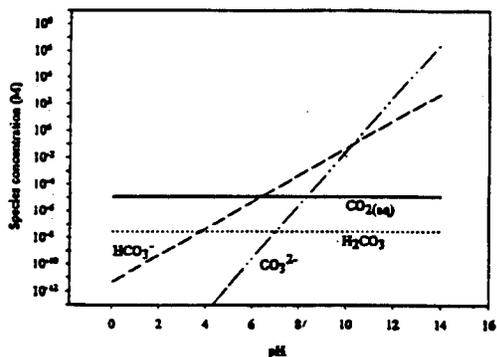


Figure 2. Comparison of empirical activity coefficient expressions with experimental data for HCL, HNO<sub>3</sub>, NaClO<sub>4</sub>, and KCL. (From Butler, 1964. Used with permission from author.)

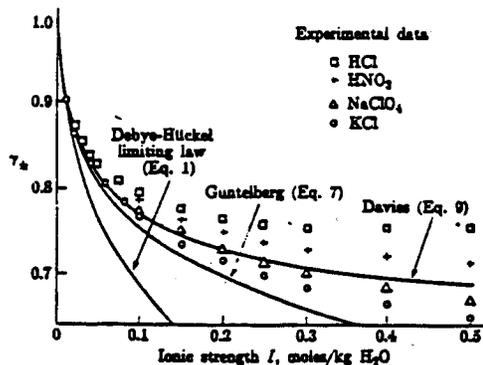
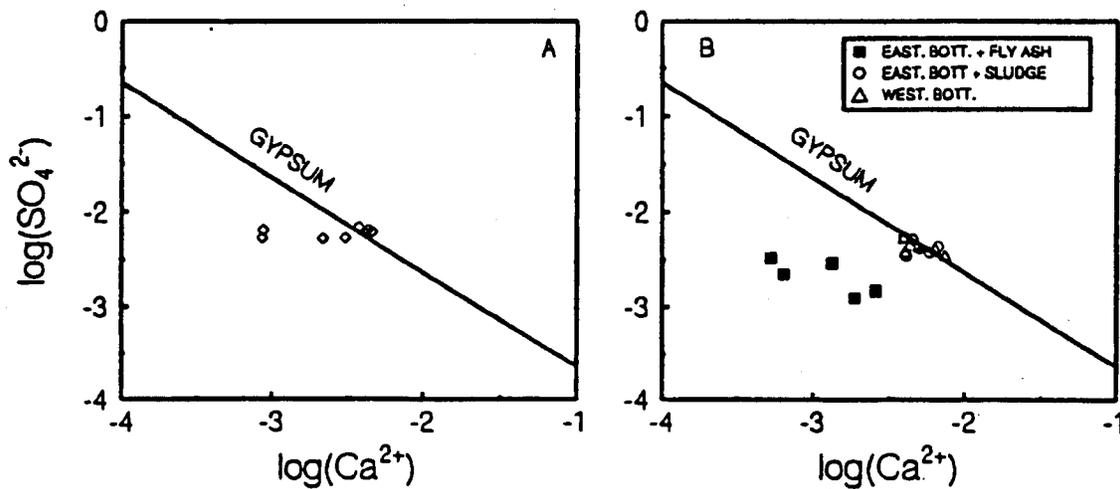


Figure 3. Activities of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> in (A) field and (B) laboratory samples. (From Schwab, 1995. Used with permission from author.)



# **INSTRUMENTS FOR MONITORING THE VADOSE ZONE OF SITES RECLAIMED WITH COAL COMBUSTION BY-PRODUCTS**

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## **Abstract**

Today, excess production of coal combustion by-products is either buried near the surface or pumped into slurry ponds, practices that take land suited for other purposes out of production. Mine reclamation with combustion by-products offers a significant beneficial use outlet for these materials. The by-products produce a leachate, however, and their future acceptance in reclamation requires a detailed analysis of environmental impacts. This paper describes instruments for monitoring the movement and quality of water in the vadose zone in mines reclaimed with coal combustion by-products; including the free drainage lysimeter, time domain reflectometer, tensiometer, suction lysimeter, infiltrometer, and a low-cost rain gauge. Two examples from recent research on the hydrology of areas disturbed by mining suggest that these instruments working together have greater value for monitoring vadose zone hydrology than any single instrument. The multi-instrumented site can provide significant data for evaluating the effectiveness of different reclamation strategies.

## **Introduction**

In an effort to meet new federal emission standards, power companies rely on scrubbers or employ new coal burning technologies, both of which lead to increased production of coal combustion by-products. Although these materials have numerous applications, production will exceed demand for the foreseeable future. Today, most excess by-products produced from coal combustion are either buried near the surface in a relatively dry state (landfill) or pumped into slurry ponds (Bahor and others, 1981), both of which take land suited for other purposes out of production, at least temporarily. Reclaiming both surface and underground mines with combustion by-products in new and innovation ways may provide a real alternative to current expensive disposal practices.

Coal combustion by-products, however, may produce a leachate containing hazardous substances (see for example Le Seur Spencer and Drake, 1987; Beaver and others, 1987; Cherkauer, 1980; Fruchter and others, 1988; Hardy, 1981; Rai and others, 1989; Simsiman and others, 1987; Theis and others, 1978; Gerber, 1981; U.S. Waterways Experiment Station, 1979). Adriano and others (1980) Ferraiolo and others (1990), Theis and Marley (1979), and Theis and Gardner (1990) provided general reviews on environmental impacts associated with the disposal of coal combustion by-products. Leachate generated by these materials is distinctly different than that generated by coal, spoil, or coal processing waste.

The acceptance of reclamation with coal combustion by-products hinges on an analysis of long-term environmental impacts. Methods and the instrumentation for evaluating these impacts must withstand the rigorous requirements established by regulatory agencies. This paper describes instrumentation applied in recent research on the reclamation of surface mine and coal processing waste sites with coal combustion by-products.

## **Monitoring Instrumentation**

Coal combustion by-products have two qualities that make them attractive materials for reclaiming areas producing acid drainage. First, they have geochemical properties that can neutralize acidic groundwater. Second, the by-products have a lower hydraulic conductivity than most spoil or coal processing waste. Therefore, not only can they improve groundwater quality, but they can retard

infiltration to acid producing materials. The monitoring well is the basic tool for conducting hydrologic tests and sampling groundwater in saturated materials. In many reclamation projects, however, the coal combustion by-products are incorporated into or layered with unsaturated materials. Because of this, research must also employ hydrologic instruments for assessing unsaturated zone (vadose zone) hydrology.

Most of this paper describes the free drainage lysimeter, a promising research instrument for determining infiltration and water quality in the vadose zone. Those instruments that can offer insight into the performance of the free drainage lysimeter, such as the tensiometer, time domain reflectometer, suction lysimeter, and rain gauge are also discussed.

### Rain Gauge

Although often neglected, a detailed analysis of site hydrogeology requires an on-site measurement of precipitation. Several kinds of gauges, including the weighing and tipping types, are readily available. The commercial units, however, may not function well in open, unvegetated terrain, like that found in disturbed areas like mines. In one study (Esling and others, 1995), a commercially available weighing-type rain gauge (Belfort Instrument Company Rainfall Transmitter (Model 5915-20), with an accuracy of  $\pm 0.25$  cm (0.1 inch) of rain, was installed on a coal refuse pile. A comparison of rainfall amounts collected with the commercial rain gauge at the site to local records of precipitation suggest that the rain gauge significantly underestimated total precipitation. Most reclamation sites are barren, lacking trees and shrubs or other barriers to the wind. Wind striking the side of an unprotected rain gauge can create updrafts which divert precipitation from the rain gauge receiver. Wind striking the side of the weighing-type gauge rain gauge can also cause vibration which can yield erratic readings. The effects of the wind can be diminished with an artificial wind shield, but Esling and others (1995) developed a different approach, one that provides more reliable rainfall data at a lower cost than commercially available gauges.

The rain gauge (Figure 1) developed for research in reclamation sites minimizes the effects of the wind. This gauge consists of two components; a 20.3 cm (8 in) ID PVC receiver and a 3 m long 5.1 cm (2 in) ID PVC pipe (herein referred to as the reservoir). Rain enters the receiver and collects in the reservoir. The new rain gauge is installed by drilling a borehole to a depth of about 3 m. The accuracy of a rain gauge increases the closer the opening of the receiver is to the ground surface (Landsberg, 1983). This design can be installed such that the top of the receiver is at grade, if desired. Esling and others (1995) installed it approximately 15 cm above grade to prevent rain splash from entering the gauge. The rain gauge capacity is a function of reservoir length. The 3 m long gauge can hold just over 18 cm of rain. Installation of the gauge below grade prevents freezing of trapped water during winter months.

Esling and others (1995), installed a vibrating wire pressure transducer (Geokon type 4500AL) in the reservoir of the rain gauge that had a resolution of about  $\pm 0.35$  cm of water. The cross-sectional area of the receiver and the reservoir differ by a factor of 16. Therefore, one centimeter of rain translates to a change in water level within the reservoir pipe of 16 cm, suggesting that the rain gauge can resolve  $\pm 0.02$  cm of rain. Other factors can affect the theoretical resolution and the range in points on Figure 1 suggest a resolution of  $\pm 0.08$  cm of rain, a value that is better than the  $\pm 0.25$  cm resolution of the weighing-type rain gauge initially installed at the site (Esling and others, 1995). Figure 1 also includes a typical plot of rainfall collected by the ram gauge. Periodically, the rain gauge must be emptied and this is indicated on graphical plots by a sudden drop in water level. The design presented here costs significantly less than the commercially available weighing type rain gauge and the added cost of a wind shield is also avoided. It has served well in studies of disturbed areas for over five years.

## Free Drainage Lysimeters

A free drainage lysimeter is a device installed below the surface which traps infiltrating water. A pan buried in soil is an example of a type of free drainage lysimeter. The principle is simple; infiltrating water on its way to the groundwater system collects in the pan. Installing the pan beneath the surface, however, disturbs the original fabric of the soil altering many of its properties, including the capacity to transmit water. In addition, the natural attraction of water to the surface of particles will hold and keep infiltrating water from entering a cavity. In fact, water enters a subsurface cavity only after a saturated zone (perched system) develops and the pressures in this perched zone exceed the pressure in the cavity (the pressure in the cavity will be equivalent to atmospheric pressure if the cavity is vented to the surface). Before the pressures in the perched zone above the lysimeter cavity exceed the pressure in the cavity, water may actually flow laterally, bypassing the lysimeter.

The monolith lysimeter is a type of free drainage lysimeter designed to avoid many of the problems described above. The term monolith refers to the undisturbed block of sediment that collects infiltrating water. Monolith lysimeters have traditionally been used to measure both infiltration and evapotranspiration directly in agricultural studies. In a study of the impact of surface mining on the groundwater of small drainage basins in eastern Ohio, Helgesen and Razem (1980) assumed infiltration was equivalent to that measured with monolith lysimeters (Harrold and Dreibelbis, 1967) on similar materials. Monolith lysimeters are expensive to install and operate, a significant disadvantage.

The free drainage lysimeter described here has many of the features of a monolith lysimeter without the installation and operation costs. The lysimeter has three components, a receiving section, a drain, and a reservoir (Figure 2). The receiving section is composed of any nonporous cylindrical material with a diameter in excess of 25 cm. Previous studies have used plastic buckets or PVC pipe (10 in; 25.4 cm). A PVC cap seals the base if PVC pipe is used. An interval at the base of the receiving section (5 to 10 cm) is filled with coarse quartz silica sand. The remainder of the receiving section is filled with compacted soil (spoil or other native materials) from the study area. The sand acts as a filter between the compacted soil in the receiving section and the reservoir. The length of the receiving section is selected to contain the perched system that will develop above the interval filled with quartz sand, thereby preventing lateral flow around the lysimeter. The height of the lysimeter is a function of the particle size distribution of the soil, but a height of 30 cm should work under most conditions. Water infiltrating through the soil enters the lysimeter and saturates the compacted soil in the receiving section. Once sufficient pressure develops, water will seep into the sand, then move through the drain and into the 5.1 cm (2 in) diameter reservoir. In laboratory tests with coal refuse, this type of lysimeter collected 93% of applied artificial rainfall (Brammer and Esling, 1989). Lysimeters with smaller diameter receiving sections collected significantly less of the applied rainfall. The free drainage lysimeter samples a representative area and allows continuous passive monitoring of natural seepage through the vadose zone.

The lysimeter should monitor soil in the study area that reflects ambient conditions. In disturbed ground this means soil compacted by heavy equipment. One option is to install the lysimeters prior to reclamation in large diameter auger holes or trenches dug with a backhoe. The soil above the receiving section then reflects actual site conditions. Installation after reclamation requires a different approach. In this case, the lysimeters are installed in the sidewalls of access pits dug into the soil to the desired depth (Figure 2). The soil directly above the lysimeter receiving section will remain relatively undisturbed with this method of installation. The void space around the lysimeters is packed with soil and the access pit is backfilled. Only the standpipe for the reservoir is apparent at the surface. Care must be taken to ensure that the soil in the lysimeter receiving section contacts the soil above the lysimeter. If gaps exist, a perched system may develop possibly diverting flow away from the lysimeter receiving section. In laboratory tests, perched conditions actually prevented any water from entering the lysimeter reservoir (Brammer and Esling, 1989).

At the end of an infiltration event, a significant quantity of water will remain in the lysimeter receiving section, water held by capillary tension that would have continued to flow downward if the

lysimeter was not installed. As drier conditions return, this water may move up and out of the receiving section, a phenomenon known as wicking. The amount of water that the receiving section could absorb at any one time will depend on the initial moisture content. The total volume of water needed to create saturated conditions to drive water into the basal reservoir of a 25.4 cm diameter lysimeter ranged from 1583 to 2350 ml, equivalent to 3.1 to 4.6 cm of infiltration (Esling and others, 1995). Wicking of this water out of the receiving section would lead to a substantial difference between actual infiltration and that measured by the lysimeter.

Esling and others (1995), however, showed that the wicking error does not occur with each infiltration event. They installed gypsum blocks (7/8 in (2.2 cm) diameter Soil Moisture Equipment Corporation Model 5201) within the receiving section of the lysimeters to monitor wicking in the field. In an environment producing acid drainage, gypsum blocks have only a short life span. The blocks indicated relatively consistent moisture contents before they failed, however, suggesting that the coal refuse in the receiving section remained saturated or near saturated for extended periods of time. These stable moist conditions suggest that wicking may not be a large source of error during the late fall and winter, when recharge is more common.

Esling and others (1995) equipped the reservoir with a vibrating wire transducer for monitoring water level continuously. The transducer has an accuracy of  $\pm 0.35$  cm of water. The cross-sectional 10.8 of the lysimeter receiving section and the standpipe differ by a factor of 25. Therefore, one centimeter of infiltration translates to a change in water level within the reservoir pipe of 25 cm, suggesting that the lysimeters can resolve  $\pm 0.014$  cm of infiltration. Other factors can affect the theoretical resolution and a typical plot of data (Figure 2) suggest a resolution off 0.06 cm of infiltration, which is excellent.

In some cases, lysimeters have collected anomalous high levels of infiltration, values in excess of rainfall (Esling and others, 1995). One possible explanation is that the backfill to the installation pit was not compacted properly and a perched water system developed in the disturbed ground. Saturated conditions in the pit till could discharge water into the lysimeter. Esling and others (1995) discussed this possibility and noted that with time the fill compacted to a density comparable to that of the undisturbed coal refuse, yet infiltration in excess of rainfall continued for shallow lysimeters. They suggested that subsurface saturated flow as a perched system at some level above the top of the lysimeter delivered water to the receiving section. This observation, although unexpected, is still valuable information on site hydrology.

It is important to clarify one very important point about the lysimeters described above. They are inexpensive, with costs of materials and installation comparable to that of a shallow groundwater monitoring well. To function, the lysimeter standpipe does not need to be equipped with a pressure transducer connected to a data logger. Field personnel can retrieve data from the lysimeter in the same way and at the same time that data are retrieved from groundwater monitoring wells. Vibrating wire pressure transducers are only necessary in order to monitor infiltration remotely over short intervals. Only one additional piece of field equipment is required, some type of pump to drain the lysimeter stand pipe.

Free drainage lysimeters can also provide samples of water that has moved through the vadose zone. The small volumes often collected, however, can make analysis difficult. In addition, the quality of the trapped water may change now that it is in contact with plastic and the atmosphere and no longer in contact with soil particles. Therefore, samples must be retrieved soon after accumulating in the reservoir.

In spite of their deficiencies, free drainage lysimeters are the only instruments that passively trap natural infiltration under ambient moisture conditions. Other vadose zone instruments, described below, can provide data on the performance of the free drainage lysimeters; data that can verify lysimeter results or warn of particular problems.

### Ring Infiltrometer

Infiltrometers artificially induce infiltration. Therefore, they cannot measure natural infiltration as a result of precipitation. They can, however, test the performance of a free drainage lysimeter. ASTM (1991) procedures recommend driving the ring of an infiltrometer into the ground to a depth of several centimeters. With this method of installation, however, water in the infiltrometer can flow through macropores and erode non-cohesive disturbed soil along the infiltrometer edge, a problem common to coal refuse sites and spoil in surface mines. A better method of installation is to set the infiltrometer 18 cm deep into an 8 cm wide and 20 cm deep trench filled with a cement/bentonite slurry, and then left to set for several days.

In infiltrometer tests, water is regularly added so that the refuse bounded by the infiltrometer walls remain below water level. A plastic tarp covers the ring to minimize evaporation losses and to prevent precipitation influx. A small hole in the tarp allows pressures inside the infiltrometer to adjust as the atmospheric pressure changes. A pan of water under the tarp can monitor evaporation. In testing free drainage lysimeters, the infiltrometer should lie directly above the receiving section of the lysimeter. The lysimeter standpipe must remain outside of the infiltrometer, however, because the interface between the pipe and soil may act as a preferred pathway for water that could by-pass the lysimeter.

### Time Domain Reflectometry

Esling and others (1995) reviewed time domain reflectometry theory, summarized here. Since the early 1940's, scientists have recognized that there is a relationship between the dielectric properties of soil, rock and other materials and their moisture content. In essence, the propagation of an electromagnetic wave is a function of the dielectric constant. Time domain reflectometry, a technique that evolved primarily from radar research in World War II, is a way of defining the dielectric relationships by measuring the transit time of electromagnetic waves along a probe placed in the soil. The theory behind the determination of the constant has been discussed by several authors (Ledieu and others, 1986; Smith and Tice, 1988a, 1988b). Topp and others (1980, 1982) and Topp and Davis (1982, 1985) described early applications of the technique.

The complex dielectric is a function of the different materials through which the electromagnetic wave passes. The velocity (V) of the waves in soil is related to the velocity in free space by the relationship:

$$V = C/\sqrt{K} \quad (1)$$

where:

K = permittivity  
C = velocity of light

For soil, consisting of three components; air (K = 1), soil grains (K = 3 to 5) and water (K = 81), the wave velocity is a function of the relative proportions of each. Since the dielectric constant of water is so much larger than either soil or air, the existence of water in the soil column is easily detectable (Ledieu and others, 1986). It should be noted that temperature corrections do need to be applied since the dielectric constant of water is temperature dependent. Ledieu and others (1986) discussed this correction.

The source generates a high-frequency electromagnetic pulse which travels down a parallel set of wave guides which are inserted into the soil (the Trase System from Soil Moisture Corporation is one system available). The reflectometer measures the time it takes the wave to travel down the guides, reflect off the open ends of the guides and return along the original path. This travel time is then used to directly calculate the dielectric constant of the soil and subsequently the volumetric water content of the soil, since the water content is the primary control on the velocity of the wave propagation.

The wave guides (Soil Moisture Equipment type) have three parallel steel probes with lengths of 30 cm. Ledieu and others (1986) and De Clerck (1985) demonstrated that the electromagnetic energy is confined to a cylinder around the rods with a diameter equal to approximately twice the distance between the outer rods. For the 30 cm probes, the distance between the outer probes is 5 cm. Hence each probe can monitor the moisture content in a horizontal cylinder 10 cm in diameter and 30 cm long.

The measurement of volumetric soil moisture by time domain reflectometry is apparently not affected by relatively large variations in soil texture (Topp et al, 1980). This makes the method particularly applicable for measurements in heterogeneous coal refuse. If measurements of moisture content are taken at regular time intervals and at a series of depths, the change in moisture content can be converted into an infiltration rate.

Time domain reflectometry does suffer from one drawback; high total dissolved solids in the water flowing through the soil can attenuate the pulse, providing suspect readings or no readings at all. Obviously, sites producing acid drainage suffer from this problem. Work in one reclamation project, however, indicates that signal loss only occurs during a first flush (Esling and others, 1995). As infiltration continues, the level of total dissolved solids declines and the reflectometer again records successful readings.

### Tensiometers

Hydraulic head has two components; elevation head and pressure head. Under saturated conditions, the pressure head exceeds atmospheric pressure. This is why water will flow into a void space in saturated materials. In the vadose zone, however, the pressure head is less than atmospheric. If atmospheric pressure is the datum, the pressure head under saturated conditions is positive, whereas in the vadose zone the pressure head is negative. This negative pressure, also known as tension, suction, or matric potential, actually develops because water is attracted to the surface of the soil grains.

The tensiometer can measure pressure head in the vadose zone. This instrument is composed of some length of plastic pipe (about 2.2 cm or 0.85 in diameter for the Soil Moisture Equipment type), attached to a porous ceramic cup. A vacuum gage is attached to the side of the tensiometer through an inverted "Y" connection molded into the sidewall of tensiometer. The tensiometer is filled with colored water to prevent algae growth and for easy detection of trapped air, then the tensiometer is sealed at the top. Water will seep through the ceramic tip, creating a vacuum in the tensiometer, until the tensiometer and soil in contact with the ceramic tip share the same pressure head. Water will flow into the tensiometer under moist soil conditions, when pressure head outside the ceramic tip exceeds that in the tensiometer.

The ceramic tip of the tensiometer must completely contact the soil in order to function properly. In spoil or coal refuse, large clasts are often dispersed in a fine matrix. The rock clast may keep the ceramic tip from completely contacting the fine-grained matrix. In these conditions, a hole is augured to the desired depth. The augured soil is screened to remove coarse clasts, then mixed with water to form a slurry which is then placed in the base of the hole. The tensiometer is pushed into the slurry so that the ceramic tip is completely covered. The remaining annular space is sealed to prevent leakage from the surface from reaching the base of the tensiometer. Well tamped soil may be sufficient, but an added seal well above the ceramic tip composed of bentonite slurry can further minimize leakage. Several hours may pass before the tensiometer and soil equilibrate.

Nested tensiometers, providing head data at different depths, can indicate the direction of water movement through the vadose zone. They can thus monitor wicking above a lysimeter. Limits on the tensile strength of soil water and physical limitations of the tensiometer, yields a lower operating limit of about 85 centibars. Therefore, under very dry conditions, tensiometers cease to function.

## Suction Lysimeters

A free drainage lysimeter passively collects water seeping through the vadose zone. In contrast, under a vacuum, the suction lysimeter actively extracts vadose zone water samples. The device has a simple design; composed of a porous ceramic tip connected to some length of 4.8 cm (1.9 in OD) plastic pipe (up to 1.8 m long for the Soil Moisture Equipment type). Only a short length of the suction lysimeter (5 cm), is evident at the surface. A stopper assembly, which includes a hose and valve, seals the top of the lysimeter. A vacuum, on the order of 50 to 85 centibars, is established by removing air with a hand pump through the hose. Water flows through the vadose zone, through the ceramic tip, to collect in the lysimeter. In soils having low permeability such as spoil or coal processing waste, sufficient sample may take days to accumulate. The sample collected is removed through a simple apparatus with a pump.

The suction lysimeter is installed in a hole augured to a diameter of 5 to 10 cm. Larger diameter holes are necessary in coarse refuse. Like the tensiometer, the key is to establish a complete contact between the soil and the ceramic tip of the suction lysimeter. As with tensiometer installation, the material removed from the auger hole is screened to remove large clasts, then mixed with water to produce a slurry. Sufficient slurry is first placed in the base of the hole to cover the ceramic tip. The suction lysimeter is pushed into the slurry. Finally, the annular space between the lysimeter walls and hole are sealed to prevent surface water from seeping along the casing to the base of the lysimeter. Again, a bentonite slurry plug well above the ceramic tip can minimize leakage.

Samples collected with the both free drainage and suction lysimeters can provide a better understanding of vadose zone water chemistry. Both instruments suffer from the same drawback; water often remains in the free drainage lysimeter reservoir or suction lysimeter casing for days, where its quality may change.

## **Applications**

This section presents two examples of multi-instrumented studies of vadose zone hydrology in areas disturbed by mining. In the first case, a single, rare, precipitation event (herein called the event) over a two day period totaling 19.37 cm, with three separate precipitation episodes of 1.97, 1.35, and 16.05 cm, impacted the study area (Esling and others, 1995). Figure 3 presents data from time domain reflectometry, an infiltrometer, one of the lysimeters, and a rain gauge at the site. Note that prior to the event, the lysimeters and rain gauge provided stable readings.

Over the duration of the event, lysimeters LIB, L2A, and L2B captured about 4.4, 2.0, and 2.6 cm of infiltration, respectively. The two shallow lysimeters, L2A and L2B, with receiving sections at depths of only 20 cm, captured a small amount of infiltration from the first two precipitation episodes (Figure 3). These lysimeters responded immediately after the onset of the third and largest precipitation episode, collecting infiltration at a constant maximum rate until precipitation ended. They continued to trap infiltration for a period of about four days after the precipitation ceased, but at a much lower rate. The maximum rate of infiltration was unique to each lysimeter with rates of 2.6, 4.8, and 5.2 cm/day for L2A, L2B, and LIB, respectively.

The infiltrometer test was conducted before and during the hydrologic event. Although the rate of infiltration as measured by the infiltrometer changed as a consequence of the event, the lack of continuous data collection precluded a detailed analysis. The moisture content beneath the infiltrometer as determined by time domain reflectometry, however, showed interesting temporal trends. At 0.6 m below the ring, just after the onset of the last precipitation episode, the moisture content suddenly jumped from 29.7% to 45.4%. This elevated moisture content was sustained until just after precipitation ended, at which time the moisture content dropped to 33.5%. Prior to the hydrologic event, moisture content

beneath the infiltrometer increased gradually and after precipitation ended, the moisture content appeared to follow a trend similar to the one that existed before the event.

The infiltrometer provided a continuous source of water for seven days prior to the hydrologic event, yet moisture content increased gradually and appeared to be leveling off just prior to the onset of the last precipitation episode. What could lead to elevated moisture contents at a depth of 0.6 m if a continuous source of ponded water could not? Lateral water movement under saturated conditions from farther upslope is the most likely explanation, although other interpretations are possible. Hillel (1980) described a unique phenomenon occurring at sites with alternating coarse and fine-grained layers. Water would not move into certain portions of the unsaturated zone until pore pressure greatly increased, as may occur with a large infiltration event. Coal refuse texture was noted while excavating the pit for the installation of the time domain reflectometry probes. The probe at 0.6 m was installed within matrix-dominated refuse about 7.5 cm above a clast supported gravel and 20.3 cm below a coarse-grained matrix-supported layer. Increased infiltration during the rainfall period indicates that increased moisture content outside the ring facilitated greater water movement through the refuse beneath the ring. Natural infiltration rates are often inferred from infiltrometer tests, but the results of this study suggest that infiltrometers do not simulate natural infiltration through heterogeneous material such as coal refuse.

The shallow time domain reflectometry probe, installed at a depth of about 0.3 m, showed a somewhat different response to the final precipitation episode. During the first seven days of the ring infiltrometer test, as the moisture content rose, the occurrence of failed readings from time domain reflectometry increased. The high acidity associated with the coal refuse leads to high ion concentrations, a condition that may cause a dissipation of energy from time domain reflectometry. During the final high intensity precipitation episode, the shallow probe again yielded successful readings, possibly because flushing by fresh rainwater decreased the ion concentration.

In the second example, Esling and others (1995) conducted an 1.8 m diameter infiltrometer test over two lysimeter receiving sections, both at depths of 0.6 m. A one meter deep access pit was excavated adjacent to the infiltrometer, outside of the cement/bentonite seal. They installed two 30 cm long wave guides horizontally in the side walls of the access pit beneath relatively undisturbed refuse, at two different horizons between the infiltrometer and the lysimeters. The wires to the wave guides were routed through a 5.1 cm (2 in) ID PVC pipe to the surface. This pipe was sealed with a cement/bentonite mixture to prevent infiltration through the loose fill of the access pit from reaching the wave guides. The pit was carefully refilled back to grade. A small channel around the pit and a plastic cover prevented runoff or precipitation from eroding the disturbed loose backfill.

Figure 4 summarizes time domain reflectometry, lysimeter, and infiltrometer data collected over a seven hour test (Esling and others, 1995). No natural precipitation fell during this time. All data were collected manually. Early in this project, lysimeter LIA provided data distinctly different than the other lysimeters, generally collecting little or no infiltration during events when the others captured significant infiltration. During the infiltrometer test, however, lysimeter LIA collected water at a rate higher than that provided by the infiltrometer. LIA collected 16.1 cm of infiltration during the first four hours of the test, whereas LIB collected only 2.6 cm and the infiltrometer delivered less than 8 cm for the same time period. What could cause such contradictory data? Leakage along the casing of the lysimeter standpipe can be discounted; the infiltrometer was not installed over the standpipes. A macropore connecting the surface to the receiving section of LIA could have transferred a quantity of water greater than that yielded through intergranular flow to LIB. The behavior of the lysimeters offers important insight into the hydrology of this particular site; information that a single instrument could not have provided.

The response of LIB to the infiltrometer test suggests that the lysimeters can be effective tools for monitoring infiltration. Early in the infiltrometer test, water seeping into the refuse increases the moisture content to field saturation. Only then can water flow into lysimeter LIB, which began capturing infiltration about 2 hours into the test. The rate of infiltration into LIB and that of the infiltrometer, just under 3 hours into the test were approximately the same. Time domain reflectometry, as a tool for

monitoring moisture content in coal refuse piles has some deficiencies. The lower probe failed to return readings on moisture content because of time measurement errors, apparently because of high total dissolved solids content in the infiltrating water. The upper wave guides (Figure 4) showed the gradual increase in moisture content as a consequence of the intiltrometer test.

### **Conclusions**

This paper describes instruments for monitoring the vadose zone in studies on the environmental impact of different reclamation methods. Even with its deficiencies, the free drainage lysimeter shows promise as a tool for monitoring natural infiltration under ambient moisture conditions through reclaimed areas. Data collected by other vadose zone instrumentation, such as time domain reflectometry, tensiometers, or suction lysimeters, can verify lysimeter results or warn of particular problems.

The instruments discussed here represent only part of the instrumentation necessary to conduct detailed study on the impact of a particular reclamation method. Other instruments for monitoring the vadose zone may also have application in reclamation research. In addition, research should also monitor groundwater conditions in the saturated zone. Readers should consult procedures for the proper installation and sampling of groundwater monitoring wells to guarantee reliable data. In particular, a sampling plan appropriate for new statistical procedures designed to confirm a detection of some contaminant downgradient, is essential.

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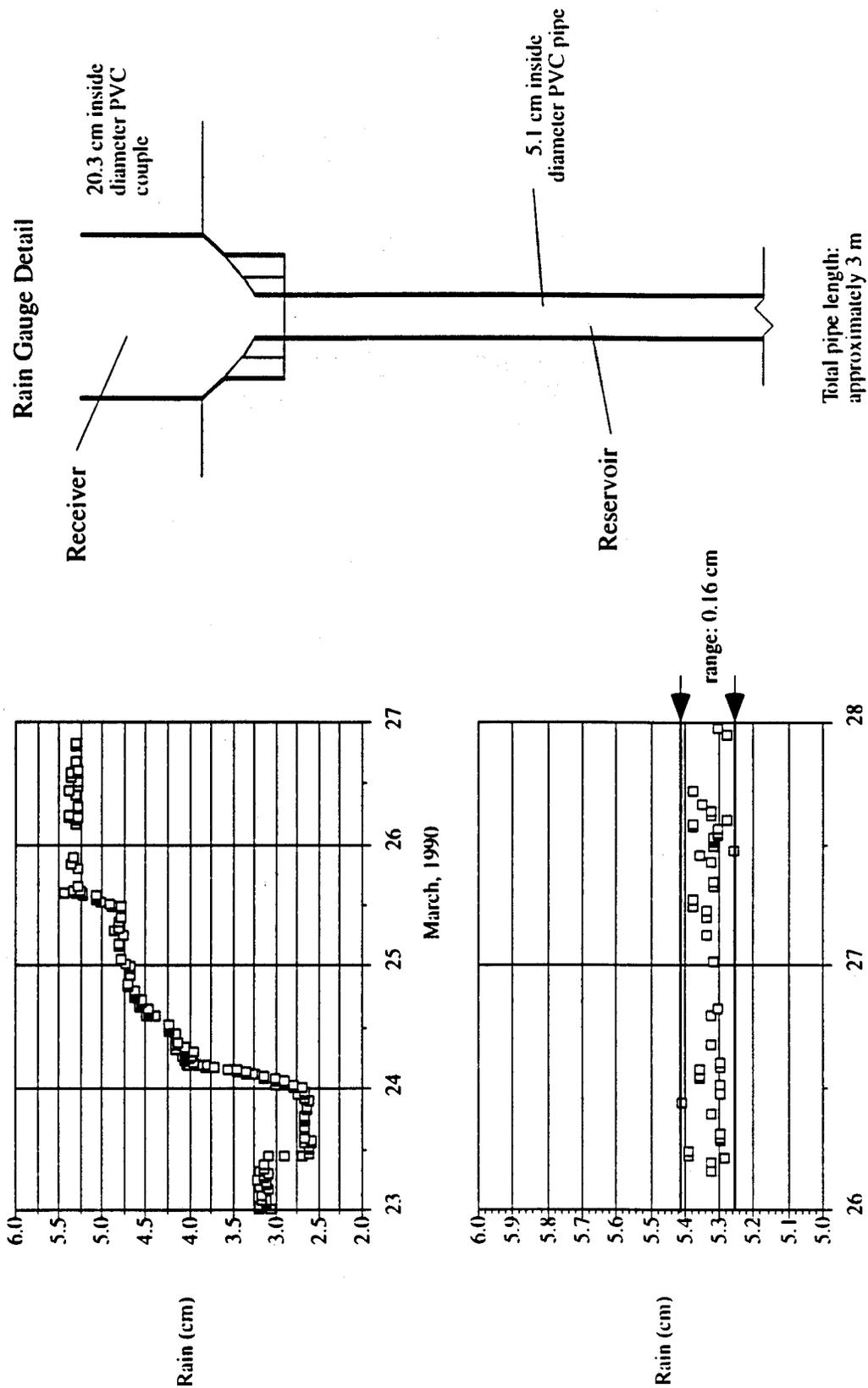
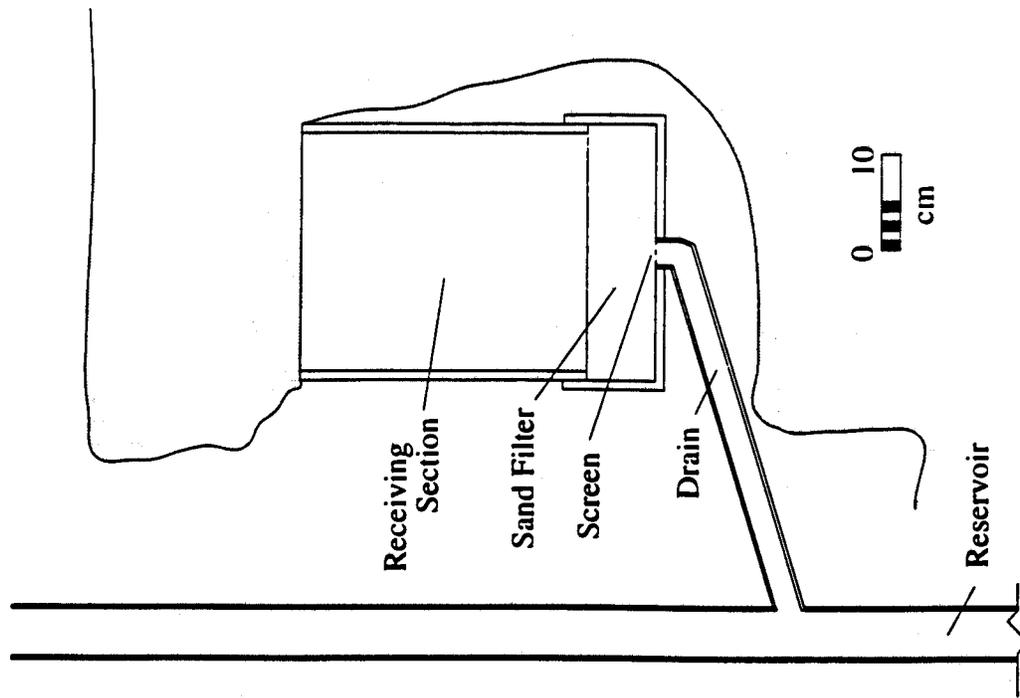


Figure 1. Schematic diagram of the rain gauge. The range in values suggest a practical resolution for the rain gauge of approximately  $\pm 0.08$  cm. The figure also shows a typical graph of rainfall data through time. A drop in water level in the rain gauge indicates a time when it was emptied. (Data from Esling and others, 1995)

Lysimeter Detail



Typical total length: 3 m

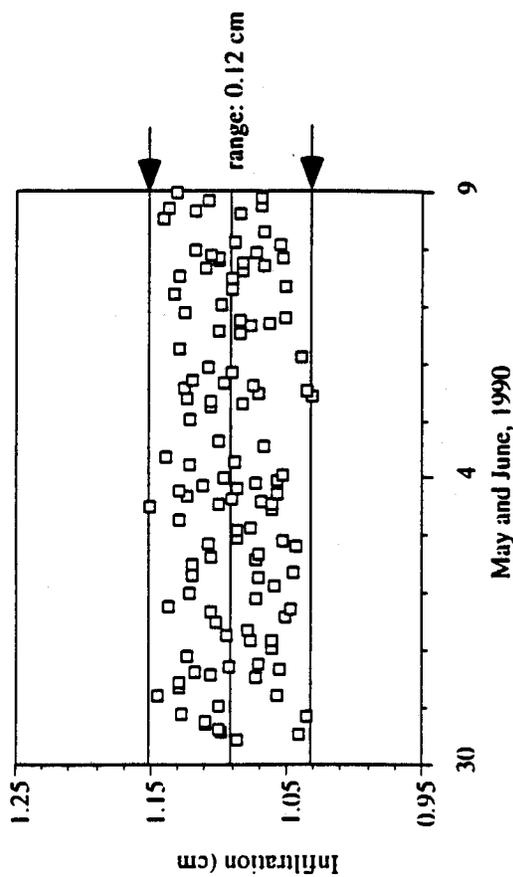


Figure 2. Lysimeter detail and data plot. The range in values (Esling and others, 1995) suggest a practical precision for the lysimeter of approximately  $\pm 0.06$  cm.

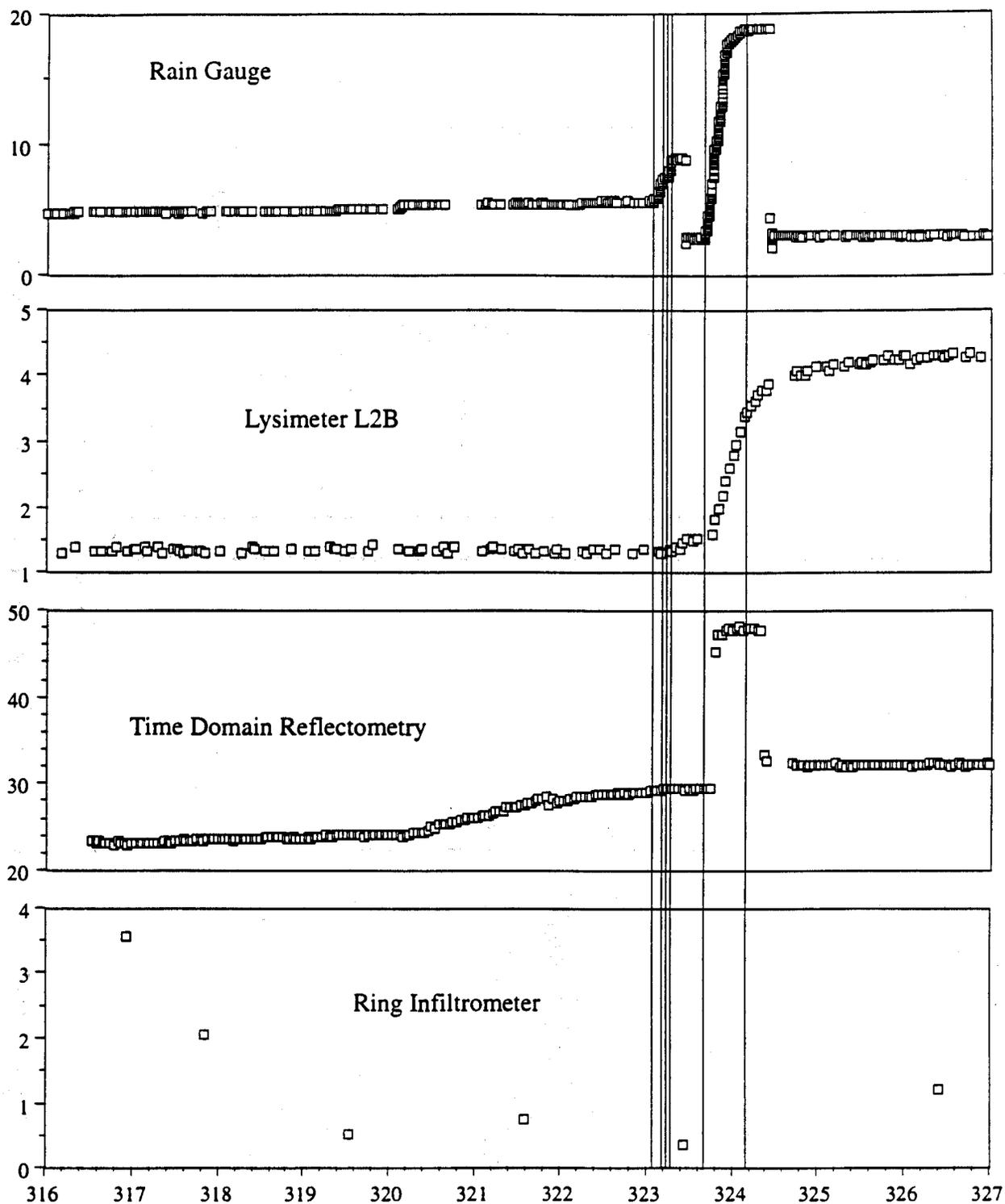


Figure 3. Hydrologic data collected from the vadose zone during a single precipitation event. Horizontal axis is in days. Vertical axis for the infiltrator is in milliliters per day. Vertical axis for the rain gauge and lysimeter is in volume of water per unit area (centimeters). Vertical axis for the TDR data is in percent by volume moisture content. (Data from Esling and others, 1995).

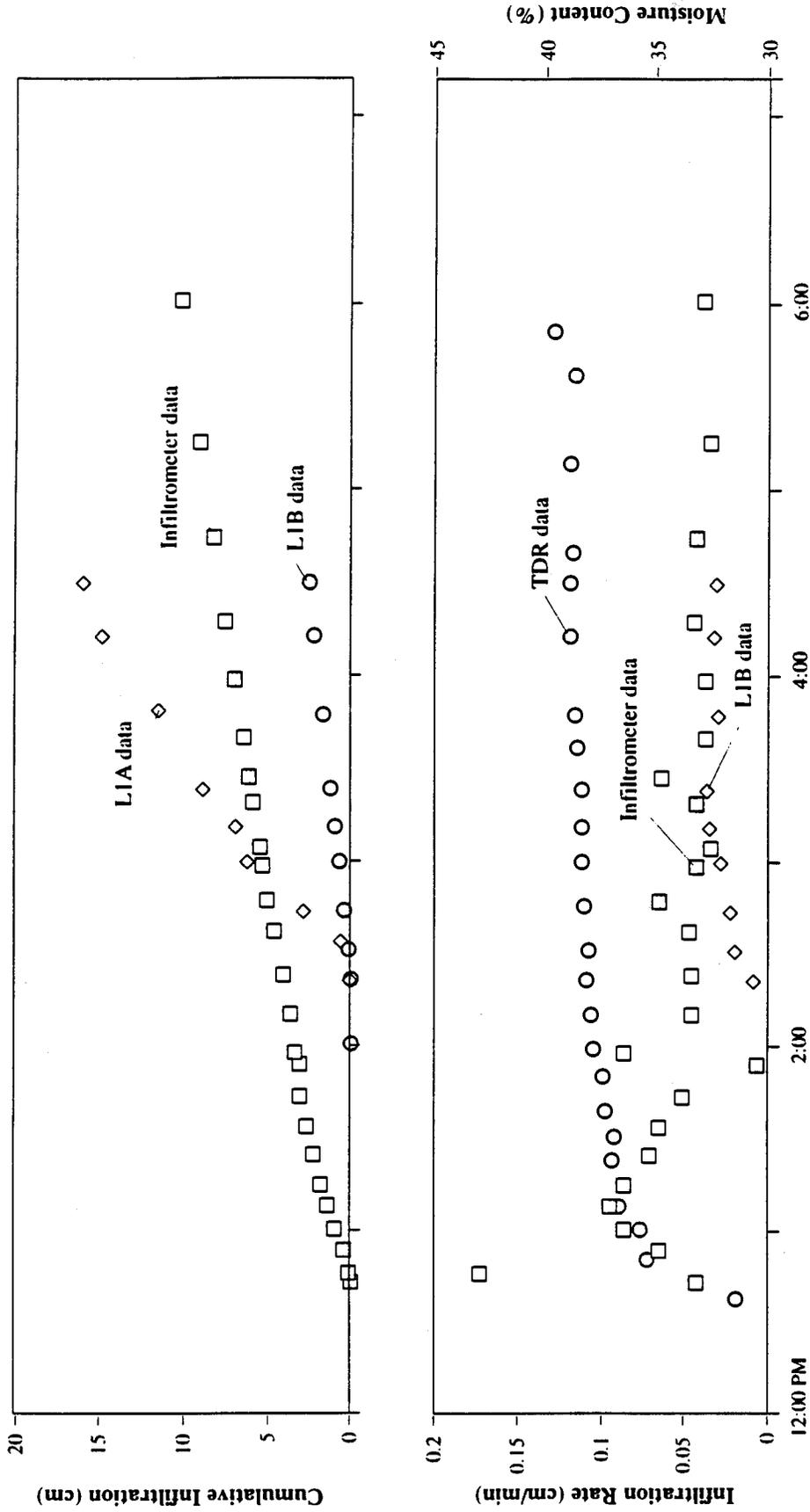


Figure 4. Plots of cumulative infiltration, infiltration rate, and moisture content for the first seven hours of an infiltrometer test (Data from Esling and others, 1995).

**Session VII:**

**CASE STUDIES**

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## COAL COMBUSTION FLY ASH AS CONSTRUCTION MATERIAL IN A SANITARY LANDFILL PROJECT

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### Abstract

This paper describes a project in which nearly one million tons of Class F fly ash were used as a substitute subgrade fill material in place of natural soil during the construction of a new cell of a sanitary landfill in southern Delaware. The paper discusses the basic design of the landfill cell, the engineering properties of the fly ash, the transportation and placement of the fly ash, and the relative economics of substituting fly ash for natural soil in this project.

### Background Information

#### Description of Landfill Facility

The Delaware Solid Waste Authority (DSWA) owns and operates three sanitary landfill facilities in the state. The Southern Solid Waste Management Center, sometimes referred to as the Jones Crossroads Landfill, is located on State Route 20 in central Sussex County. The facility is situated near the town of Hardscrabble and is approximately 14 miles away from Millsboro to the east and 10 miles away from Seaford to the west.

The Hardscrabble landfill was originally opened in September, 1974. The entire landfill property occupies 572 acres of land, much of which is still wooded. For the first 14 years of operation, municipal solid waste was placed into a single cell. In 1988, a second cell was constructed at the landfill. At that time, DSWA officials agreed to the use of fly ash on an experimental basis as a portion of the subgrade fill material that was used for cell number 2 construction.

In 1995, construction began on cell number 3 of the landfill. This involved the clearing of approximately 15 acres of woodlands and the removal and re-use of topsoil within the cleared area. Groundwater in the vicinity of the new landfill cell was generally found within 2 feet below the ground surface, causing soft soil support conditions.. The depth of subgrade fill material beneath the new liner system for cell number 3 was designed to vary from 6 to 22 feet.

Approximately 690,000 cubic yards of subgrade fill material were required to be placed and compacted beneath the liner system for cell number 3. An additional 60,000 cubic yards of fill material were required for berm construction. Because of the availability of granular borrow material in Sussex County, original cost projections by DSWA for earthwork construction were based on the use of select borrow from sand and gravel suppliers in the general area.

Figure 1 is a site plan of the Sussex County landfill facility, showing the layout of the two existing landfill cells and the location of new cell number 3. Figure 2 is a cross-section of the new cell, indicating the configuration of the subgrade fill material and the design of the liner system and associated leachate collection systems.

### Initial Ash Marketing Efforts at the Landfill

After the construction of cell number 2, Baker Engineers of Beaver, Pennsylvania analyzed the shear strength of the fly ash and reported that the fly ash performed acceptably in cell number 2. In anticipation of the construction of cell number 3, Delmarva Power, together with VFL Technology Corporation, its ash marketing contractor, developed a long-range strategy for obtaining DSWA approval for the use of fly ash on this project.

Because of the successful use of fly ash in cell number 2, key personnel at DSWA were already familiar with the characteristics and benefits of Indian River fly ash. Also, in 1986, VFL Technology had constructed a new 2 mile long haul road into the Hardscrabble facility and the road was built with a cement-fly ash-bottom ash stabilized base, resulting in a cost savings of more than \$250,000 compared to the original design using crushed stone base. Over its 10 year life, this haul road has performed very well and has still not needed to be resurfaced.

The first step in the formal approval process for using fly ash in cell number 3 involved a meeting between representatives of Delmarva Power and personnel from DSWA and Geosyntec Consultants of Baltimore, Maryland, the designers of the new landfill cell. This meeting was useful in identifying what additional information was needed in order to permit fly ash to be incorporated into the design of the new cell.

As a follow-up to this meeting, Delmarva Power engaged the services of John Hynes Associates of Salisbury, Maryland to obtain representative samples of Indian River ash and to analyze the geotechnical properties of the fly ash. The analysis concentrated on the grain size, unit weight, moisture-density, shear strength, and permeability characteristics of the ash, especially on the relationship of the shear strength to the degree of compaction of different ash samples with a variable amount of carbon. Additional factors favorably influencing the selection of fly ash were its low unit weight and low permeability.

### Ash Approval as Alternate Material

In the spring of 1994, after an extensive review of the geotechnical information submitted by Delmarva Power, Geosyntec modified the project specifications for subgrade fill material to permit fly ash to be used as an alternate to granular borrow material. Fly ash was also permitted to be used for constructing the interior portion of the perimeter berm and sedimentation basin embankments, although fly ash placement was limited in the specifications to within 3 feet of the exterior portions of the berms and embankments.

Additional data was also provided to DSWA and Geosyntec on the leachate characteristics of Indian River fly ash using the Synthetic Precipitation Leaching Procedure (SPLP). After a careful review of the engineering and environmental properties of the fly ash, DSWA granted its final approval for the use of fly ash in cell number 3 in November, 1994.

### **Description of Ash Sources**

Fly ash approved for use in the Hardscrabble landfill project was produced from two sources in southern Delaware. The primary source of fly ash was from Delmarva Power's Indian River power plant, located approximately two miles east of Millsboro. An alternate source of fly ash was from DuPont's Seaford nylon plant, located in Seaford. Each of these plants and ash sources is described in this section.

### Indian River Power Station

The Indian River power station consists of four coal-burning units having a total rated capacity of 782 megawatts (Mw). Bituminous coal is supplied to the plant by rail from sources in Pennsylvania,

Virginia, West Virginia, and Kentucky. The plant is equipped with electrostatic precipitators and cooling towers. Approximately 240,000 tons per year of fly ash are produced at the Indian River power station. The fly ash is collected and stored in silos. The majority of the fly ash in the silos is water conditioned and placed into an on-site storage area. Ash is excavated and removed from the storage area as utilization opportunities occur. Some dry fly ash is also made available to local ready-mix suppliers for producing flowable fill.

### Delmarva Power Ash Marketing Program

In the late 1980's, Delmarva Power recognized that, in order to develop a credible-and successful ash marketing program, it was necessary to spend money up front to establish the necessary infrastructure at the power plant to facilitate supplying large volumes of ash to end use locations. In the fall of 1991, a new haul road was built on site to handle ash deliveries. Shortly thereafter, construction began on a new weigh scale and adjacent ash marketing building, both of which were placed into service in early 1992.

Delmarva Power then contracted with VFL Technology Corporation for management of all the ash from the Indian River power plant, including an estimated 2 to 3 million cubic yards of ash that is contained in the on-site storage area. Delmarva Power and VFL are constantly seeking opportunities for utilization of Indian River fly ash and bottom ash, particularly in high-volume applications. In addition to DSWA, users of Indian River ash include Delaware and Maryland state highway agencies, contractors, and ready-mix suppliers.

Indian River fly ash was used for embankment construction on a section of State Route 1 near Dover, Delaware and at the new Route 301-213 interchange near Galena, Maryland. This material has also been used as a structural fill for the construction of lagoon containment berms at wastewater treatment plant facilities in Georgetown, Delaware and Berlin, Maryland, as well as for flowable fill. Both the fly ash and bottom ash from Indian River have been used to produce cement-stabilized roller compacted base materials for parking lots, local streets, and haul roads, including ones for the Hardscrabble landfill and the power plant itself.

### Experimental Ash Haul Road

During October, 1991, in anticipation of the additional truck traffic associated with supplying large volume ash projects, Delmarva Power constructed and designed a 3,500 foot long ash haul road on the Indian River power station property. The purpose of the haul road was to facilitate access to and from the Indian River ash storage area for ash hauling vehicles while demonstrating the performance of cement-stabilized roller compacted ash base materials to the Delaware Department of Transportation (DEL DOT). Delmarva Power also envisioned the use of this haul road as the quickest and least congested route for dump trucks hauling ash to high volume utilization sites.

The haul road consisted of five 700 foot long sections, involving a control section at each end with three cement-stabilized ash sections in the middle. The composition of the five test sections is as follows:

- Control A - Crushed concrete aggregate base
- Mix No. 1 - Indian River fly ash -bottom ash - cement
- Mix No. 2 - Indian River fly ash -borrow soil - cement
- Mix No. 3 - DuPont Seaford fly ash - borrow soil - cement
- Control B - Borrow soil - cement base

The crushed concrete aggregate was placed to a total thickness of 12 inches. The three ash test sections, as well as the soil-cement control section, were placed to a compacted thickness of 8 inches. A total of 3 inches of asphalt was placed over all the base course test sections. The borrow soil in three of the test sections was a well graded coarse to fine sand that was obtained from an existing on-site borrow

pit that was only a few hundred yards away from the haul road.

Aside from the late season temperatures, which resulted in fairly low initial curing, there were few problems encountered in the construction of the haul road. This road has been in service for five years and has accommodated a substantial amount of heavy wheel loadings during that time; In fact, it is estimated that at least 1.5 million tons of ash have been hauled over this road during the past five years.

With the exception of a few small isolated areas of cracking, the surface of the haul road is virtually free of distress. This haul road has been extremely beneficial in allowing Delmarva Power to load and supply large quantities of ash to construction projects in lower Delaware and the Eastern shore of Maryland without disrupting traffic within the power station or in the immediate surrounding area.

#### DuPont Seaford Nylon Plant

The other approved source of fly ash for the Hardscrabble landfill project was the ponded ash from the DuPont nylon manufacturing facility, located at Seaford, Delaware. This facility was the first nylon manufacturing plant in the United States and was constructed in 1939. The power plant at this facility burns coal from Virginia and West Virginia and produces approximately 25,000 tons per year of fly ash and bottom ash, which is sluiced into two on-site ash holding ponds. Ash is periodically reclaimed from the ponds and stockpiled on nearby ground to assist in dewatering the ash. The stockpiled ash from these ponds was also occasionally supplied to the Hardscrabble landfill project.

### **Project Description**

#### Design of Landfill Cell Number 3

New landfill cell number 3 measures approximately 1,000 feet long by 1,000 feet wide. During the next 8 to 10 years of operation, it is projected to extend to a maximum overall height of approximately 50 feet. The cross-section of the landfill berm, as shown in Figure 2, is designed with slopes of 3 horizontal to 1 vertical. It is anticipated that cell number 3 will be able to receive an estimated 655,000 tons of solid waste during its operating lifetime.

The new cell is designed to have a leachate collection system underlain by a double liner. The leachate collection system consists of a network of perforated PVC collection pipes surrounded by bedding gravel sandwiched between a layer of washed sand above and below the gravel. The leachate collection system includes leachate-collection manholes located on either side of the landfill cell, solid PVC leachate collection piping, and a pumping station which directs the leachate into one of four 30,000 gallon above ground leachate storage tanks, two of which are located on either side of the landfill cell. The leachate is ultimately recirculated back through the solid waste within the landfill cell.

The double liner system beneath the leachate collection system consists of two 30 mil polyvinyl chloride (PVC) synthetic liners. Between the primary and secondary liners is a 12 inch thick layer of washed sand that comprises the leak detection system. This leak detection system operates independently from the leachate collection system and is installed to detect leachate which may have permeated the primary liner. The leachate detection system drains the leachate through solid PVC piping into leachate detection manholes located on either side of the landfill cell.

The secondary liner is supported by 6 to 22 feet of subgrade fill material, with an average depth of 15 feet. The secondary liner was designed to be at least 5 feet above the seasonal high water table at the site. Test borings taken in the area prior to the design of the cell indicated that groundwater in the vicinity of the new cell generally fluctuated within 2 feet of the ground surface. As shown in Figure 2, the subgrade fill material is also placed within the perimeter berm that surrounds the base of the cell. The double liner system is also extended up to the top of the perimeter berm and is supported by the subgrade fill material.

The Hardscrabble landfill accepts only municipal solid waste. The solid waste is placed and compacted in the landfill cell in 10 foot thick layers. At the end of each day, the active portion of the landfill area is covered with 6 inches of soil to minimize odor, vermin infestation, and wind-blown waste. The side slopes of the landfill cell will be maintained at a 3: 1 slope as the height of the landfill increases.

#### Bidding and Contract Award

Bids for the construction of cell number 3 at the Hardscrabble landfill were received on July 13, 1995. A total of 8 contractors submitted bids for this work. All but one of these contractors based their bids on using fly ash as subgrade fill material instead of granular borrow material. The low bidder for the project was a joint venture of George and Lynch of New Castle, Delaware, and David A. Bramble of Chester-town, Maryland, who had bid the project using fly ash.

The contract was awarded to George and Lynch/Bramble on August 8, 1995 and work commenced on September 13, 1995. VFL Technology Corporation engaged the services of David Horsey of Georgetown, Delaware to do all of the hauling of fly ash from the Indian River power station to the job site. VFL, with assistance from David A. Bramble, loaded all of David Horsey's trucks. Fly ash from the DuPont Seaford plant was loaded and hauled to the job site by George and Lynch.

#### Delivers and Placement of Fly Ash

Fly ash from the Indian River power station began being delivered to the job site on September 13, 1995. Two front end loaders and one power excavator were used to excavate and load the fly ash. For the first month, fly ash was delivered using 30 end dump vehicles and an average of 4,800 tons per day of fly ash was delivered to the job site.

After the first of the month, the number of end-dump trucks was increased from 30 to 80 and the average amount of fly ash from Indian River that was delivered to the job site was increased to approximately 8,000 tons per day. The maximum tonnage of fly ash that was delivered on any one day was 15,606 tons on December 12, 1995. The last day Indian River fly ash was delivered was on June 13, 1996. In all, a total of 872,105 tons of Indian River fly ash were delivered to the job site on 109 different days, involving a total of 43,605 truckloads.

Fly ash from the DuPont Seaford facility began being delivered to the job site on October 10, 1995. The last day fly ash from DuPont Seaford was delivered was November 5, 1995. In all, a total of approximately 51,000 tons of DuPont Seaford fly ash were delivered to the job site on 17 different days, which is an average of 3,000 tons per day. The total amount of fly ash from both power plants used as subgrade fill and/or berm construction material on this project amounted to 923,105 tons, making this one of the largest single ash utilization projects in the eastern United States.

According to the project specifications, subgrade fill and/or berm construction material was to be placed in loose lifts not exceeding 8 inches in depth, resulting in a compacted thickness not exceeding 6 inches. Each lift was to be compacted to at least 95 percent of maximum dry density, as determined by the standard Proctor method (ASTM D698). The moisture content of the subgrade fill and/or berm construction material when placed was required to be within 2 percentage points below to 1 percentage point above of the optimum moisture content, also as determined by ASTM D698.

#### Technical Aspects of Ash Placement

Moisture control of the Indian River fly ash was a cooperative effort between VFL's ash management personnel at the power plant and the project's geotechnical engineering consultant (Harding and Knight of Bishopville, Maryland). Ash to be delivered to Hardscrabble was excavated from the Indian River landfill the day before, stockpiled, and a series of one-point Proctor tests, were performed by VFL. The results of the one-point Proctor tests were shared with Harding and Knight, who determined

from a family of moisture-density curves what, if any, adjustments were needed in moisture content of the ash prior to delivery. Normally, the fly ash from the landfill required some additional water to be brought up to the target optimum moisture content of 37 percent. During rainy periods, ash from the landfill could be added to wet ash to lower the moisture content, as needed.

Field quality assurance of fly ash compaction was performed by using nuclear densimeter test methods, together with visual monitoring of lift thickness, number of passes, and response of each lift to the passage of construction equipment. One in-place nuclear density test was specified to be performed for every 10,000 square feet (100 feet by 100 feet) of surface area, with a minimum of six tests for every lift placed.

Fly ash was placed and compacted at the Hardscrabble landfill project on a total of 109 working days during the course of the project. During that time, an average of at least 50 in-place nuclear density tests were performed daily. On a typical day, the working area involved approximately 4 acres and at least three lifts of subgrade till material were placed. A total of 5,870 in-place density tests were performed during the course of ash placement.

Throughout the entire 10 months of construction of the base of cell number 3, only 2 percent of all the in-place density tests indicated that the specified 95 percent compaction value had not been achieved. During that time, only 1.8 percent of the moisture content values were found to not be within the specified percent of the designated 37 percent optimum moisture content. Nearly all of these instances occurred during rainy weather conditions. In locations where there was less than 95 percent compaction, additional compactive effort was applied. Normally, four passes of a vibratory roller were sufficient to achieve the desired compaction.

In locations where the moisture content was more than 2 percent below optimum, additional water was applied and the area recompacted. In locations where the moisture content was more than 1 percent above optimum, the area was scarified the full depth of the lift, allowed to air dry for a sufficient time, and then recompacted. Normally, these measures were able to bring the affected areas back into compliance within the specification requirements.

Early in the project, the contractor, in an effort to expedite the project, investigated the possibility of increasing the lift thickness from 8 to 12 inches. Because the fly ash is a relatively light material, compared to granular soil, it tended to form a small wave ahead of the roller when placed at the greater depth, making compaction more difficult. The additional roller passes needed to achieve the required degree of compaction more than offset any potential time savings from increasing the lift thickness. Therefore, it was decided not to modify the specified 8 inch loose lift thickness.

## **Logistical and Climatic Considerations**

### **Logistical Considerations**

The principal logistical considerations associated with supplying fly ash from the Indian River power station involved providing the necessary trucks and equipment and the routing of the trucks. In order to keep the project on schedule, it was necessary to supply George and Lynch with about 5,000 tons of fly ash for each working day. There were many days when VFL was able to supply 8,000 tons or more of fly ash to the project.

To supply at least 5,000 tons of fly ash per day required 30 dump trucks and two front-end loaders and one large power shovel with an 8 cubic yard bucket working a full 8 hours a day. Each truck hauled approximately 20 tons of fly ash per trip and was able to complete a round trip in roughly one hour. When supplying up to 8,000 tons per day of fly ash, as many as 80 dump trucks were used on a given day and a second power shovel was needed. When it was not possible to obtain enough dump

trucks, the hours per day were extended to 10 or even 12 hours, on those days there was sufficient daylight.

During the first month in which fly ash from the Indian River power station was delivered to Hardscrabble, all of the dump trucks hauling fly ash used the same route through the nearby town of Millsboro. This prompted concerns on the part of some residents along this route with regard to noise, dusting, safety, and long-term damage to the roadway.

Following a meeting between all involved parties, it was agreed that dump trucks, upon leaving the Indian River power station property, would take one of three possible routes through Millsboro. Once out of the town of Millsboro, all trucks took Delaware Route 20 to the Hardscrabble site. This minimized road damage and satisfactorily resolved the concerns of the local residents in Millsboro.

Throughout the duration of the project, care was taken to tightly tarp all loaded dump trucks in order to minimize or eliminate dusting during transport of the fly ash. There were no incidents of spillage or complaints about dust generation at any time during the 16 months that fly ash was being hauled.

### Climatic Considerations

By using fly ash as the subgrade fill material on this project, the number of days in which construction could not proceed due to weather conditions were minimized. The winter of 1995-96 involved a record snowfall accumulation. The spring and summer of 1996 were unusually wet. Very few working days were lost during the winter, except for days with heavy snowfall or accumulation. Virtually no time was lost due to sub-freezing temperatures because the fly ash was able to be spread and compacted below freezing and was still able to satisfy density requirements.

During the spring, the use of fly ash as a subgrade fill material resulted in no lost construction time due to wet conditions, even though all other earthwork construction in the region was forced to shut down for extended periods because of the rainy weather. Even when there were wet conditions at the Hardscrabble site, fly ash from the Indian River landfill, which was at a moisture content below optimum, was hauled to the site and blended with the wetter ash so that construction work could still proceed.

## **Overall Assessment of Project**

### Ability of Fly Ash to Meet Specifications

Throughout the 10 month duration of this project, nearly 1 million tons of fly ash were delivered and placed in the new landfill cell. During this time, the fly ash was supplied from two approved sources - Delmarva Power's Indian River power station and DuPont's Seaford nylon manufacturing facility. Over 95 percent of the ash was supplied from the Indian River power plant. The fly ash consistently met the project specifications for particle size (less than 1 inch) and moisture-density-requirements (95% of standard Proctor density with a total 3% deviation from optimum moisture).

### Fly Ash Handling and Performance

The fly ash used for subgrade fill and berm construction at this project performed excellently, insofar as there was no dusting and the moisture content was very carefully controlled prior to delivery. The material spread easily, compacted readily, met density requirements consistently without the need for additional compaction, and was even able to be placed under adverse weather conditions that are normally a problem for granular borrow materials.

### Economic Considerations

The overall cost of constructing cell number 3 at the Jones Crossroads landfill was approximately 15 million dollars. The low bid price submitted by George and Lynch/Bramble was at least \$50,000 less than the second bidder, who had bid the project using granular borrow soil.

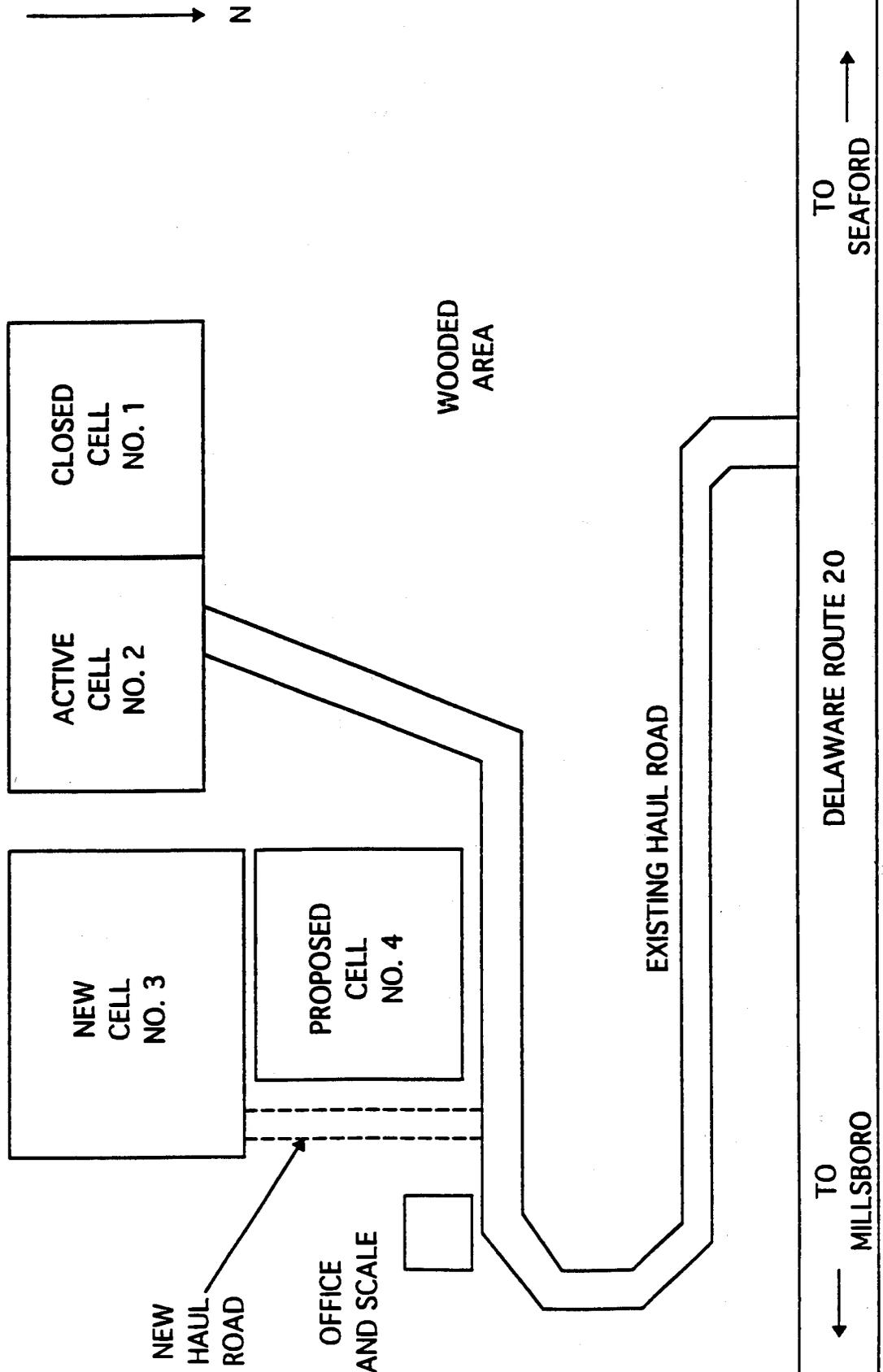
### Future Development

Beginning in 1997, a fourth cell will be developed at the Jones Crossroads landfill. Based on the successful use of fly ash to construct cell number 3, DSWA has agreed to allow the use of fly ash the subgrade fill and berm material for cell number 4. Since this new cell will be comparable in size to cell number 3, there is the potential to utilize nearly one million more tons of fly ash at this landfill. Construction of cell number 4 is expected to be spread out over a 3 to 4 year time period.

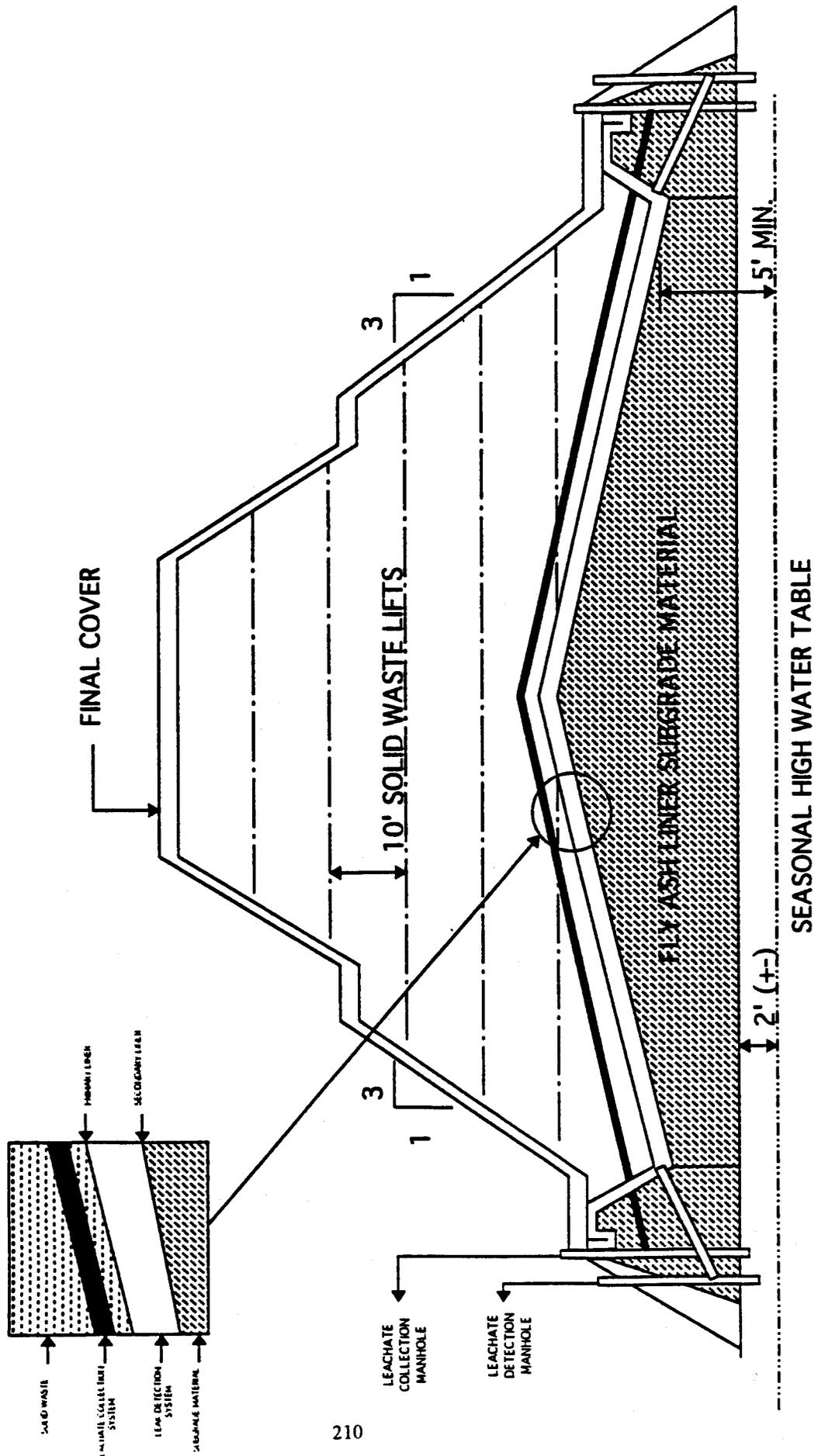
### **Acknowledgments**

The authors of this paper wish to express their sincere appreciation to Ms. Kathy Coppins of VFL Technology Corporation for her excellent work in typing and organizing this paper, and to Mr. Robert Roseborough of VFL Technology Corporation for his outstanding efforts in the preparation of the two figures that accompany this paper.

**FIGURE 1**  
**SITE PLAN OF THE**  
**SUSSEX COUNTY LANDELL FACILITY**



**FIGURE 2**  
**CROSS-SECTION OF NEW CELL #3**



# **FLUID PLACEMENT OF FIXATED SCRUBBER SLUDGE IN ABANDONED UNDERGROUND COAL MINES TO REDUCE SURFACE SUBSIDENCE AND TO ABATE ACID MINE DRAINAGE**

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## **Abstract**

The goal of this project was to demonstrate the technical feasibility of placing fixated scrubber sludge (FSS) into abandoned underground coal mines to control subsidence and to reduce acid mine drainage. The effectiveness of the technology was determined by the total reduction of the mine void and the strength of the injected FSS. The overall effect on the hydrogeologic environment by using this technology was determined through a ground water monitoring program. Laboratory and bench scale testing determined the composition for optimum flow, minimization of free water, and the optimum settling / physical characteristics. The full scale demonstration involved the injection of approximately 16,400 cubic yards of FSS. Borehole photography and core sampling of the placed FSS provided the data necessary to determine the effectiveness of subsidence reduction. The investigative techniques documented good overall roof contact of the injected FSS, unconfined compressive strengths greater than 100, and low permeability coefficients. The groundwater monitoring detected changes in the concentration of chemical parameters in the mine pool water, but no significant changes in ground water chemistry surrounding the mine.

## **Introduction**

Indianapolis Power and Light Company (IPL) began this research to develop a technology to reduce surface subsidence using fluid placement techniques of the FSS because abandoned underground coal mines surrounded property adjacent to existing coal combustion by-product (CCBP) landfill area. Landfill expansion into the area is in question because of the high potential for sinkhole subsidence. Sinkholes manifested at the surface put the integrity of a liner or runoff pond containment structure for CCBP disposal facility at risk. The Indiana Solid Waste Regulations prohibit the construction of a land disposal facility over abandoned underground mines without some demonstrated method of subsidence control. The fluid placement techniques of FSS as a subsidence abatement technology was demonstrated during an eight week period in September, October, and November, 1994 at the Petersburg Generating Station located in Pike County, Indiana. The EPA (Region V) required IPL to register the injection boreholes used during the demonstration in the Underground Injection Control Program.

## **Site Selection**

The abandoned underground coal mines evaluated for this project are found in the Illinois Basin No. V coal seam. The abandoned mines at or around the Petersburg Station were ranked on the basis of the following criteria:

- probable open voids
- ability to isolate the area to receive the injected material
- ability to locate the mine by the use of mine maps and land surveying
- probable surface conditions.

The Arnold Willis "City" Mine was selected primarily because of its small size, available mine maps, easy surface access, and proximity to the power plant. The initial borings documented the accuracy of the City mine map and determined the condition of the mine workings. Depth to the mine voids varied from 32 to 64 feet. Mine void varied from 2.0 to 7.0 feet in height. The borings encountered both dry mine and flooded conditions. Due to the mine floor slope, sections of the mine workings were completely flooded. The mine pool elevation was at 436 and remained constant throughout the

monitoring period. A map of the Arnold Willis "City" Mine *Figure 1. Mine Map* depicts the existing surface topography, and coal seam elevations. The coal was removed from this mine in the late 1940's and early 1950's at different extraction rates varying from 50% to 70%.

### Environmental Monitoring

The objectives of the water quality monitoring plan were to define baseline conditions existing prior to the FSS injection and to monitor changes during and after the demonstration. The monitoring program assisted in identifying environmental changes related to the mine stabilization and defined the migration patterns of FSS constituents and the fluids that were displaced from the mine by the injected grout. The monitoring wells were placed in close proximity to the mine workings so that any water quality impacts would be readily detected and evaluated. There were two monitoring wells located upgradient to determine background water quality (SC-1 and FW-1). The monitoring points located in voids and pillars were used to monitor the water quality of the mine pool (B-4, B-7, B-12, B-14, B-16, B-22, B-23). Other monitoring points were located in the coal seam downgradient of the mined area (B-17, B-18, B-19, SC-3, and SC-4). The location of these monitoring points with respect to the mine can be found in *Figure 2. Borehole Location*.

A total of nine sampling events were completed. The monitoring points were sampled during each event and tested for twenty two different water quality parameters. In examining the post injection ground water monitoring data as compared to the leachate data for the FSS, the constituents that emerged as the most useful or as primary indicators of water quality changes related to the FSS injection were, in order of decreasing significance, sodium, potassium, calcium, boron, chloride, and magnesium. Sulfate, TDS, and specific conductance were secondary indicators of FSS injection effects, i.e., changes in these parameters were observable at some monitoring sites but were generally of lesser magnitude and frequency. Arsenic, cadmium, chromium, lead, selenium, aluminum, barium, nitrate, and sulfide were relatively unaffected by the injection of FSS into the mine. The pH (6.0 to 7.5) and acidity of the mine pool were not significantly affected by the injection of FSS into the mine, suggesting that the mine water's buffering capacity effectively resisted changes in these parameters.

Ground water in rock and unmined coal exhibited no increases or only subtle, attenuated increases in constituent concentrations and in the number of affected chemical constituents compared to water in mine voids. Comparisons of leaching test and field monitoring data suggest the laboratory data can be employed as broad indicators of probable chemical changes within the mine pool.

### **'Fixed Scrubber Sludge - FSS**

FSS is a flue gas desulfurization by-product blended with dry flyash and quicklime. The Petersburg Generating Station burns bituminous coal mined in Indiana. The resultant fly ash (Type F) is a good quality pozzolan meeting ASTM C-593. The flue gas desulfurization systems are wet limestone scrubbers. The scrubbers are inhibited oxidation systems which produce a by-product that is primarily a calcium sulfite hemihydrate, containing minor quantities of calcium sulfate dihydrate (gypsum) and silicon dioxide (as quartz). The pozzolanic activation additive is calcitic quicklime (calcium oxide) with minor quantities of magnesium oxide and silicon dioxide (as quartz). All of the CCBP components of FSS and the quicklime were characterized to develop a baseline of the constituents of the FSS grout. A surface water source (an abandoned strip pit) and the actual mine pool water were also characterized. The abandoned strip pit was used as dilution water source for the FSS blend during the demonstration.

### Microstructure/Cementation/Stability Evaluation

EPRI has found in related studies of cementation in coal combustion residues, developing this type of chemical information is critical to optimizing performance and stability. FSS materials are chemically active in the sense that the main constituents (i.e., fly ash, scrubber sludge, lime and water) react over time with each other to form other distinct chemical and mineralogical phases. These phases

are responsible for the “self-cementing” action which produces the physical strengths in the FSS by-products after they have “cured”. Understanding the chemical processes responsible for cementation of the FSS grout would determine the chemical stability of FSS by-product when exposed to the mine water environment.

The principal hydration product in FSS is calcium sulfoaluminate or ettringite  $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12}\cdot 26(\text{H}_2\text{O})$ . The cementation in the FSS grouts occurs largely through the formation of the ettringite by sulfo-pozzolanic reactions involving the gypsum and aluminate derived from flyash in an alkaline media. The mineralogy data confirmed the reactive phase in the scrubber sludge is the gypsum ( $\text{CaSO}_4$ ), representing 5-10% by mass of total solids. The reactive component in a Class F flyash is principally the aluminosilicate glass representing 45-50% by mass. Other reactive components in flyash include soluble alkali sulfates (typically deposited on the surface of ash particles) and free lime.

The growth of ettringite strongly parallels the strength development in FSS. Also a notable feature is the steady increase in bound water with time which correlates with the compressive strength gains. The microstructure shows good densification by six months with cementing by the ettringite and C-S-H. Some expansion ( $\approx 5$  vol%) during curing appears to be a characteristic feature of the FSS grout system which proved to be a beneficial effect underground improving contact with the walls and roof of the mine.

### **Bench Scale Test Program**

Although a considerable amount of information has been generated by the utility industry and others on the chemical and physical properties of FSS by-product materials (e.g., strength, permeability, leachability), very little is known about the fluid and/or FSS grout materials used for injection. In meeting the goals of the project, the placement of FSS eliminated the mine void space with a minimal number of injections points. To accomplish this, the FSS mix design had to be optimized for flowability and strength development in a bench scale test program. The objective of the bench scale study was to provide information focused toward determining the best compositions for mine injection. Dispersion in underground voids is necessary if the voids are to be filled. In addition, quantities of supernatant fluid after settling, and resistance to acidic mine water were critical criteria.

The bench scale test program studied a wide range of compositions consisting of 36 test different compositions. Four levels of solids content (45%, 50%, 55%, 60%, wet weight basis), three levels of fly ash to FGD by-product ratios (0.7:1, 0.9:1, and 1.1:1 dry weight basis) and three levels of quicklime content (2%, 3%, and 4%, dry weight basis) were explored. The various compositions were evaluated for viscosity, density as blended, density after settling, flowability in a one-dimensional “tunnel flow” protocol, and angle of repose. The various compositions were then cured under accelerated conditions to project strength development. The underground void temperatures have been found to be in the range of 50° F to 55° F. Ambient conditions as defined by ASTM, focus on 73° F. Time temperature relationships for pozzolanic or sulfopozzolanic reactions are approximately as follows: 50° F for eight weeks is approximately equal to 73° F for four weeks. The accelerated cure test promoted the desired hardening chemistry in half the time.

### **Optimization of Strength of the FSS Mix Design**

Laboratory testing determined the range of strengths available from different FSS mix designs conforming to the flow characteristics developed during the bench scale testing. The solids content of the FSS grout mixtures is the dominant factor in determining strength property. Quicklime content is also a critical component of the FSS grout. It was determined that a minimum of 4% lime content is required to meet a design specification of 100 psi or greater. It is possible to tailor the strength potential of the FSS to different areas of the mine by increasing flyash to sludge ratios or increasing quicklime content without changing the moisture content. The higher strength mix could be designed into the “batch mix”

when additional ground or lateral support is required; and a lower strength used when bulk filling a large underground void.

### Optimization of Flow/Rheological Properties of FSS Mixes

The relationships between the rheological properties and mix proportions of the range of FSS mix designs over a wide range of solids contents were determined. Fluid characteristics were determined to be cohesive and stable under shearing conditions. The flyash to sludge ratio of the grouts was a less important design variable. However a higher flyash content has been shown to improve fluidity of the grout. Higher flyash contents are also expected to improve stability of the grout underground.

An examination of the effect of selected chemical flow additives (such as water reducers or plasticizers) on the rheological properties of the FSS mixtures was conducted. Chemical agents of this type are widely used in the concrete construction industry as a means of reducing the amount of water needed in a cementitious mixtures for a given flow/workability. The feasibility of using these flow enhancing additives determined the solids content of the FSS mixtures can be increased while at the same time maintaining adequate flow. Selection of the proper plasticizers is critical because some effect the pozzalonic chemistry that can result in a decrease in strength

*Equipment Testing:* One critical equipment component extensively tested was the fluid placement pump. Both centrifugal and positive displacement pumps were considered. The centrifugal pumps have characteristics of high capacity but low to medium discharge head delivery and extreme sensitivity to viscosity. The general experience shows that the centrifugal pumps can be used to pump slurried grout 45% to 50% solid. The positive displacement pumps have been widely used in the concrete and the mining industry for a variety of applications. In the mining industry, these pumps are used to pump mine tailing and backfill material, which can be as much as 80% in solids content. These pumps are known to exhibit high discharge head delivery. Generally, positive displacement pumps are more expensive to purchase and maintain than centrifugal pumps. A series of pipeline tests were performed to determine the flow characteristics of the slurries on the centrifugal pump performance. The experimental work was conducted in a 3 inch diameter pipeline loop powered by a centrifugal pump. The FSS tested in this pipe loop test would be classified as pseudo-plastic material. FSS, with high solids content, clearly indicates its non-Newtonian behavior.

### **Project Demonstration**

**The** field work was designed to demonstrate the concept of the fluid placement of FSS at full scale. The demonstration was a continuous operation requiring large inventories of the FSS. During the demonstration approximately 250 to 600 cubic yards of FSS was placed each eight hour working day for a total of 16,351 cubic yards over the eight week period. The demonstration plant was operated one shift a day, five days per week.

### Process Equipment

Freshly produced FSS was trucked to the demonstration site and stored on a small temporary storage pad adjacent to the dilution plant. The dilution plant used for this full scale demonstration was a tractor trailer mounted unit manufactured by Excel Machinery Co., see *Figure 3. Dilution Plant*. The portability of this unit allows it to be moved to multiple locations for injection on projects covering large areas. For this demonstration the unit was centrally located over the City mine and was not moved during the eight week demonstration period. The discharge piping was flexible and easily moved to the various injection points, some were located as far as 300 feet from the unit. The mixing of FSS materials for small projects can also be accomplished utilizing cement mixing trucks or other portable batch plants.

A front end loader was used to transfer the material from the temporary storage pad to the feed hopper of the dilution plant. The FSS was weighed on a belt scale as it discharged from the feed hopper

which discharged into a 4' x 8' heavy duty twin shaft pugmill mixer. A programmable controller operated the lime and water feed equipment to achieve the desired ratios of the grout mix. This dilution plant was able to consistently mix the FSS grout to the optimum percent solids content required for fluid placement. The FSS grout discharged from the pugmill onto an inclined belt conveying it to the surge hopper located over top of the injection pump. The FSS was then pumped into the mine voids using a Schwing trailer mounted concrete pump (max. capacity - 127 yds<sup>3</sup> / hr). The positive displacement injection pump delivered the FSS through an overland slurry line to the various injection points. A 90° elbow directed the FSS down the injection hole.

At the beginning of the demonstration, the FSS was allowed to fall unrestricted down the hole and into the mine workings. After a few premature refusals, the free-fall method was changed to a "tremie" method. A tremie system is simply a pipe that is long enough so that the lower end of the pipe is always kept below the mine roof, see *Figure 4. Injection Borehole with Tremie Pipe*. The length of the tremie pipe varied from borehole to borehole depending on the depth of individual mine void from the surface, generally, from 30 to 60 ft.

As with any equipment startup, adjustments to the equipment were required initially. After making the startup revisions, injection proceeded at a satisfying pace. The first injection hole was B-10, borehole television examination showed good void height and interconnected mine workings. Injection into the mine workings was monitored at the injection site utilizing a pressure gauge mounted on the 90° elbow at the top of the hole. Pressure would build as injection proceeded and then suddenly fall off to zero as the grout's path opened into another room or void. The pressure would begin to increase again and the process would repeat itself. Injection into a particular borehole continued until the hole refused by blowing FSS out the top of the hole between the casing and the injection pipe or when the sustained injection pressure became high enough to cause concern. At the completion of injection each day, water was pumped through the pugmill, concrete pump and injection piping to both clean all the equipment and to open the flow path through the FSS in the mine workings for startup the next day.

*Injected FSS Monitoring:* During the field demonstration, monitoring of the FSS placement consisted of two different methods. The first method consisted of observations of depth to bottom of the mine in the boreholes located in the mine workings. The changes to the water level in the mine pool and to the water quality, specifically the pH and specific conductance, also indicated the path that the FSS traveled. The other method was conducted only briefly but was the most informative, that being the borehole photography. Daily monitoring during the FSS injection was concentrated in the boreholes directly around the injection point, although all open boreholes into the mine workings were monitored every few days. The results of the monitoring gave good indications of FSS movement. Once the FSS arrived at a monitoring hole, the grout level in the hole rose to the mine roof within one or two days of injection. Water levels in the mine varied little during injection but on occasion, a rise in the mine pool of about one tenth of a foot was noted at the end of a day. The mine pool would be at its normal level the next morning. No evident changes were noted in the pH or specific conductance of the mine pool until FSS was actually measured in a particular hole.

*Injection Rates:* The injection rates varied from about 280 to 650 cubic yards of FSS per day, with the lower rates occurring primarily during the first two weeks of injection and the rates generally increasing thereafter as the system operation was refined. Overall, 16,351 cubic yards of FSS was injected during the eight week field demonstration with 6,782 cubic yards in B-10 (covering approximately 1.3 acres), 4,318 cubic yards in B-20 (covering approximately 1.2 acres), 4,874 cubic yards in B-35 (covering approximately 1.1 acres). All of the injection holes were filled to refusal. In general, the FSS fluid placement material contained about 55% to 60% solids, fly ash to filter cake ratio per plant production (to be 0.7 to 1 or higher as circumstance allowed), and more than 4% total lime content. *Figure 5. FSS Injection Calculated Volumes* detail the quantities injected and test results of core samples retrieved after the demonstration can be found below.

*Borehole Television:* Three rounds of borehole photography was conducted by a crew from the Eastern Technical Center of the Office of Surface Mining, Reclamation, and Enforcement (OSMRE), U.S. Department of the Interior, Pittsburgh, Pennsylvania. The camera work was requested from OSMRE through the Abandoned Mine Lands Program of the Indiana Department of Natural Resources. The initial camera work was used to determine which borings had encountered open voids and which were into obstructed (broken rock) mine workings. The camera work completed during demonstration concentrated on observing FSS as it was placed in the mine void. While injecting into B-20, and photographing in B-21, movement of FSS was recorded almost from the time it entered the mine room where B-21 was located, until the room was completely filled. The camera showed that the FSS did move as a mass in a lava type flow. The third and final round of camera work was used to verify roof contact into the random boreholes drilled to retrieve core samples and also in the existing boreholes.

### **Conclusions**

- The demonstration clearly showed that the FSS flow from the injection borehole exceeded 100 feet, and based upon volume estimates, approached 135 feet. A mine void area in excess of one acre can be filled with one injection point.
- The lava-like flow of FSS does not appear to mix with mine water but rather displace it, only the outer surface of the FSS grout is exposed to the mine water. Air and water in the voids can be completely displaced by FSS grout injection, the potential for acid generation from pyrites and organic sulfides is then greatly diminished.
- The FSS grout does not shrink or settle away from the mine roof and generally achieves unconfined strength of 100 psi or higher.
- FSS grout injection can be accomplished with “off the shelf” equipment with only minor modifications required.
- Short term results indicate no discernible chemical effects from FSS on mine water and no chemical effects on the surrounding ground water.

### **Acknowledgments**

The funding for this research project was provided by the Electric Power Research Institute, Indianapolis Power & Light Company, and the Indiana Department of Commerce -Energy Policy Division (Indiana Coal Research Grant Program), Hoosier Energy, and Conversion Systems, Inc. (cost sharing). I would like to recognize the project managers involved with project. Dean Golden, Electric Power Research Institute. Richard E. Gray and Robert Turka, GAI Consultants Inc.. Dr. Wei-Chung Yu and Charles Smith, Conversion Systems, Inc.. Dr. Ray Hemmings, Radian, Inc.

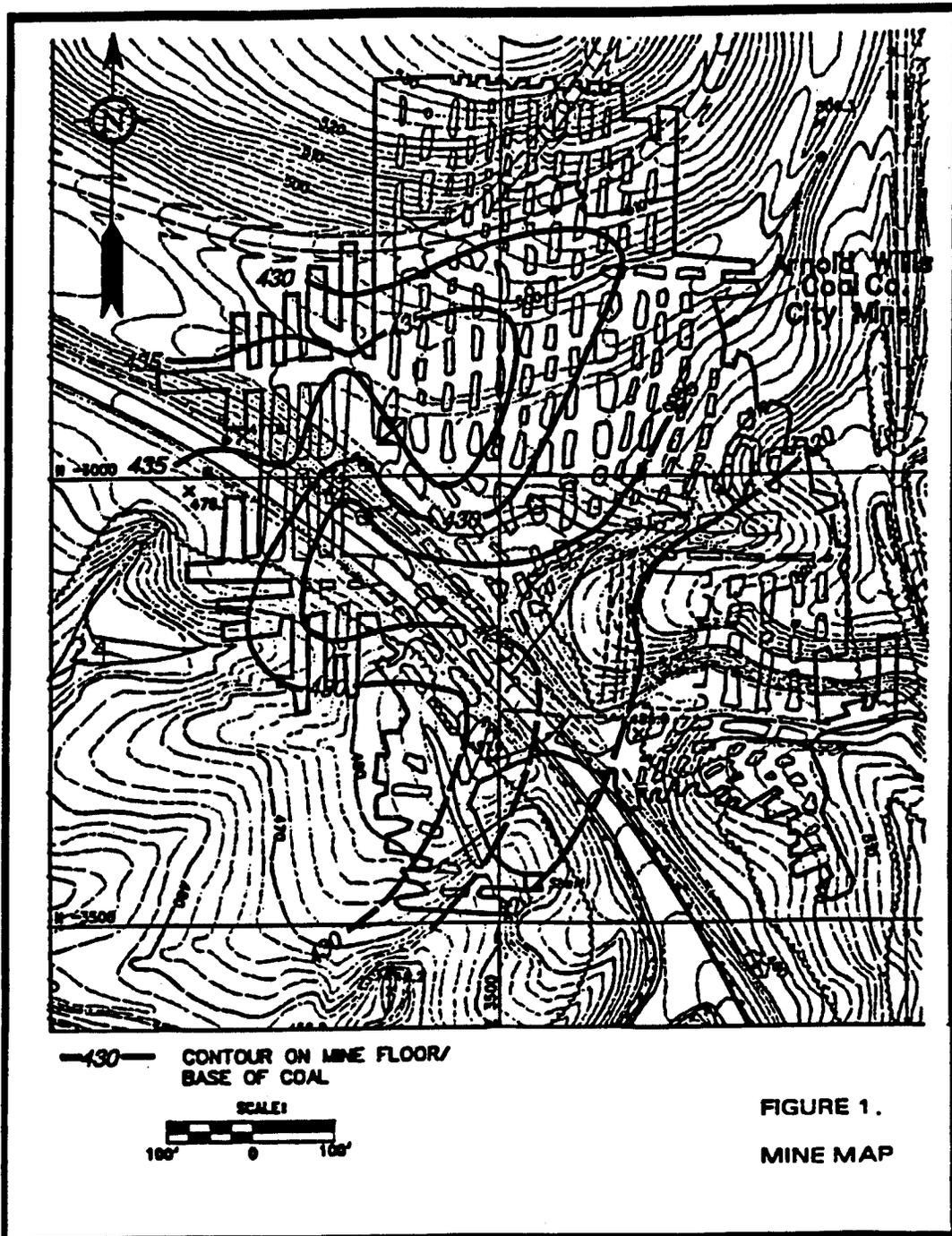
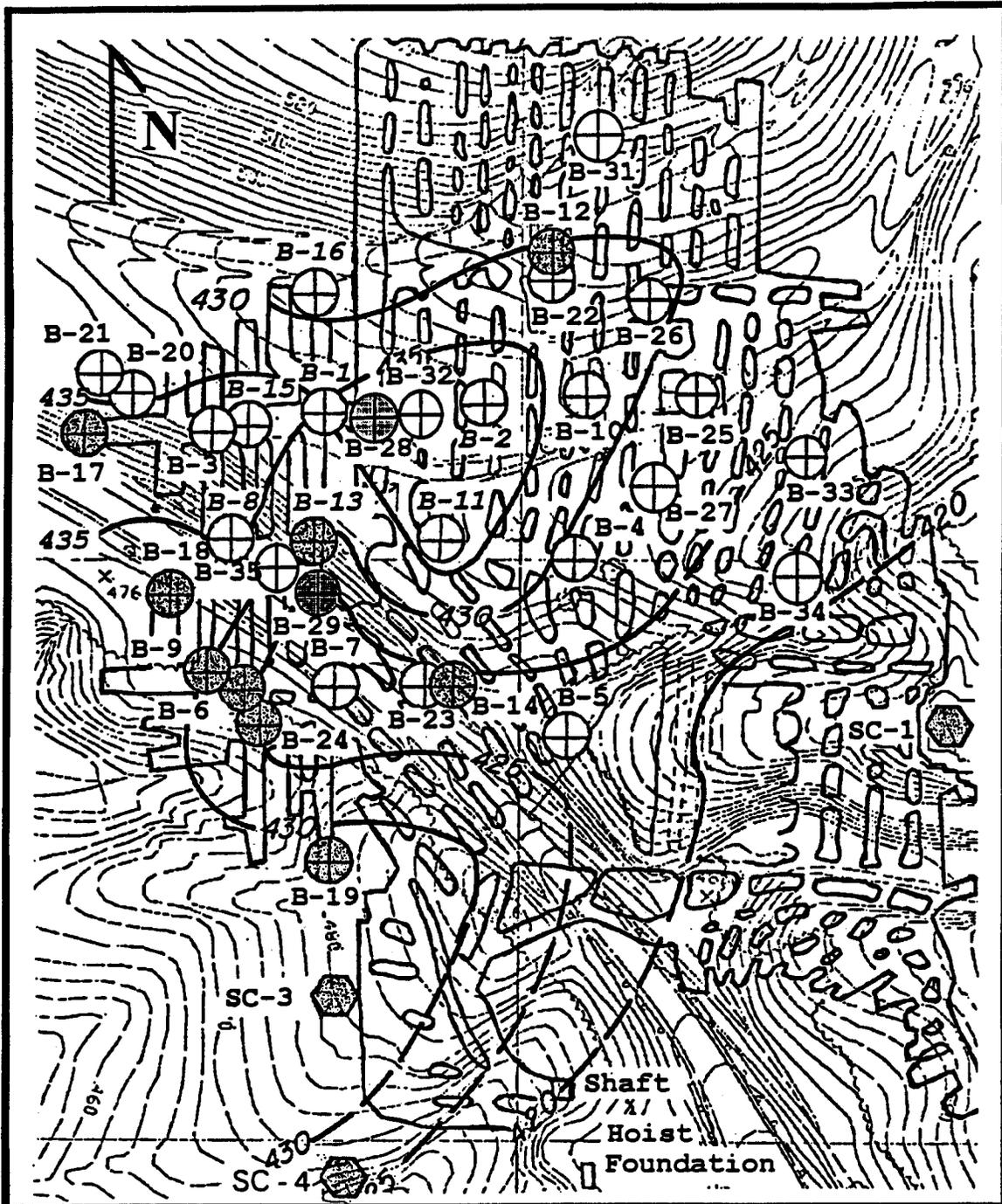


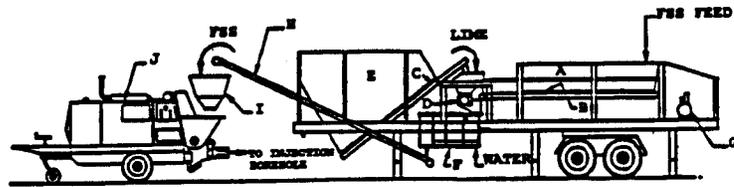
FIGURE 1.

MINE MAP



- ⊕ BOREHOLE - VOID
- ⊗ BOREHOLE - COAL
- ⊙ MONITORING WELL

FIGURE 2.  
BOREHOLE LOCATION



- A - Feed Hopper
- B - FSS Belt Feed
- C - Lime Screw Feed
- D - Lime Weigh Scale
- E - Lime Silo
- F - Pug Mill Mixer
- G - Air Compressor
- H - Mixer Discharge Belt
- I - Pump Feed Hopper
- J - Injection Pump

FIGURE 3.  
DILUTION PLANT

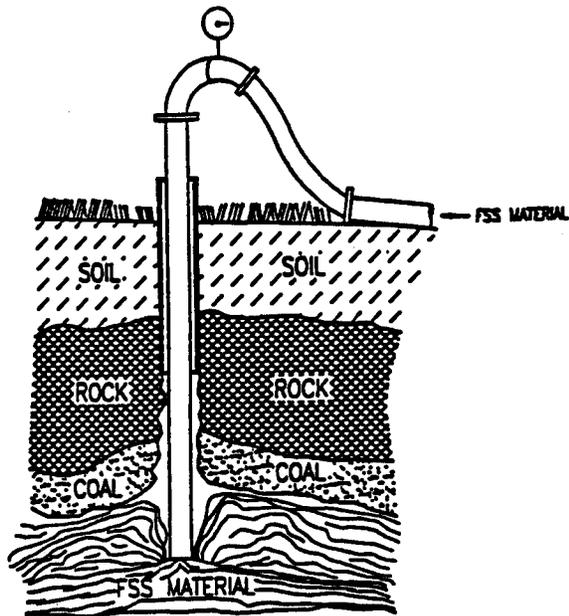
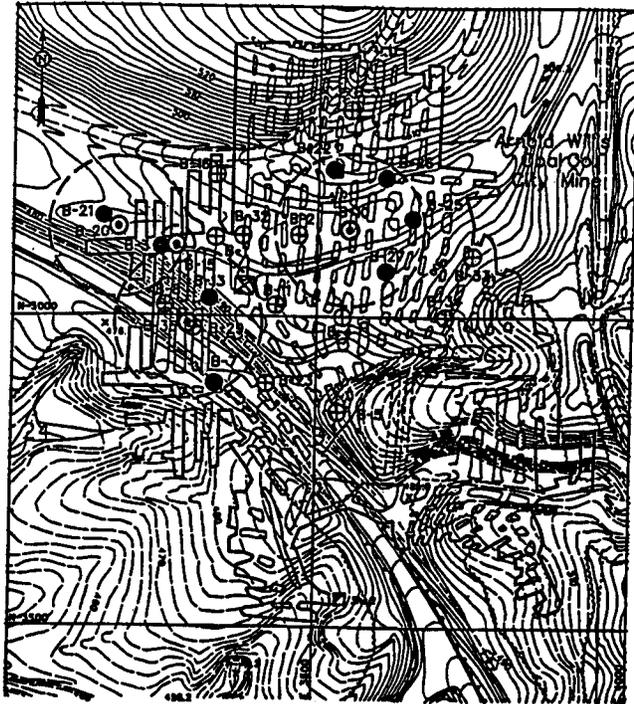


FIGURE 4.  
INJECTION BOREHOLE  
WITH TREMIE PIPE



- ⊙ INJECTION POINT
- GROUT FOUND IN MONITORING BOREHOLE
- ⊕ BOREHOLE-OPEN IN MINE
- CALCULATED MINE VOLUME FILLED



FIGURE 5.  
FSS INJECTION  
CALCULATED VOLUMES

**Borehole B-10 Flooded Mine Void**

FSS 6,315 tons Ave. 371.5 tons/day  
 Dilution Water 522,040 gals. Ave. 30,708 gals./day  
 Quicklime 229 tons Ave. 13.4 tons/day  
 FSS Grout Injected 9,374 tons or 6,782 cubic yards  
 QA/QC tests → 17 Samples = 1 test / 398 yds<sup>3</sup> injected  
 Ave.: Solids - 56.10 % Lime - 4.36% FA/FC Ratio - 0.80:1.00

**Cores - Test Results**

9 cores collected, 9 months after injection  
 Ave. Strength (U.C.S.) 190.1 psi Range → 99 - 479 psi  
 Ave. Density (Wet) 96.9 lbs/ft<sup>3</sup> Range → 93 - 102 lbs/ft<sup>3</sup>  
 Ave. Permeability (2 cores) 3.58 x 10<sup>-5</sup> cm/sec

**Borehole B-20 Dry Mine Void**

FSS 3,938 tons Ave. 393.8 tons/day  
 Dilution Water 351,100 gals. Ave. 35,110 gals./day  
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 Ave. Permeability (3 cores) 3.14 x 10<sup>-6</sup> cm/sec

**Borehole B-35 Partially Flooded Mine Void**

FSS 3,814 tons Ave. 381.4 tons/day  
 Dilution Water 46,200 gals. Ave. 34,620 gals./day  
 Quicklime 149 tons Ave. 13.5 tons/day  
 FSS Grout Injected 5,993.7 tons or 4,874 cubic yards  
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 Ave.: Solids - 56.50 Lime - 4.39% FA/FC Ratio - 1.03:1.00

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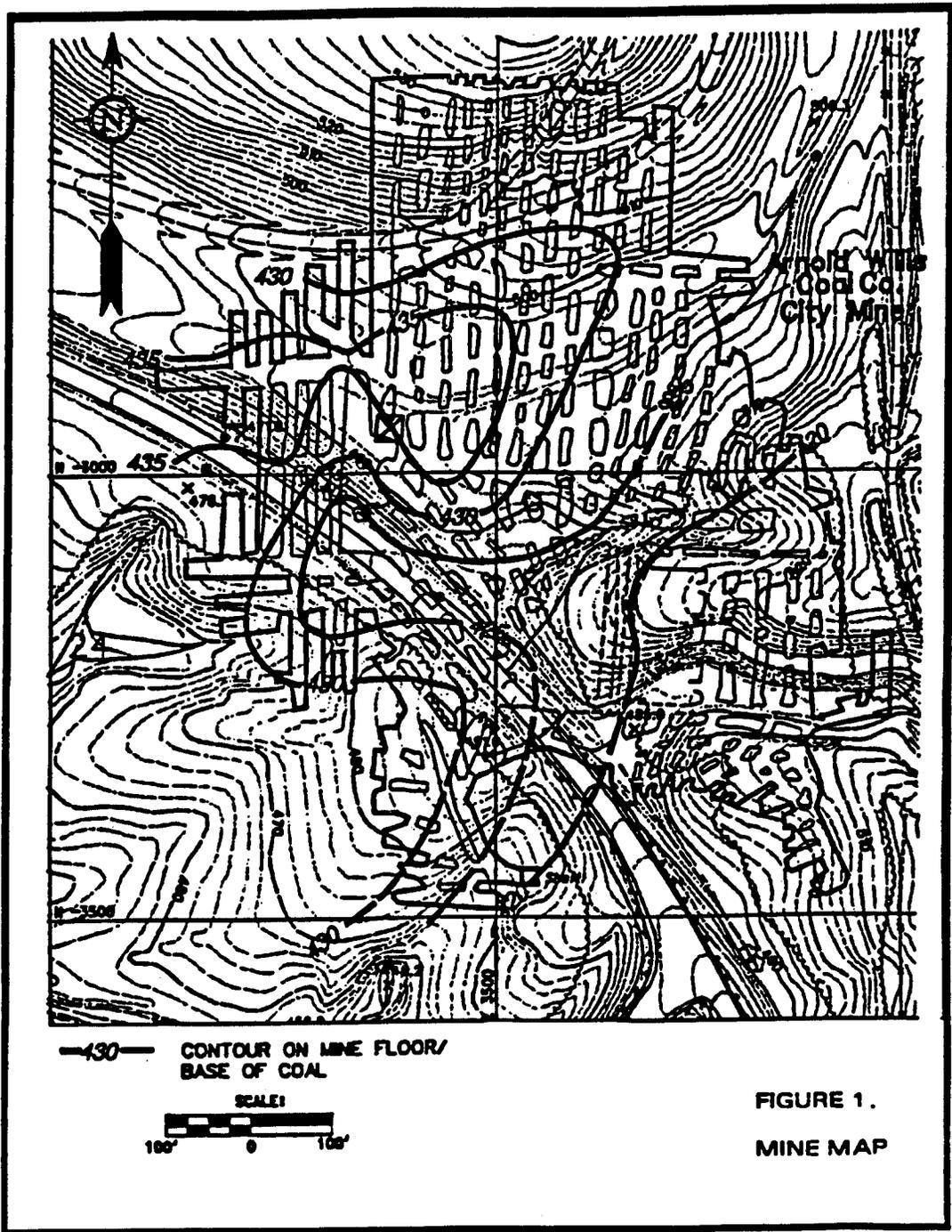
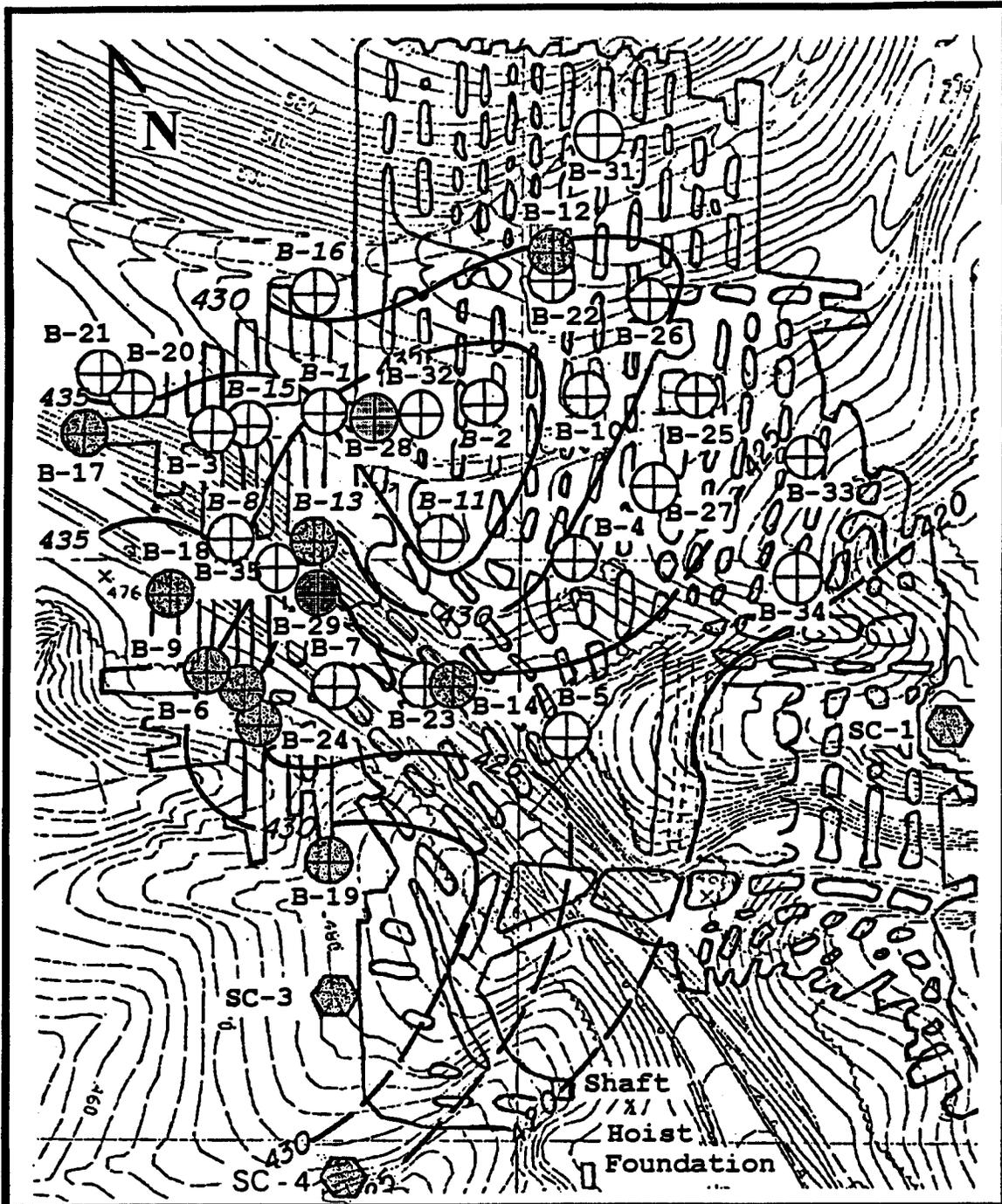
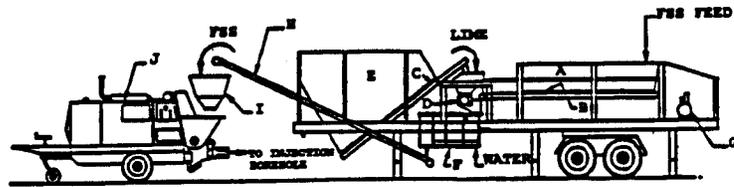


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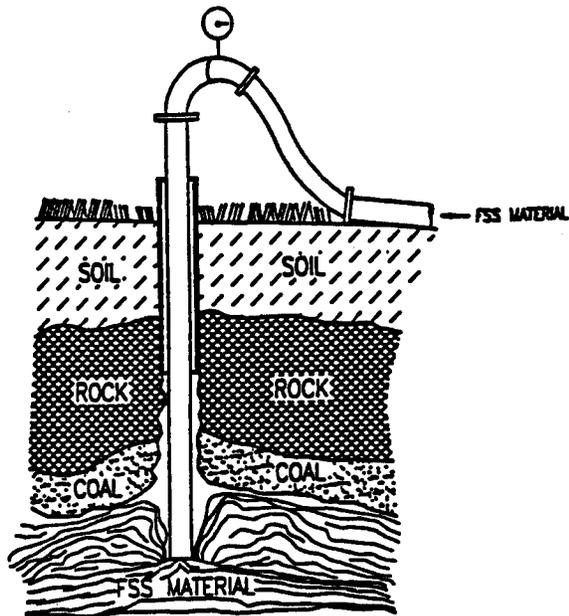
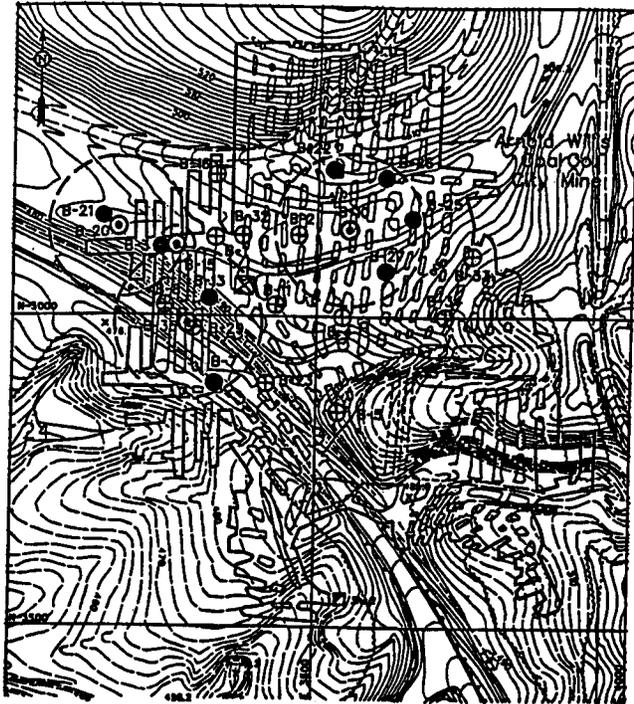


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ENGINEERING DESIGN FOR THE INJECTION OF ALKALINE CCBs INTO A MARYLAND  
COAL MINE TO ABATE ACID MINE DRAINAGE

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Abstract

The Maryland Department of Natural Resources Power Plant Research Program and Maryland Department of the Environment Bureau of Mines have undertaken the Western Maryland Coal Combustion By-Products (CCB)/Acid Mine Drainage (AMD) Initiative, a joint effort with private industry to permanently abate AMD in Western Maryland. The Initiative's current undertaking, the Winding Ridge Project, is a small-scale demonstration of the wet injection of alkaline CCBs into an underground coal mine in Garrett County, Maryland, with injection scheduled for Fall 1996.

The engineering design includes logistical, transportation and on-site storage considerations, construction/injection components, quality control procedures, and injection procedures. Design criteria were based on mine geometry and expected in-situ grout behavior. The optimal grout formulation was determined by subjecting candidate alkaline CCBs, with varying admixtures of water, fly ash, and quick lime, to laboratory tests. Testing included grout flowability under submerged AMD conditions, unconfined compressive strength, and grout cohesion.

Introduction.

The Maryland Department of Natural Resources (DNR) Power Plant Research Program (PPRP) and the Maryland Department of the Environment Bureau of Mines (MDE) have undertaken the Western Maryland Coal Combustion By-Products (CCB)/Acid Mine Drainage (AMD) Initiative, a joint effort with private industry to develop permanent solutions to abate AMD. The Initiative is based on the concept that alkaline CCBs generated by clean coal technologies, such as fluidized bed combustion (FBC) and flue gas desulfurization (FGD), can be injected into underground mines to prevent the formation of AMD by sealing mines from exposure to oxygen and water. The Initiative's goal is to demonstrate the beneficial application of alkaline CCBs to abate AMD from underground coal mines, through the implementation of several scale-up projects. Ultimately, the Initiative is targeting abatement of AMD from serious AMD sources in the state, such as the Kempton Mine Complex.

The Winding Ridge Project (the Project) is the Initiative's first demonstration project. The Project began with a site screening and selection process conducted by MDE in which mine size, geometry, acidic discharge flow, access, topography, and land ownership characteristics were evaluated to identify the most suitable mine site for injection. The Frazee Mine, located at the top of Winding Ridge about one mile east of Friendsville, Maryland, was determined to be the most favorable location for the first demonstration project. The Frazee Mine produced coal from the Upper Freeport seam.

The Project Scope of Work consists of multiple tasks grouped into six phases, extending from the initial mine characterization to eventual mineback at the site. Project phases and objectives include

the following:

1. Phase I - Frazee Mine Characterization: Develop a mine map, determine the hydrology of the mine, establish baseline water quality conditions, and identify the regulatory permitting requirements for implementation of the Project.
2. Phase II - Characterization and Procurement of Alkaline CCBs for Mine Injection: Determine the optimal formulation for the alkaline CCB grout and procure material sources.
3. Phase III - Design of Underground Injection Program: Prepare an engineering design for the injection of alkaline CCBs and procure all necessary permits.
4. Phase IV - Injection of Alkaline CCBs: Inject the CCB grout into the Frazee Mine in accordance with the engineering design.
5. Phase V - Post-Injection Monitoring: Monitor the effectiveness of the injected alkaline CCBs to abate AMD and observe the physical characteristics of the injected materials.
6. Phase VI - Mineback for In-Situ Grout Inspection: Expose the injected materials for detailed examination of their emplacement and in-situ weathering. Phase VI could also include recovery of the remaining coal at the site.

The remainder of this paper focuses on Phases II and III of the Project. The characteristics of the alkaline CCB grout formulations are presented first, as they influence the engineering design for grout injection. The engineering design is then discussed in terms of materials handling, water management, mixing and injection, and site restoration.

### **Phase II - Summary of Alkaline CCB Grout Formulation Laboratory Study**

The Project team set as its primary goal the complete filling of mine voids at the Project site using a hydraulic (wet) injection of alkaline CCBs. This will minimize the contact between exposed coal surfaces, air and water, thus preventing the future formation of any significant amount of AMD.

The optimum grout, therefore, must have good flowability with minimum bleed and settlement. These properties of grout workability are balanced against the need for acceptable long-term strength characteristics to prevent mine subsidence. A laboratory study was conducted by Southern Illinois University at Carbondale (SIUC) to evaluate different ratios of the following grout components, in order to determine the grout formulation that would best meet the Project requirements:

1. FGD by-product from Virginia Power Company's Mt. Storm power plant, Mt. Storm, West Virginia;
2. PCC Class F fly ash from Virginia Power Company's Mt. Storm power plant, Mt. Storm, West Virginia;
3. FBC by-product from Morgantown Energy Associates' power plant in Morgantown, West Virginia.
4. Quick lime - used only with the FGD by-product and Class F fly ash materials.
5. Water - mine water and potable spring water were investigated.

Essentially, two grout mixes were tested. One consisted of FGD by-product, FBC by-product, and Class F fly ash, while the other consisted of FGD by-product, quick lime, and Class F fly ash. Each grout mix was tested with varying percentages of the component materials, and each was prepared using mine and spring water.

In addition to requiring a grout mix with suitable workability and strength properties, the Project seeks to minimize costs by utilizing readily available CCBs generated or handled near the Project site, and nearby water sources, particularly mine water. The emphasis on cost minimization throughout the Project will encourage the development of mine injection techniques that will be economically feasible for larger scale projects. The Project therefore did not consider using additives, such as plasticizers or bentonite, that could improve grout characteristics.

Selected results of the final mix testing are summarized in Table 1. The FGD-FBC mixes in Table 1 demonstrated a bleed of less than 2%, slumps in the range of 8 to 8.5 inches, and 28-day compressive strengths ranging from about 600 to 700 psi. Trial mix testing had shown that increasing the water content will increase flowability of these mixes, but will also cause a high bleed (i.e., above 3%). When the FBC content was reduced to 20% during trial testing, greater bleed and settlement and lower compressive strength were observed.

FGD-lime mixes were also investigated. These mixes generally had better flowability, less bleeding, and higher 28day strength compared to FGD-FBC mixes (Table 1). Mixes with 10% lime, by dry weight, had much better strength characteristics than those made with only 5% lime. However, using large quantities of lime poses operational difficulties, and entails much greater cost. Mixes with 10% lime and 40% water content, and approximately equal parts fly ash and FGD by-product, had a slump in the range of 8 to 8.5 inches. The compressive strength after 28 days was about 1,100 to 1,200 psi.

SIUC concluded that it is possible to formulate either type of mix (FGD-FBC or FGD-lime) to safely achieve suitable workability and strength properties for mine injection. The FGD-FBC mix was selected for the demonstration project over the FGD-lime mix largely because of the lower costs of FBC by-products compared to lime. Use of the FGD-FBC mix also has an environmental benefit in that the injection materials consist of 100% by-products that otherwise would require disposal, typically by landfilling. The Project team selected the grout mix consisting of 38% fly ash, 32% FGD by-product, and 30% FBC material, with 38% water, as the optimal formulation.

### **Phase III - Engineering Design for Mine Injection**

#### **Permitting**

Permitting issues were addressed while preparing the engineering design. The Project team determined that both an approved Erosion and Sediment Control Plan and an Air Permit to Construct must be prepared and implemented for injection. However, other permits, including Wetlands/Waterways Construction, Underground Injection Control, and NPDES were deemed unnecessary by the appropriate state agencies, based on the unique nature and scope of the Project.

#### **Site Preparation and Materials Handling**

In order to allow heavy equipment and by-product delivery trucks to reach the Project site, the access road must be improved. This is being done through the placement of a gravel road that primarily follows the existing dirt/gravel access road to the site. On-site temporary roads will also be required for trucks to access the material stockpiles. Erosion and sediment control measures will be required for the improved access road and for soil disturbances on the site itself, such as the construction of the on-site temporary roads and the material stockpile areas.

Grout injection will take place during a two-week field effort in Fall 1996. As a conservatively large estimate, about 3,900 cubic yards (cy) of material is needed to fill the Frazee Mine, which will entail about 20 to 25 truckloads of CCBs delivered daily during the injection. Using the mix ratios determined in the laboratory study, the following volumes of CCBs and water will be needed for the Project:

1. Fly ash - 2,050 cy, assuming a non-compacted density of 66 pounds per cubic foot (pcf) and a moisture content of 16 percent.
2. FGD by-product - 1,970 cy, assuming a non-compacted density of 62 pcf and a moisture content of 24 percent.
3. FBC by-product - 1,300 cy, assuming a non-compacted density of 80 pcf and a moisture content of 12 percent.
4. Water - 206,000 gallons for mixing and 20,000 gallons for daily flushing of equipment and

lines, for a total Project water requirement of 226,000 gallons.

5.

Up to 250 trucks will be required to deliver this volume of material to the site. All CCBs will be transported in a pre-conditioned state in covered, bottom dump trailers to minimize fugitive dust emissions. All transportation activities will be conducted under air permits currently held by the coal companies and/or power plants donating the CCBs.

It is anticipated that material stockpile areas will be sized to accommodate a minimum of 250 cy of fly ash, 160 cy of FBC by-product, and 240 cy of FGD by-product. This represents a 1.5-day supply of material, at an expected injection rate of nearly 40 cy/hour. When material is not being delivered or being removed to the mixing plant, the piles will be covered in plastic. Additional dust suppression controls, such as hydration of the surface of exposed material, will be implemented as necessary. Prior to placing CCBs on the ground, the top 8 to 12 inches of topsoil will be removed and stockpiled, to be replaced later during the site restoration. The topsoil stockpile will also be covered in plastic.

### Water Management

As mentioned in the previous section, approximately 226,000 gallons of water will be needed over the course of the Project. The mine pool is estimated to consist of about 350,000 gallons of acidic water (pH about 3 to 4). Assuming 50% of the mine water is recoverable, about 175,000 gallons may be available for the grout mix. Additional water, if needed, will be obtained from the Town of Friendsville's abandoned water line adjacent to the Project site, a maximum of about 500 feet from any injection hole (Figure 1).

The injection will require 13,000 to 20,000 gallons of water daily. Aboveground storage tanks will be provided at the site, with a capacity of about 40,000 gallons, equivalent to two or three days of storage. The water supply to the tanks will consist of connections from both the mine dewatering and the municipal water line. The tanks will be filled with mine water during contractor mobilization and site preparation, prior to the commencement of grout mixing. The storage facility will be the sole supply of water to the mixing and injection equipment.

Besides ensuring an adequate supply of mixing water, another significant water management issue involves the handling of mine water as injection proceeds and displaces the mine pool. Based on our current understanding of mine conditions, the proposed injection sequence will direct water towards open boreholes where it can be extracted with a submersible pump. The current flow of AMD from the mine opening may continue throughout the injection activities and may increase somewhat during injection at the most down-dip boreholes. A small discharge may also occur at a currently dry mine opening, due to changes in flow paths as grouting proceeds. Depth-to-water measurements will be taken in open boreholes prior to the start of injection each day to monitor the movement of mine water during the Project.

### Mixing and Injection

Injection holes and their associated mine voids will typically be filled in one continuous grout injection stage (a stage being an uninterrupted period of injection at a particular hole). If mine backfilling at an injection borehole requires two or more injection stages (due to mechanical problems, end-of-day time constraints, or other reasons), the borehole will be completely flushed with water to provide a clear flow path for the next stage of the injection.

The injection system will be capable of pumping a minimum of 40 cy/hour while producing 150 psi of pressure at the injection point, assuming a slump of 8 inches for the grout mixture. The anticipated injection sequence has been developed based on three key factors:

1. Injection will be completed in an up-dip manner (i.e., from areas of lower tunnel elevation to higher tunnel elevation) where possible. This will help reduce the chance of accidentally

- sealing adjacent boreholes prior to using them for injection.
2. Grout injection will be used to assist in the control and recovery of mine water. Sealing certain areas of the mine first will reduce the possibility of uncontrolled discharge through the mine openings. The grout backfill will also be used to displace the mine water toward open boreholes to aid in dewatering.
  3. Grout injection will occur in both dry and submerged conditions. The injection sequence is set to allow injection under both types of mine conditions. The Project will start with injection into dry portions of the mine and then move towards injection under submerged conditions.

As noted earlier, the selected optimal grout mix consists of 32% FGD by-product, 38% fly ash, and 30% FBC by-product. Moisture content was quite variable in the laboratory samples, which in turn has a significant impact on the amount of water required for the mix. Therefore, moisture contents will be determined in the field periodically by sampling material stockpiles. Slump tests will be conducted on the mixed grout for quality control, in addition to visual inspection of the materials prior to and after mixing.

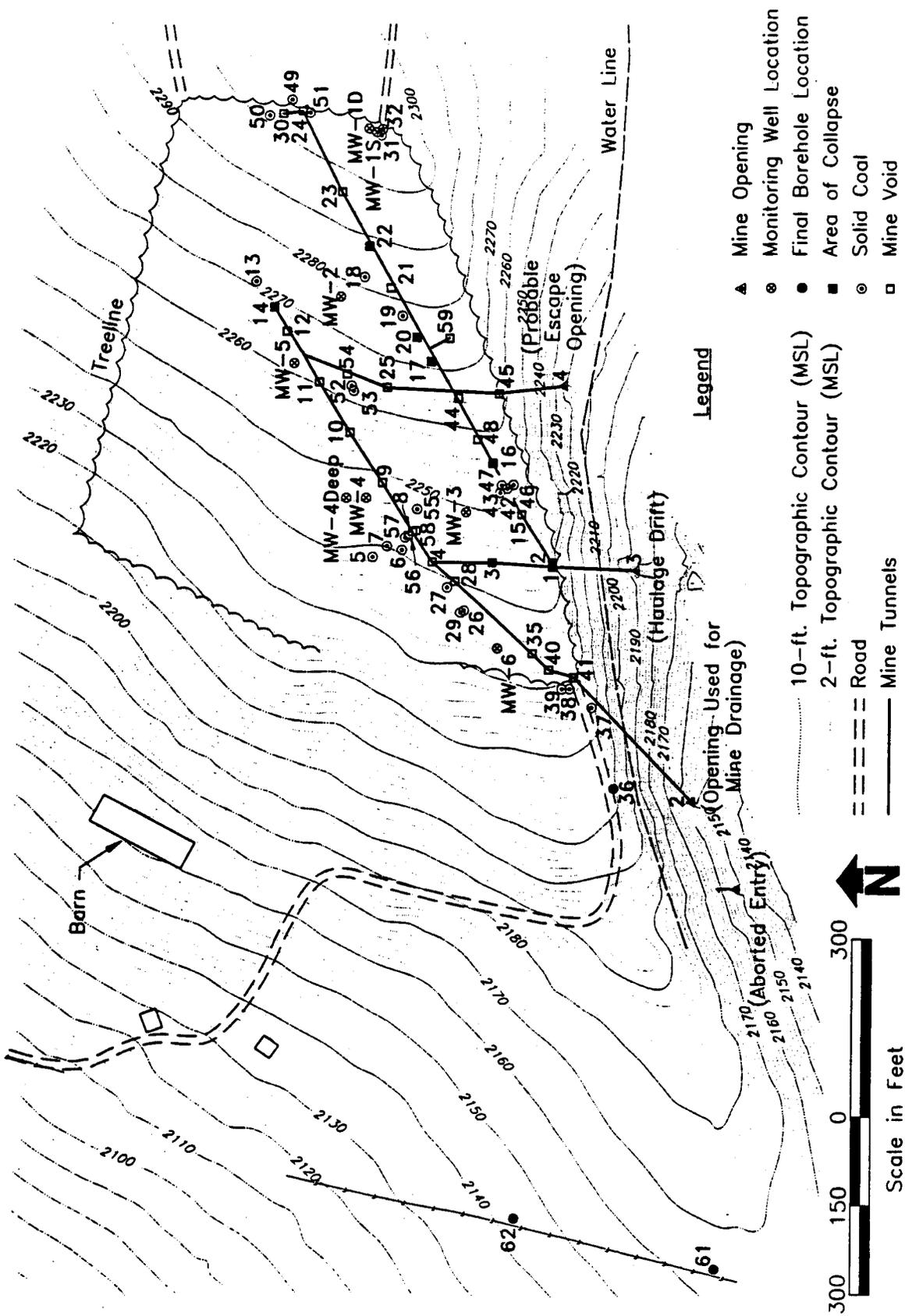
#### Site Restoration

When mine injection activities are complete, each borehole will be backfilled with grout to within two feet of the ground surface. After the grout within the injection hole has set, the soil around the top two feet of the casing will be excavated, the casing will be cut, and the top two feet of casing removed. The excavated area will then be backfilled with topsoil and the entire site regraded to match pre-project contours. Some boreholes will be preserved for future observations and core sampling during post-injection monitoring.

Table 1. Selected Results of Grout Mix Testing

Grout Mix	Slump (in.)	Bleed (%)	28Day Strength (psi)
30% fly ash, 40% FGD, 30% FBC plus 38% water	8.25	1.7	627
38% fly ash, 32% FGD, 30% FBC plus 38% water	8.50	1.8	711
50% fly ash, 40% FGD, 10% lime plus 40% water	8.10	1.0	1,095
40% fly ash, 55% FGD, 5% lime plus 38% water	9.40	1.8	548

Figure 1. Detailed Site Location Map for the Winding Ridge Project.



# USE OF WET FGD MATERIAL FOR RECLAMATION AND AMD ABATEMENT IN ABANDONED ACIDIC COAL REFUSE PILES

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## Abstract

American Electric Power (AEP) and the Ohio State University conducted a field and laboratory greenhouse research program at the Rehoboth Mine Reclamation site to determine if direct revegetation of acidic coal refuse was possible by amendment with wet FGD material and to determine what the potential effects of such amendment would be on coal refuse, plant and water quality. Also, AEP and the Ohio Department of Natural Resources conducted a pilot program at the Rehoboth site to study the slope stability, strength, and other construction constraints associated with application of FGD material as a neutralization agent as well as an impermeable cap.

## Introduction

In the Eastern U.S.A., coal mining and coal preparation practices in the years prior to enactment of stringent environmental protection and reclamation laws frequently resulted in dumping of coal cleaning refuse into large piles. Oxidation of pyritic material in the coal refuse can cause these piles to become hyper-acidic with extremely high levels of soluble  $\text{Fe}^{3+}$ ,  $\text{Al}^{3+}$ , and  $\text{SO}_4^{2-}$ . The refuse piles, which can be several hectares in area and several meters in depth, can cause severe offsite degradation of water quality due to acidic drainage and leaching of Fe and S, as well as deposition of acidic sediments in waterways<sup>2</sup>. Revegetation of such sites is challenging and traditionally has involved application of limestone to the pile surface and covering the pile with a 20-cm layer of topsoil to provide a suitable medium for plant growth<sup>3</sup>.

Frequently, however, suitable borrow soil does not exist adjacent to the refuse pile. Cost of reclamation increases dramatically as the distance to the borrow area increases and necessitates disturbing another landscape. Direct revegetation of the refuse using suitable amendment materials would represent substantial economic and environmental benefits.

Flue gas desulfurization (FGD) material is a by-product of scrubbing  $\text{SO}_2$  from the emissions of coal-fired boilers. This material, which is primarily  $\text{CaSO}_3$ , is normally blended with coal fly ash at a 1: 1 ratio and stabilized with 2-3% CaO prior to landfilling. When FGD is placed in an aerobic soil environment the  $\text{CaSO}_3$  component of FGD will readily oxidize to form gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ). Gypsum has been shown to have beneficial effects in acidic subsoils primarily by supplying Ca and reducing toxicity of Al<sup>4</sup>. Thus the combination of gypsum and alkalinity in FGD may make it an ideal AL substitute for reclamation of acidic coal refuse.

Greenhouse and field experiments were conducted to investigate the revegetation efficacy and potential environmental impacts of FGD and compost as amendments for revegetation of acidic coal refuse. In each experiment FGD was applied with and without compost and the effects on plant growth and refuse quality were determined in relation to those of agricultural lime (AL).

The pilot program was conducted to study the slope stability, strength, and other construction constraints associated with the application of FGD material from AEP's Conesville Plant to an abandoned coal refuse pile. The FGD material, due to its neutralization potential (TNP of 15%) will act as a buffering agent when mixed with the acidic coal refuse pile. Also, due to the low permeability of FGD material, it will also be applied to the mine gob as an impermeable cap to reduce infiltration and the resulting production of acid mine drainage. Results of this experimental project will be used to determine design and construction parameters for the future full scale reclamation project at the site.

## Materials and Methods

The field experiment and the pilot program were conducted at an abandoned coal refuse pile located near New Lexington, OH. Coal refuse for the greenhouse study was collected from the O-6 in depth of this refuse pile. The refuse was extremely acidic with a pH of 2.3 and a potential acidity of 160 cmol kg<sup>-1</sup>. The FGD used in these experiments had a neutralizing potential of 15% calcium carbonate equivalency and was obtained from the Conesville, Oh power plant of the American Electric Power Corporation. Compost used in these experiments was produced at the Kurtz Brothers Inc. composting operation located near Columbus, OH. The compost was produced from a feedstock of leaves, brush and grass clippings and had a C to N ratio of 20: 1.

### Greenhouse Experiment

All materials were air-dried and passed through a 10 mm screen before being used. A 15 in layer of coal refuse was placed in the bottom of a 24 in tall x 6 in diameter PVC pot. Above this layer was placed a 7.5 in layer of coal refuse mixed with either FGD (500 g kg<sup>-1</sup>) or AL (80 g kg<sup>-1</sup>) both alone and with compost (50 g kg<sup>-1</sup>). Preliminary incubation studies with coal refuse and FGD and AL showed that these amounts would increase refuse pH to 7. Each amendment combination was replicated 3 times. The pots were planted with a mixture of orchardgrass, fescue, timothy, and birdsfoot trefoil. Pots were watered to maintain sufficient moisture for plant growth, and once each month were leached to simulate leaching due to natural rainfall. After a 3 month establishment and growth period plant growth was harvested once each month for 4 harvests. Harvested plant material was dried and weighed, and material from the final harvest was ground, digested and analyzed by ICP for total concentration of Al, As, B, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, S, Se, and Zn. Leachates collected at time 0, 2, and 5 months were analyzed for pH and electrical conductivity (EC) and by ICP for the elements listed above. At the conclusion of the experiment columns were sampled in 3 depth increments: 0-7.5, 7.5-15, and 15-22.5 in. Sampled material was dried, ground to pass a 2-mm screen, analyzed for pH and EC, and extracted with a 1: 10 ratio (w/w) of water. The water extracts were analyzed by ICP for the elements listed above.

### Field Experiment

In the fall of 1994 four rates of FGD (300, 500, and 700 tons acre<sup>-1</sup>) and one rate of AL (80 tons acre<sup>-1</sup>), each with and without compost (50 tons acre<sup>-1</sup>) were applied to 20x22 ft plots and incorporated to a depth of approximately 8 in with two passes of a moldboard plow and multiple passes with a rototiller. These treatments were arranged in four randomized complete blocks. Immediately after treatment the plots were planted with orchardgrass, perennial ryegrass, timothy, birdsfoot trefoil, ladino clover, and winter wheat and mulched with wheat straw. One week after treatment, and again in spring and fall of 1995 core samples (24 in depth) were collected from the plots in 4 in increments. Sampled material was dried, ground and analyzed as described for the greenhouse pot samples. Vegetative growth was cut on July, 1995 and harvested plant material was analyzed as described in the greenhouse study. Data presented and discussed in this paper will focus on the AL and 500 ton acre<sup>-1</sup> FGD treatments.

## Pilot Program

### Staging Area

A staging area for unloading and stockpiling FGD and lime kiln dust for mixing these materials was prepared at the base of the coal refuse pile. A large area was bulldozed level to provide ample space for tractor-trailer rigs to turn around and unload. Also, enough space had to be provided to stockpile 7,000 to 10,000 tons of FGD and up to 160 tons of lime kiln dust.

### Coal Refuse Pile

Site grading for the reclamation pilot project was targeted at 4-5 acres on the north-northwest slope of the coal refuse pile. The objective of the site grading was to develop firm, smooth, uniform slopes of at least 4h:1v as a base for an FGD cap. Upon completion of grading with the dozers, the reconfigured slope was proof rolled with a smooth drum vibratory roller in an effort to locate and eliminate any soft spots and to tighten the surface so as to minimize erosion prior to capping.

### Sediment Basin

A sediment basin was constructed, lined with FGD, to test the material's suitability as pond liner and to capture the runoff from the pilot site. The location chosen was an old basin which was filled with coal fines. The fines were saturated and soft, and could not support equipment loads. A sump was excavated using a hydraulic excavator at the northeast corner of the basin and water was pumped out. As the site was dewatered the coal fines were excavated and spoiled.

Once all the coal fines and mud were removed, the dike slopes were repaired and graded to approximately 3h:1v using locally borrowed clay and shale.

A ditch to convey runoff water from the test site to the basin was concurrently constructed using in-situ materials. The ditch and basin were constructed so that only runoff from the test areas is captured. A primary spillway consisting of two 24 inch diameter pipes was provided, and an emergency spillway was also provided.

## **Results and Discussion**

### Greenhouse Experiment

Leachate pH remained low throughout the study, however EC and concentrations of S, Ca, Al, and Fe in the leachate decreased with time for all surface treatments. This indicates that once the pile surface has been stabilized and revegetated the quality of water seeping from the refuse pile will gradually improve.

Concentrations of Ca were larger with FGD than with AL which would be expected given the large solubility of gypsum compared to calcium carbonate. Boron, however, was in the range 6 to 17 mg L<sup>-1</sup> for FGD leachates and 0.8 to 1.5 mg L<sup>-1</sup> for AL leachates. This reflects the presence of relatively soluble B in FGD and indicates the B was being moved out of the surface layer.

Amendment with FGD increased coal refuse pH to 7 or greater in the depth of incorporation, but had no effect on the pH on underlying coal refuse.

Plant uptake of all measured elements was similar for FGD and AL with the notable exception of B. Plant tissue B concentrations were in the range 380 to 450 mg kg<sup>-1</sup> with FGD and in the range 13 to 16 mg kg<sup>-1</sup> with AL. While there was some evidence of B toxicity with FGD in the first harvest, it was no longer visible in subsequent harvests.

### Field Experiment

As was seen with pH and in the greenhouse study, downward movement of Ca was greater with FGD than with AL. One year after amendment application the FGD combined with compost was the most effective treatment in reducing soluble Fe throughout the profile. The amendment treatments had similar effects on soluble Al. As was seen in the greenhouse, FGD produced large increases in water soluble B which again decreased with time.

Although some plant growth was produced with all amendment treatments, FGD produced larger yield than AL. Addition of compost to the FGD further increased yield whereas with AL there was no effect from compost. Plant tissue concentrations of major elements were similar for FGD and AL treatments. Compost, however, increased tissue P and K concentrations with both FGD and AL. Plant tissue trace element concentrations were not affected by the amendments, again with the exception of B. With AL tissue B was 1.2 mg kg<sup>-1</sup> while with FGD it was 40.5 mg kg<sup>-1</sup>, and with FGD and compost tissue B increased to 83.8 mg kg<sup>-1</sup>.

## Pilot Program

### Sediment Basin and Ditch Liner

The criteria for basin and ditch liner material are that it be relatively impervious ( $k_v = 10^{-6}$  cm/set) and durable (resist erosion). To increase durability and strength in an exposed situation, where the FGD will be subjected to erosion and freeze-thaw forces, the FGD should be enriched with a reagent (lime kiln dust, cement kiln dust, lime, or cement). FGD, as produced at the plant, typically has a compressive strength at 56 days of 60-100 psi. The minimum compressive strength necessary for the FGD to resist the actions of freeze-thaw has not been specifically defined, but, based upon experiences at other test projects, it is believed that a minimum compressive strength of 400 psi must be achieved before it is exposed to freeze-thaw cycles. The reagent added at this project was lime kiln dust (LKD) donated by the Dravo Lime Company. The lime kiln dust has a free lime content of 15% to 18% and we attempted to produce an FGD/LKD blend that had 25% to 30% LKD.

Absent the availability of a pug mill, which was not economical for this scale of project, we were forced to develop a field mixing procedure which would produce a thoroughly mixed homogenous product of approximately the desired proportions using front end loader, agricultural disc and rototiller.

The best method of mixing was determined to be when a front end loader was used to initially blend the materials. The front end loader turned over the combined pile of FGD and lime kiln dust several times. This helped to break down large clumps in the FGD and achieved a moderately uniform mixture of the two materials. This mix was then loaded into a truck and taken to the basin where it was dumped and spread in an 6-8 inch thick lift. This action provided additional mixing and breaking down of clods. Finally, the material was rototilled with 3 to 4 complete coverages by the rototiller. This produced a very uniform blend with clumps no larger than 3/4" to 1" in diameter. The mix was then compacted with a Bomag smooth drum vibratory roller (Bomag model BW6) towed by a D6H dozer.

### Coal Refuse Cap

This portion of the pilot project investigated various construction techniques for placing FGD on the regraded surface of the mine refuse to act as an impervious cap to minimize the infiltration of surface water, and thereby prevent the creation of acid leachate. The project also investigated various construction methods for blending FGD and mine refuse to create deep root penetration zones for the cap, and to create artificial topsoil.

The 5 acre test site was initially divided into 10 plots with each plot being capped with a different technique or method. However, during the course of the project it was decided to reduce the number of tests, and plots 8, 9, and 10 received the same treatment. Plots 1, 2, and 3 were each capped with FGD in lift thicknesses of 2', 4', and 1' respectively. The remaining plots were capped with a 1:1 mix of FGD and coal refuse blended with different construction equipment and methods.

Once the cap zone was completed the site was divided into three equal segments and topsoiled. Each segment received a different artificial topsoil cover. Segment 1 had a topsoil which consisted of 12 inches of coal refuse blended with 1000 tons per acre of FGD; Segment 2 had a topsoil which consisted of 12 inches of coal refuse blended with 1000 tons per acre of FGD and with 100 tons per acre of yard

waste compost blended into the top 3 inches; Segment 3 had a topsoil which consisted of 12 inches of coal refuse blended with 1000 tons per acre of FGD and with 33 tons per acre of sewage sludge blended into the top 3 inches. The yard waste compost was obtained from the Kurtz Brothers composting facility in Grove City, Ohio, and the sewage sludge was obtained from the city of Baltimore, Ohio.

## Conclusions

### Greenhouse/Field Experiments

Wet FGD scrubber material was found to be an effective amendment for revegetation of hyperacidic coal refuse. When applied at rates with equivalent alkalinity to AL it was equally effective as AL in neutralizing refuse acidity. With FGD Ca was more soluble and moved more rapidly down the profile than with AL. Application of compost with FGD provided additional pH buffering and appeared to enhance downward movement of Ca. Compost also appeared to increase the solubility and downward transport of Al and Fe, two elements which can be phytotoxic in acid conditions. In the greenhouse FGD was equally effective as AL in ameliorating phytotoxic conditions in the refuse and allowing plant growth, in the field, plant growth with FGD was superior to AL. Compost improved plant growth with both AL and FGD, although in the field the increase was greater with FGD. Salt-loading of drainage waters was not increased by FGD, nor was there a detectable increase in concentrations of trace metals in leachates from FGD amended refuse. Potential problems with use of FGD include high soluble salts and soluble B in the rooting zone immediately after FGD application. Phytotoxicity was not observed in the field and concentrations of soluble salts and B decreased with natural leaching. Therefore, the potential for detrimental effects of FGD on early growth and establishment could be diminished by delaying planting for several weeks after FGD incorporation.

### Pilot Program

Unless there are overriding load bearing requirements, it is recommended that liners be constructed with raw FGD without any additional pozzolanic agent added. The liner thickness should be at least 44 inches and it should be placed and compacted in multiple lifts. This will ensure that 12 inches of liner are below the maximum frost penetration (32" +/-) for this area. The liner should be covered with topsoil and seeded, or with geotextile and cover stone, in all exposed areas above the water and to a point at least 18 inches below the water line to provide surface protection. To attain the necessary strength to resist freeze-thaw it now appears that approximately 50% (by dry weight) of LKD would have to be blended in with the FGD. At that ratio a cost analysis must be made to compare the economics of adding LKD, versus quick lime, or cement at lower percentages but higher unit cost.

When the FGD material being used for impervious cap has been stockpiled for several weeks the curing process will be quite advanced, and in those cases it is recommended that the impervious cap be constructed in thinner, multiple lifts to ensure the construction of a homogenous cap system. Subgrade slopes should be at 5h:lv or flatter in an effort to allow trucks hauling FGD or coal refuse to traverse across preceding lifts. This will greatly expedite the placing operation.

As shown in table 1, the undisturbed water from the site was highly acidic and toxic with high concentrations of heavy metals. On the other hand the water quality of the FGD lined sediment basin meets the Ohio EPA's drinking water standards which highlights the profound environmental benefits of FGD material in an abandoned coal refuse pile.

Unfortunately, bad weather set in before the entire site could be seeded and mulched, and that work will have to be done in the spring of 1996, so a large scale evaluation of sewer sludge versus yard waste compost versus a mixture of only refuse and FGD is not yet available.

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Table 1. Water Quality Analysis Data

Parameter	Site Undisturbed Water (mg/l)	FGD Pond Water (mg/l)	OEPA Drink'g Water Standards (mg/l)
Aluminum, Al	414	0.12	
Arsenic, As	0.566	0.01	0.05
Barium, Ba	0.03	0.041	2
Beryllium, Be	0.0224	< 0.0002	
Cadmium, Cd	0.0023	< 0.0005	0.005
Chromium, Cr	0.189	0.003	0.1
Copper, Cu	0.167	0.003	
Iron, Fe	2640	0.12	
Lead, Pb	0.117	< 0.002	0.05
Manganese, Mn	14.52	0.01	
Mercury, Hg	< 0.0002	< 0.0002	0.002
Nickel, Ni	0.381	0.003	
Selenium, Se	< 0.02	0.012	0.05
Silver, Ag	< 0.0002	0.0006	
Sodium, Na	9.4	34.9	
Thallium, Tl	0.033	0.002	
Vanadium, V	0.264	< 0.003	
Zinc, Zn	1.46	< 0.004	
Acidity	10400	< 1	
Alkalinity	< 1	39	
Chloride, Cl	5	211	
Conductivity	8380	2930	
Fluoride, F	< 0.1	< 0.1	
Residue- Filterable, TDS	13100	2740	
Sulfate, SO <sub>4</sub>	9040	1490	
pH	2.06	8.56	

Figure 1. Effect of AL, FGD, and compost on the distribution of pH, and water soluble concentrations of Fe in 22.5 inch pots of coal refuse.

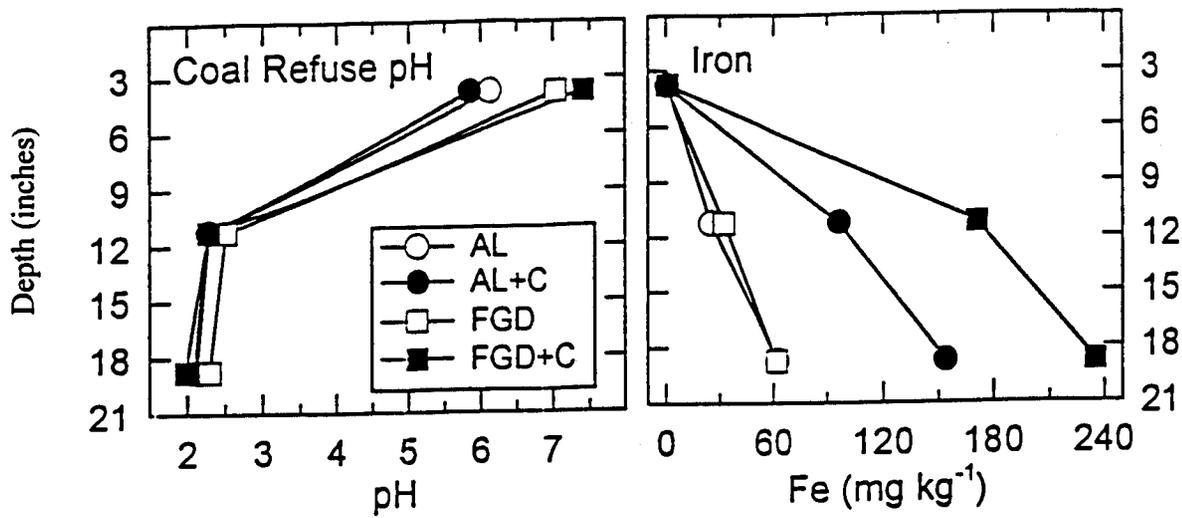
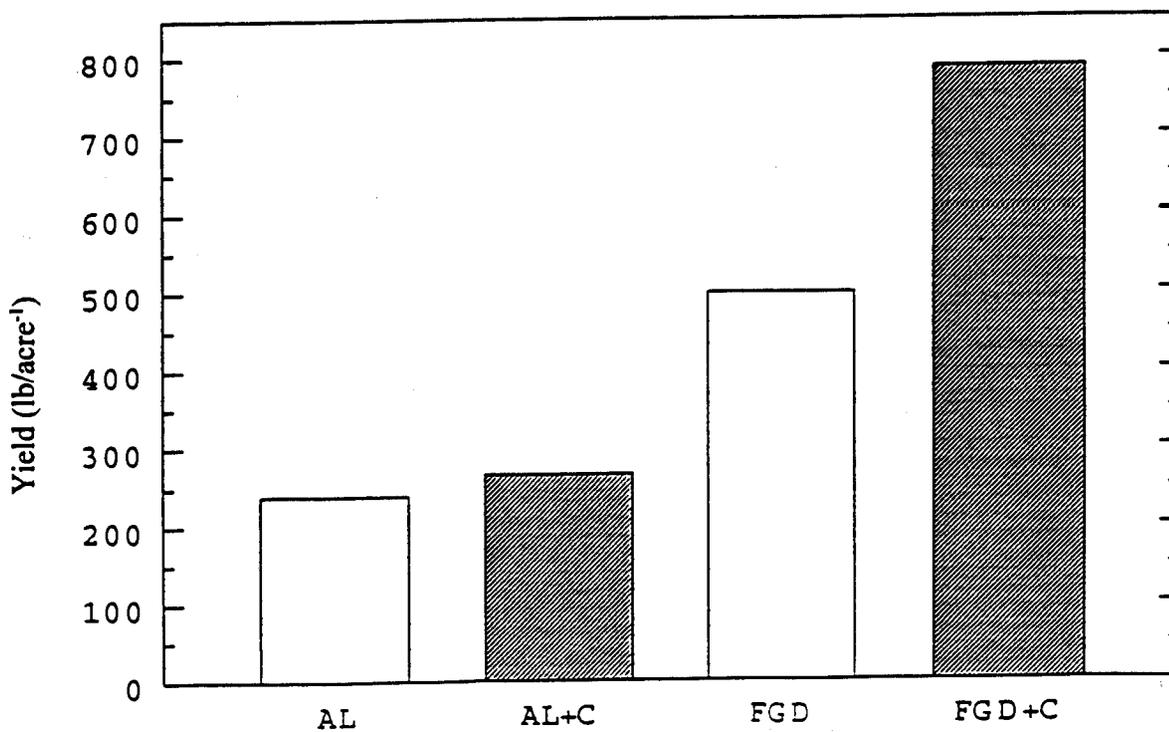


Figure 2. Total 1995 plant yield from coal refuse amended with AL, FGD, and compost.



## **BAKER SOIL TEST® DEVELOPMENT AND FIELD CASE STUDIES PROVIDE THEORY AND DATA SHOWING THAT PLANTS DON'T GROW IN SOILS.**

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### **Abstract**

Initial experiments conducted in 1977 by the senior author involved the use of chemical ion activities of the solution phase of coal combustion by-products (CCB's) and cement kiln dusts (CKD's) used for land reclamation. Using combinations of soil and CCB's or CKD's in layers with depths ranging from no soil and no ash to combinations up to 4 feet, we found that from the point of view of plant nutrition, CCB's and CKD's are equivalent to soil. However, both materials are more susceptible to erosion than soils. Using standard erosion station methods, we found that with proper water management for erosion control, CCB's and CKD's can be used as cover soil for land reclamation, and as a substitute for soil in several applications. The cellulose to organic matter connection is important with respect to substrate air-water relations. The Baker Soil Test (BST) is used routinely to evaluate mixtures of wastes used under field conditions as synthetic soils. Data and experience from these sites and our projections for the future are the subjects reviewed here.

### **Introduction**

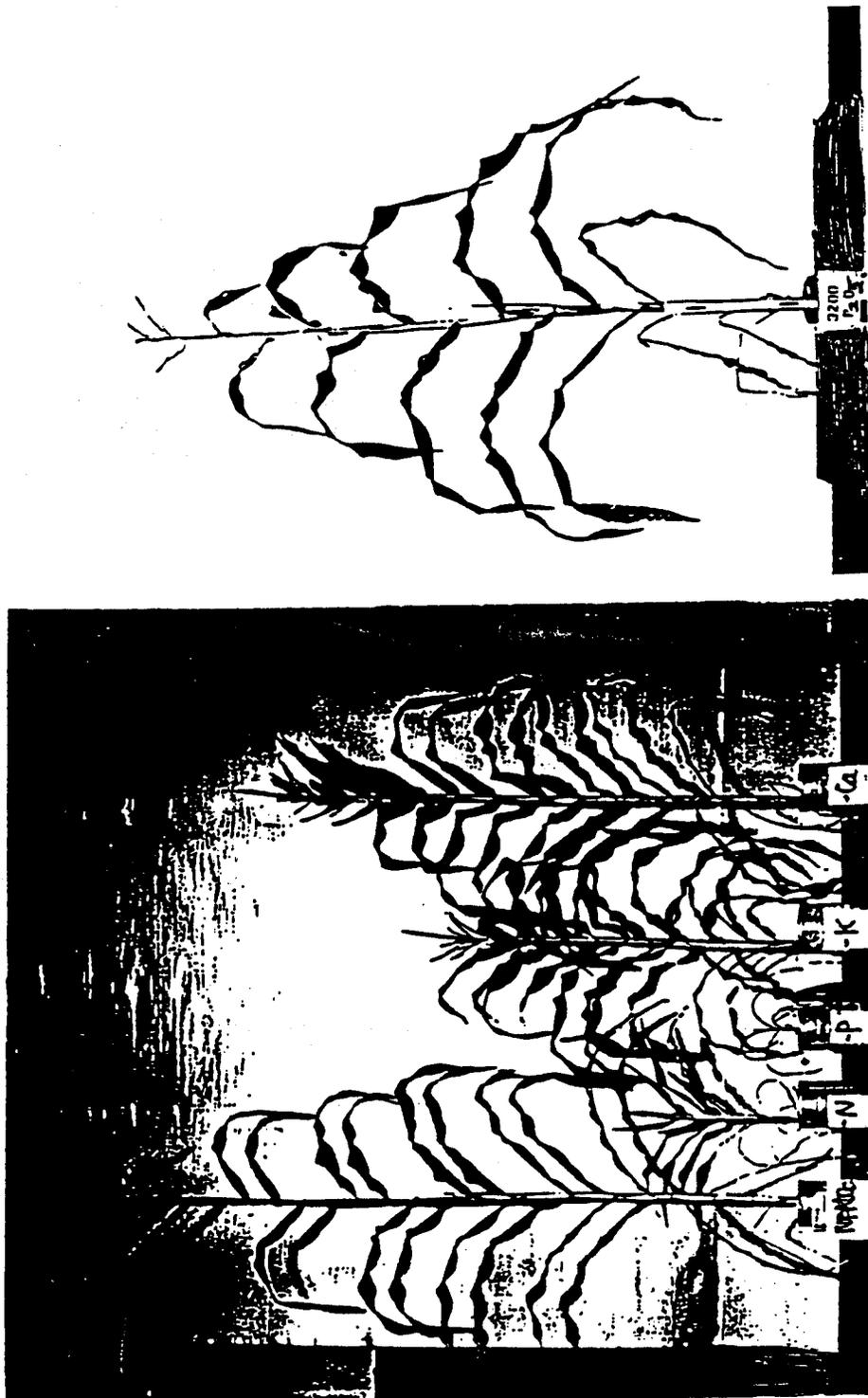
With a Ph. D. in Soils from the University of Missouri and a Year at the University of Minnesota, Northeast Experiment Station, the senior author's career at Penn State University started in 1961. With help from many Penn State graduate assistants and Leon Marshall, his research aide for 30 years, numerous investigations were conducted to evaluate and explain data enabling integrated land and waste management systems for crop production and environmental quality. The Baker Soil Test® (BST), (Official ASTM Method D5435-93 "Standard Diagnostic Soil Test for Plant Growth and Food Chain Protection") enables the use of mixtures of non-soil, silicate wastes and selected organic wastes as soil substitutes. A high surface area per unit volume of soil per plant is important for crop production. Based on theory and experience as a University of Missouri student, Dale produced a mature corn plant in soil contained within a one quart oil can (Plate 1). The "rootless wonders" and related results were important factors leading eventually to the Baker Soil Test from theory and case studies. As evaluated by the BST, fly ash (CCB's) and CKD's, sewage sludges, manures, and industrial wastes have been used as synthetic soils.

### **Magic Green Corporation® Utilizes CKD's for Increased Crop Yields**

Gregory, "Greg", Wommack has excellent field evidence that combinations of existing N, P, & K commercial fertilizers combined with CKD's result in synergistic crop growth responses. His technology is now being offered local growers and marketing agencies for distribution as the products "Ura-Cal®", "Potassa-Cal®" and "Combined Nutrient Positioning®" technology. Magic Green Corporation® materials are being offered to marketing partners for distribution in the USA and abroad.

The Wommack technology is an example of needed land management technology. Land managers must seek an understanding of the components of their systems. Interacting effect involving differential responses of crops to new technology will be important as the Magic Green Corporation's technology evolves. Cement Kiln Dust (CKD's) as a source of potassium was mentioned by Tisdale and Nelson. Land Managers must seek an understanding of the components of existing systems. Interacting

Plate 1. Corn plants grown in greenhouse studies by Dr. Baker while a student at the University of Missouri, showed that phosphorus was the most limiting element when corn plants were grown in no. 10 tin cans. This led to his trial in which a mature corn plant was grown in a 1 quart can of soil receiving 3200 lbs. of phosphorus as  $P_2O_5$  per acre (2,000,000 lbs.) equivalent.



Technology evolves. Land management decision making requires that one seek an understanding of the components of the system and their interactions. Crop Production requires a knowledge of cultural practices and soil management, as affected by climatic conditions, and other components of each system. Scientific bases for management practices often are discovered after they have become standards.

### **Education and Experience are Essential for Land Managers**

Dr. Baker, as an undergraduate at the University of Missouri, was employed during the summer months for 3 years as a student trainee for a career appointment as a USDA-SCS Farm Planner in Higginsville, Mo. He holds this work as his enlightening experience. With the freedom to seek help when he was not sure that he could provide the best advice to farmers, he gained confidence as he assisted farm operators in making Land Management Decisions. The authors are well aware that in order to serve the farm production sector with new products and reliable decision support, they must seek an understanding of the components of each system and their interactions. Crop production requires a knowledge of cultural practices and soil management, as affected by climatic conditions and all other art and science components of each system.

While attending the Southwest Fertilizer Industry Conference in San Antonio, Texas; Dr. Baker was impressed with the knowledge and dedication of Gregory Wommack and his crop production experiences with CKD's. Greg was invited to coauthor this manuscript in order to provide readers with another approach for providing "decision support". Decision support requires that we seek an understanding of the needs and goals of clients without just being critical of existing systems. For some systems, especially dairy operations, that Dr. Baker works with, are so complicated that one has to "leave it to the operator" when it comes to many of the business management decisions that must be made. Here, we only consider field operations involving waste utilization and problem solving for environmental quality and compatible land use systems involving CKD's and CCB's. User initiated decision support for the management of land and industrial wastes for erosion control, crop production, and interactions provide exciting, new vocations, within the LMD areas of emphasis.

Theory and practices applied to case studies over time involve concerted efforts to integrate land and waste management systems. For this manuscript, attention is focused on the concepts leading to the Baker Soil Test (BST) and its application for land management, which includes the theory supporting the conclusion included in the title that "plants don't grow in soil". It is important that soil management include the concepts relating to the importance of the soil solution as the continuous phase from which plants obtain water and the required nutrients. In addition, the approach of authors regarding CKD's as components of crop management systems and related university research are worthy of emulation.

### **Land Reclamation Studies Indicated a Need for A New Approach to Soil Testing**

Mine land reclamation has been under investigation by Baker and others for many years. Often land reclamation programs fail because the site has very low pH associated with phytotoxic levels of Al and Mn, limiting water holding capacities and/or steep, long slopes causing excessive soil erosion. With proper site preparation, including the return of overburden soil with topography and vegetative cover to prevent excessive erosion, the next major step requires the BST and surface application of waste mixtures to serve as mulch, a source of plant nutrients, and erosion control. Many wastes now going to land-fills are suitable for the production of synthetic soils and mulch materials for reclamation of many disturbed sites. For agricultural lands, we must take precautions to protect the food chain and environmental quality. The elements cadmium and copper require special attention to protect animal and human health, and soil productivity for the respective elements.

Using standard erosion station methods, we found that with runoff management for erosion control, CCB's and CKD's can be used as cover soil for land reclamation, and/or as substitutes for soils. Using a slope of 9%, with a slope length of 22.3 m, a K factor from 0.71 to 0.82 were obtained by Lehrs, et.al.. 1981. With erosion control, CCB's and CKD's can be used as cover soil for land

reclamation, and/or as substitutes for soil in many applications. For field plots with slopes of 9 %, fly-ash erosion was somewhat greater than for soil, but acceptable, for slope lengths of 100 feet. In 1975, Baker, et al. demonstrated that CKD's were more effective than lime for vacuum filter processing of sewage sludge. However, the plant operators speculated that the silicate waste was more abrasive to equipment than hydrated lime. Therefore, the sludge conditioning technology was never adopted. Risser, Doty and Baker in 1980 demonstrated that CKD's are useful as a lime-potash fertilizer. With our past experience, we are delighted with the technology under development by Magic Green Corporation.

### **Magic Green Corporation@ CKD's and Pulverized Limestone Compared for Liming**

For each material (dry kiln dust and pulverized limestone) 300 grams were placed in 500 ml beakers and distilled water was added to produce saturated pastes (no air or free water were present within or on top of the suspensions at equilibrium). Under vacuum to remove capillary water, the 300 g of limestone with a guaranteed calcium carbonate equivalence of 103% held 75.2 g water, while the 300 g of CKD material held 159.3 g of water. As expected, the silicate material has a substantially higher water holding capacity than pulverized limestone. The pH of the CKD suspension was 12.57 and the liquid filtrate had a pH of 13. For the limestone suspension, the pH was 9.08 and the filtrate had a pH of 8.95, which is higher than the theoretical pH of 8.1 for pure calcium carbonate ( $\text{CaCO}_3$ ) in equilibrium with the  $\text{CO}_2$  pressure of the atmosphere. From these results it is obvious that by blending fertilizers containing Wommack's CKD's which are banded 4 inches to the side of the rows and 2 inches deep, the plant environment is enriched with water,  $\text{Ca}^{++}$ , and other many components included in Table 1.

The analyses presented in Table 1 were performed to ascertain if any potentially toxic elements could be encountered by animals consuming crops grown where CKD's are used as a nutrient source. The composition of the CKD is compatible with soil and soil parent materials for all parameters. Since the CKD's are produced from bedrock that is also parent material for soils, no adverse effects were expected. From an environmental quality perspective, however, one should verify that no adverse effects are possible.

### **Soil Biology Related to the Physical Chemistry of Soil Solutions**

The soil solution, as the continuous phase in soil-plant systems, even in relatively dry soil, insures that growing plants stand in water, which exists as a continuous film, stretched over soil particles and plant root surfaces. As the soil dries, the thickness of water films decrease and water properties change to conform with the structure of both the soil solid phase and the plant vascular system even as the living plants wilt. When plants wilt, the water films approach water of hydration which is immobile (the structure of adsorbed water is more ice like than free water).

Productive soils include those with deep, well drained profiles that allow plant rooting depths of 4 feet or more. While nutrient availability with depth is important with respect to water availability to plants, nutrient management within the soil surface plow layer can provide crops with all essential chemical elements taken up as chemical ions by plants. The deep, well drained silt loam soils developed under prairie vegetation represent the more productive agricultural soils of the USA because of their greater plant available water holding capacities. The silt loam soil texture, which prevails in loess soils where the native vegetation was prairie grasses; have nearly ideal air-water relations for farm crops. While water availability over the growing season is very important, nutrient availability is often the limiting factor for crop production. Justus von Leibig (1803-1873), a German chemist, made historically valuable statements regarding the factors which determine plant growth:

1. Most of the carbon in plants comes from  $\text{CO}_2$  (carbon dioxide within the atmosphere).
2. Hydrogen and oxygen come from water.
3. The alkaline metals are needed for acid neutralization of from plant metabolite activity.
4. Phosphates are necessary for seed formation.

Table 1. Total Chemical Composition of Water Filtrate Removed Under Vacuum To Determine the Water Holding Capacity of The Material.

ICP Metal	Filtrate (ppm)	Total (ppm)	ICP Metal	Filtrate (ppm)	Total (ppm)
Ag	<0.003	<1.13	Mo	0.360	1.51
Al	<0.01	7638.002	Na	285.55	3773.58
As	0.004	8.516	Nb	<0.005	<1.89
Au	0.029	<1.89	Nd	<0.005	10.059
B	0.022	12.254	Ni	<0.006	19.244
Ba	0.720	48.420	Oe	<0.005	<1.89
Be	<0.004	<1.51	P	<0.50	234.879
Bi	<0.005	<1.89	Pb	0.038	42.029
Br	1.921	<188.68	Pd	<0.005	<1.89
Ca	391.587	341,195.174	Pr	<0.005	5.200
Cd	<0.003	1.225	Pt	<0.005	<1.89
Ce	<0.005	12.136	Rb	14.235	11.674
Cl	2660.725	18,833	Re	0.008	<1.89
CO	<0.004	2.285	Rh	<0.005	<1.89
Cr	0.204	8.596	Ru	<0.005	<1.89
Cs	4.245	6.359	Sb	0.008	<1.51
Cu	0.016	2.271	Sc	<0.005	2.522
Dy	<0.005	<1.89	Se	0.391	<1.13
Er	<0.005	<1.89	Si	<0.50	<188.68
Eu	<0.005	<1.89	Sm	<0.005	<1.89
Fe	0.154	6018.106	Sn	<0.003	<1.13
Ga	<0.005	2.090	Sr	5.273	148.454
Gd	<0.005	<1.89	Ta	<0.005	<1.89
Ge	<0.005	<1.89	Tb	<0.005	<1.89
Hf	<0.005	<1.89	Te	<0.005	<1.89
Hg	<0.0005	<0.19	Th	<0.005	<1.89
HO	<0.005	<1.89	Ti	2.254	827.278
I	4.19	<188.68	Tl	0.019	<0.75
In	<0.005	<1.89	Tm	<0.005	<1.89
Ir	<0.005	<1.89	U	<0.005	<1.89
K	88.492	38,382.75	V	0.010	77.629
La	<0.005	15.51	W	<0.005	<1.89
Li	1.681	9.005	Y	<0.004	<1.509
Lu	<0.005	<1.89	Yb	<0.005	<1.89
Mg	<10.00	7,184.04	Zn	<0.004	39.575
Mn	0.034	372.83	Zr	<0.005	5.346

Please note that 2 g of the solid sample was digested in both nitric and hydrochloric acid, and then diluted to a final volume of 100 ml. This solution was then analyzed by ICP-Mass Spectrometer. The filtrate was directly injected into the ICP-Mass Spectrometer.

## 5. nonessential materials.

While all of Leibig's ideas were not correct, he eventually developed his "Law of the Minimum", which, in effect, says that the growth of plants is limited by the plant nutrient element or growth factor present in the smallest relative quantity, with all others being present in adequate amounts. Plants require C as  $\text{CO}_2$  from the atmosphere above and below the soil surface, H as  $\text{H}_2\text{O}$  from water within the rooting area and from deposition on leaves, O as  $\text{O}_2$  from the atmosphere; P as  $\text{H}_2\text{PO}_4^-$  or  $\text{HPO}_4^{2-}$ , K as  $\text{K}^+$ , N as  $\text{NO}_3^-$  and/or  $\text{NH}_4^+$ , S as  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{+2}$ ,  $\text{Fe}^{+2}$  or  $+3$ ,  $\text{Mg}^{+2}$ , (C HOPKINS CA Fe, Mg) and other trace elements including Mn, Zn, Cu, Mo, B, and Cl. It is interesting that aluminum (AL) and Silicon (Si), the most abundant elements in soils are not essential for higher plants or and animals..

### **The Baker Soil Test<sup>®</sup> (BST) Applied to Land Reclamation Studies**

Mine land reclamation has been under investigation by Baker, graduate students, and colleagues for many years. Often reclamation programs fail because the sites have a very low pH associated with phytotoxic levels of Al and Mn, limiting water holding capacities, and/or steep, long slopes causing excessive soil erosion. With appropriate site preparation including the return of overburden surface soil combined with topography and vegetative cover to prevent excessive erosion, and use of the BST, the next major step should include the surface application of waste mixtures to serve as mulch, a source of plant nutrients, and soil erosion control. Many wastes now going to landfills are suitable for the production of synthetic soils and mulch materials for reclamation of many disturbed sites. Magic Green Corporation has demonstrated some of the technology for which Land Management Decisions, Inc was founded.

Using standard erosion station methods, we found that with runoff management for erosion control, CCB's and CKD's can be used as cover soil for land reclamation, and/or as substitutes for soils in many applications. Using a slope of 9%, with a length of 22.3 m, a K factor ranging from 0.71 to 0.82 were obtained. For field plots with a slope of 9%, fly-ash erosion was somewhat greater than for soil, but acceptable, for a slope of 9 %, with a length of 100 feet. In 1975, Baker, Welch, Stout and Doty demonstrated that CKD's were more effective than lime for vacuum filter processing of sewage sludge. However, the plant operators speculated that the silicate waste would be more abrasive to their equipment than hydrated lime. Therefore, the technology has never been accepted. Kissner, Doty and Baker demonstrated that CKD's are useful as lime-potash fertilizer. From our past experience, we are looking forward to the time when the Magic Green Corporation becomes established.

Clients currently use the Baker Soil Test to provide the data and interpretations required for the use of CCB's and CKD's combined with other wastes to produce synthetic soils and/or soil conditioners. The cellulose (organic matter) connection is important with respect to air-water relations. The methods have been successfully applied to fly-ash piles, ash amelioration of abandoned mine lands and severely eroded sites.

It has been known for centuries that the soil solution is the continuous phase in soils-plant systems. Even in relatively dry soil, growing plants stand in water which exists as continuous films, stretched over soil particle and plant root surfaces. As the soil dries the thickness of water films decrease, and water properties change to conform with the structure of both the soil solid phase and the plant vascular system, even as living plants wilt.

### **Evolution of the The Baker Soil Test (BST) as Related to Soil-Plant Interactions**

After six years at Penn State, Dr. Baker spent six months at Purdue University working with Dr. Philip Low. Low and his students had shown that silicate, clay gels when disturbed by tapping the container on the lab bench changed to a sol (liquid suspension). Using radioactive sodium (Na) as a tracer. Baker postulated and verified that the "physical change" was accompanied by a "chemical

change” with respect to availability of Na ions to plants. Using radioactive Na, he found Na in a sodium saturated bentonite clay became higher in ionic activity and plant availability when the gel was disturbed by tapping on the laboratory bench (Low, Davey, Lee, & Baker, 1968; and Baker and Low, 1970).

Upon his return from Purdue University, Dr. Baker began to ponder the soil physical chemistry involved. He set up chemical equations that were known to be important to soil-water-plant relations and solved them simultaneously. To his surprise, all of the soil parameters fell out leaving only the solution chemistry (Baker, 1971). Baker asked the late Dr. Louis Kardos to check his results to see if he had made a mistake. He returned in a few hours feeling grim. He said to Dr. Baker, “No, you didn’t make a mistake, but do you know what you have done?” Baker replied, “Yes, plants don’t grow in soils”.

An example of the Baker Soil Test (BST) report is presented as Figure 1. For routine soil test operations, the BST includes 2 pages of output, which includes concentrations of toxic metals. The results include a “small exchange”, quantity and intensity parameters for each element expressed as the negative logarithm of the solution activity (pH, pK, pCa, pMg, pFe, pMn, pCu, pZn, pCd, etc.). As indicated above, The Baker Soil Test is not like other soil test methods, it measures the parameters of the soil solution in equilibrium with the solid phase of soils. The results include “small exchange”, quantity and intensity parameters. (pH, pK, pCa, pMg, pFe, pMn, pCu, pZn, pCd, etc.).

We are at a dawning of new knowledge of waste-soil-plant relations. We may continue to rely on knowledge of soil properties and their management for crop production, but several factors indicate a need to begin to use suitable wastes to improve the air, water, and nutrient relationships of soils. Beneficial utilization of wastes that are now going to landfills, at a substantial cost, could lead to even more economical waste utilization and increased crop production. Colored slides are available to illustrate the concepts and data presented. One can rest assured that a soil management revolution is in the making. While the products developed by Wommack are not expected to be “cure alls”, they are examples of products that combine common sense with technology and experience that show great promise for CKD’s and synergistic effects yet to be quantified. Aspiring college students are urged to seek to integrate the knowledge they obtain from the pure sciences to better define and interpret soil properties using laws of physics and chemistry.

### Summary

1. CKD’s improve the three-phase systems called soils. An Ideal Soil System contains on a volume basis half solids and half pore space with half of the pore space full of water after the soil is saturated and allowed to drain for 24 hours. The most important role of CCB’s and CKD’s as soil amendments involve their role as sources of nutrients and as “more soil” defined as “Those surface layers or deposits in which plants grow”, Hunt, 1972.
2. The Baker Soil Test provides investigators with a means of evaluating CKD’s, CCB’s, etc. for use as soil amendments.
3. Chemical elements in the solid and solution phases provide the plant nutrient requirements of plants. In Figure 2, we present an over-simplified, but operational definition of soil systems. The oxides of the biologically nonessential elements, Al and Si, combined with the essential elements, Fe and Mg, may be considered as the major components of the matrix of all soils. However, it is water that is the continuous phase in soils and the compound that is central to all living organisms. Plant growth, then, relates to the properties of the aqueous solution phase which surrounds every soil particle which makes up the solid phase of soil or any media in which plants grow.

Figure 1. Copy of a Baker Soil Test output form for soil assumed to be at normal background levels for most parameters

LMD OUTPUT FOR ASTM BACKGROUND FOR BAKER SOIL TEST.		LAND MANAGEMENT DECISIONS, INC. 3048 RESEARCH DRIVE STATE COLLEGE, PA 16801 SOIL CHEMISTRY, LAND & WASTE MANAGEMENT DECISIONS									
LMD INTERPRETATION OF BAKER SOIL TEST (BST) DATA. THE BST IS ASTM OFFICIAL METHOD # D5433-93.											
IDENTIFICATION	DATE	LAB NO	COUNTY	SOIL	LINE REQ.(T/AC)	SOIL PH	BST PH	CEC (MEQ/100 G)	ELEC.COND.		
ASTM1	09-04-1996	12	34	56	0.50	6.50	7.00	10.00	2.20		
TEST LEVEL		LOW				NORMAL			HIGH		
<b>NITROGEN:</b>											
NITRATE N (PPM)	20.00	.....									
<b>PHOSPHORUS:</b>											
CALCULATED EPC(PPB)	27.01	.....									
Mehlich 3 P (PPM)	30.00	.....									
<b>BAKER SOIL TEST POTASSIUM:</b>											
BST pK	3.66	.....									
BST K (PPM)	9.80	.....									
Exchangeable (ppm)	78.00	.....									
Percent Of CEC	2.00	.....									
<b>BAKER SOIL TEST MAGNESIUM:</b>											
BST pMg	3.25	.....									
BST Mg (PPM)	24.00	.....									
Exchangeable (PPM)	98.40	.....									
Percent of CEC	8.20	.....									
<b>BAKER SOIL TEST CALCIUM:</b>											
BST pCa	2.57	.....									
BST Ca (PPM)	200.00	.....									
Exchangeable (PPM)	1400.00	.....									
Percent of CEC	70.00	.....									
<b>BAKER SOIL TEST CATION RATIOS:</b>											
(Ca plus Mg)/N	5.76	.....									
Mg/K	2.04	.....									
Ca/Mg	0.67	.....									
<b>BAKER SOIL TEST MANGANESE:</b>											
BST Mn (PPM)	20.00	.....									
BST pMn	8.27	.....									
<b>BAKER SOIL TEST IRON:</b>											
BST Fe (PPM)	10.00	.....									
BST pFe	20.89	.....									
<b>BAKER SOIL TEST COPPER:</b>											
BST Cu (PPM)	2.00	.....									
BST pCu	14.95	.....									
<b>BAKER SOIL TEST ZINC:</b>											
BST Zn (PPM)	4.00	.....									
BST pZn	11.58	.....									
<b>PLANT NON-ESSENTIAL ELEMENTS:</b>											
<b>BAKER SOIL TEST SODIUM:</b>											
BST Na (PPM)	50.00	.....									
<b>BAKER SOIL TEST ALUMINUM:</b>											
BST pAl	12.35	.....									
BST Al (PPM)	5.00	.....									
<b>BAKER SOIL TEST LEAD:</b>											
BST pPb	12.72	.....									
BST Pb (PPM)	2.00	.....									
<b>BAKER SOIL TEST NICKEL:</b>											
BST pNi	14.33	.....									
BST Ni (PPM)	0.50	.....									
<b>BAKER SOIL TEST CADMIUM:</b>											
BST pCd	14.10	.....									
BST Cd (PPM)	0.10	.....									
				LOW	NORMAL			HIGH			

PK, PMG, PCA, PAL, ETC. INDICATE THE AVAILABILITY OF RESPECTIVE ELEMENTS AND ARE CALCULATED NEGATIVE LOGARITHMS OF IONIC ACTIVITIES WHICH ARE ANALOGOUS TO PH, ACTIVITY OF THE HYDROGEN ION.  
pLICAND=14.76 DILUTION FACTOR= 1.00

Figure 2: Master Variables with Al and Si

Mater Variable With Al and Si In Soil-Water-Plant Systems
pH <sub>2</sub> O, pO <sub>2</sub> , pH, pCO <sub>2</sub> , pNO <sub>3</sub> , pNH <sub>4</sub> , pCa, pMg, pK, pH <sub>2</sub> PO <sub>4</sub> , pHPO <sub>4</sub> , pSO <sub>4</sub>

Essential Trace Elements:
pFe, pMn, pB, pZn, pCu, pMo, pCl (+ For Animals pNa, pCo, pO <sub>2</sub> , pI, pNi, pSe, pV)

Non-Essential, Potentially Toxic Elementnts:
pAl, pPb, pCr, pAs, pCd, pHg+ ?(pAg, pSb, pBr, pGe, pRb, pSr, pSn)

- Ionic activities in soil-water systems and the Quantity/Intensity (Q/I) concept. The quantity (Q) value for an essential plant nutrient other than water, refers to the amount of that nutrient element of ionic form (I) that is in dynamic equilibria with the true activity  $A_i$  within the soil solutions. The (Q) value then may be thought of as the “labile pool”, “adsorbed fraction”, or other terms for the concentration © in the equation:

$$A_i = f_i C_i \quad (I)$$

Where  $A_i$  is the chemical activity of ion, I, in true solution and f is the activity coefficient. The activity coefficient relates inversely to the bonding energy with which an ion (I) is retained as an adsorbed, exchangeable ion within the soil.

- Decision support for users of the BST is based on LMD Technology gained from soil chemistry theory and experience.
- By-product usage developed by Magic Green Corporation is an example of the “integrated Land and Waste Management Systems for soil improvement, increased crop production, and a truly sustainable agriculture for the 21st century.

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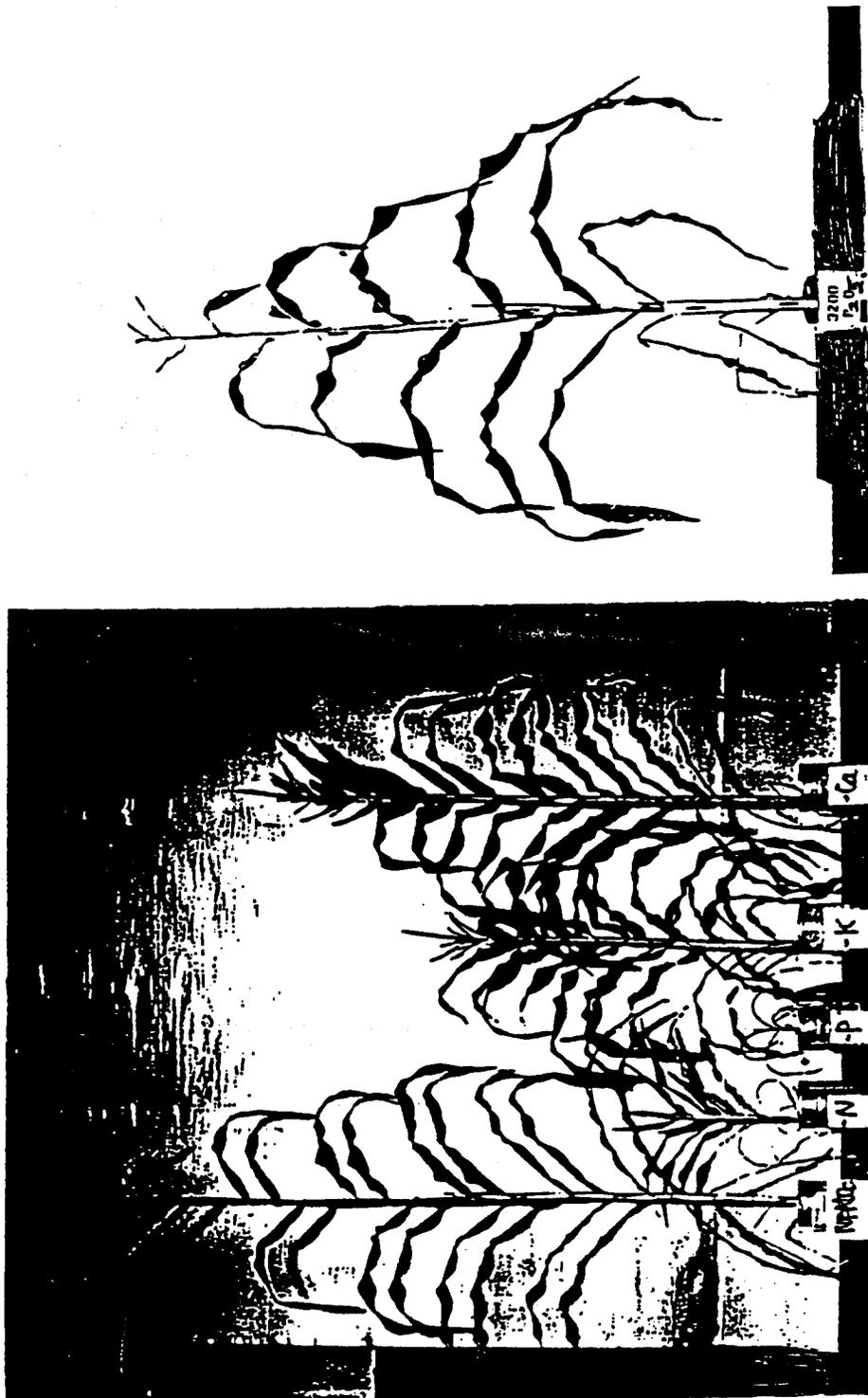
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Plate 1. Corn plants grown in greenhouse studies by Dr. Baker while a student at the University of Missouri, showed that phosphorus was the most limiting element when corn plants were grown in no. 10 tin cans. This led to his trial in which a mature corn plant was grown in a 1 quart can of soil receiving 3200 lbs. of phosphorus as  $P_2O_5$  per acre (2,000,000 lbs.) equivalent.



## Leachate Quality from Coarse Coal Refuse Mixed with Coal Fly Ash: Effects of Ash Blending Rates

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### Abstract

The exclusion of coal fly ash from regulation as a hazardous waste has led to increased interest in returning ash to the coalfields for disposal. Bulk-blending alkaline fly ash with acid forming coal refuse may present a disposal option that aids in the control of acid mine drainage. A preliminary column leaching study examined the leachate quality from acid-forming, coal refuse:fly ash blends. Coal refuse (2.2 % total-S), and two refuse:fly ash blends (20% and 33% ash w/w) were packed into leaching columns and leached under unsaturated conditions for over four years. The coal refuse columns acidified quickly, producing peak leachate levels of acidity (pH 1.7), Fe (10,000 mg I<sup>-1</sup>), SO<sub>4</sub><sup>-2</sup> (30,000 mg I<sup>-1</sup>), and Mn (300 mg I<sup>-1</sup>). Both ash blended treatments provided alkaline leachate with low metal levels. A second column study used a refuse with higher potential acidity (4% total-S), and two alkaline ash sources; one blended at two rates (20% and 33%) and one at four rates (5%, 10%, 20%, and 33%). Bulk-blended ground agricultural limestone, rock phosphate ore, and topsoil treatments were also studied. The unamended refuse treatment acidified rapidly and produced acidic (pH 1.7) leachates with high peak dissolved metal levels (>15,000 mg I<sup>-1</sup> Fe; 200 mg I<sup>-1</sup> Mn). Treatments blended with 33% ash produced alkaline (pH >8.4) leachates with low metal levels (Al <1.0 mg I<sup>-1</sup>; Cu-0.10 mg I<sup>-1</sup>; Fe < 2.0 mg I<sup>-1</sup>; Mn < 3.0 mg I<sup>-1</sup>). Treatments containing less ash eventually acidified and ash bound metals (Mn and Cu) were stripped from the ash and eluted in quantities proportionate to the amount of ash in the blend. Treatments in which a low alkalinity ash was augmented with ground limestone produced alkaline leachates with low metal levels. Examination of the soil phases from the column studies confirmed that pyrite oxidation had taken place in the columns producing acidic leachates. Overall, the inhibition of pyrite oxidation by high ash blends was attributed to alkalinity effects, chemisorption, decreased hydraulic conductivity, and decreased oxygen diffusion to pyritic surfaces. Ash alkalinity and refuse potential acidity must be balanced for environmental safety in this co-disposal environment.

### Introduction

This project is a comprehensive investigation of the potential use of fly ash as a liming agent and/or soil conditioner on coal refuse and mine soils. Using fly ash in this manner would represent a beneficial reuse of a material that is currently land tilled. The fly ash would benefit nonacidic, coarse textured, mine soils by adding fine particles that would increase the water holding capacity which is a limiting factor in many mine soils. Alkaline fly ash could also be applied to most refuse materials and to acidic mine soils. The alkalinity in the ash would serve to neutralize the acidity generated by the oxidation of iron pyrite (FeS<sub>2</sub>). The fine texture of the fly ash would also enhance the water holding capacity of the refuse, which generally has a very low level of available water.

Current mining regulations allow for the release of acidic mine drainage (AMD) from refuse piles to holding ponds, where the drainage is impounded and treated with caustics to neutralize the acidity before the water is released to local waters. The AMD and the associated impoundments present a threat to the quality of both ground and surface waters near the refuse pile. One may also question the effects of releasing high pH water into surface waters. An alternate solution would be to bulk blend a liming agent, such as limestone, with the refuse at a rate that would neutralize all the acidity potentially produced by pyrite oxidation within the refuse pile. A problem with this treatment would be cost.

Alkaline fly ash could offer a cheaper alternative to limestone. Fly ash is produced at coal fired power plants, which burn coal that was cleaned at a prep plant with an associated with a refuse pile. The fly ash is currently land filled at a suitable site near the power plant. Back hauling fly ash could offer a cost effective liming agent for use on refuse piles and surface mined lands. Returning the ash to where the coal was mined and cleaned also makes some sense from a material balance point of view.

It has yet to be determined if this is a worthwhile practice from an environmental standpoint. Fly ash is enriched in many trace elements, particularly metals. These metals are part of the pyrite structure in the coal and become concentrated in the fly ash during the combustion process. These elements may be surface adsorbed on the glassy spherical fly ash particles or they may exist internally in the sphere. Elements that are surface adsorbed can be quite mobile. Many of these trace elements could be quite leachable under low pH conditions. We must examine the interactions between the fly ash and the coal refuse. Can pyrite oxidation occur rapidly enough to allow the material to become acidic? Is there enough alkalinity in the fly ash to keep the pH high and retard or stop pyrite oxidation or neutralize the acidity generated by any pyrite oxidation that does occur? Will pyrite oxidation simply be delayed until the alkalinity of the material is exhausted and then recommence? These are fundamental questions that must be answered before the co-disposal of fly ash and coal refuse can become a widespread practice.

To answer these questions we have undertaken several studies. This paper will concentrate on the results of two column studies which we have been conducting over the last 4 years.

### **Objective**

The objective of the column studies was to determine the influence of the various treatments on acid sulfate weathering and reaction products and to these findings to the quality of the coal refuse drainage.

### **Materials and Methods**

#### Preliminary Column Study

The initial column study (experiment 1) was started in Feb. 1991. This study was initiated to examine the general quality of leachate from refuse/fly ash bulk blends. The refuse used in this study had a potential acidity of 73 tons  $\text{CaCO}_3$ /1000 tons of refuse. This study used columns described in a dissertation by Stewart (1996). They were 18 cm (diam) by 60 cm(L). Two columns were packed with unamended refuse. Three columns were packed with a 4: 1 refuse:ash mix (20% ash), and three columns were packed with a 2:1 refuse:ash mix (33% ash). The ash (WV) used in this study was generated at Westvaco's paper mill in Covington, VA. The calcium carbonate equivalent (CCE) of the ash was 5.0 % by the method of Sobek et. al, 1978. These columns were not totally balanced as far as alkalinity added:potential acidity, but it seems that the 33% ash mix is about the highest rate of ash that could be practically handled.

#### Second Generation Column Study

The second set of columns (experiment 2) used larger columns (24 cm diameter) of varying lengths. Each column was packed with the same amount of refuse (36 kg) and the prescribed amount of amendment(s) for each treatment. There are 15 treatments in this study and each treatment is replicated three times. The treatments were:

1. unamended refuse (control)
2. unamended refuse + topsoil
3. refuse + 5% Westvaco fly ash (5% WV)
4. refuse + 10% Westvaco fly ash (10% WV)

5. refuse + 20% Westvaco fly ash (20% WV)
6. refuse + 33% Westvaco fly ash (33% WV)
7. refuse + 33% Westvaco fly ash + topsoil
8. refuse + 33% Westvaco fly ash + 5% rock phosphate
9. refuse + 20% Clinch River fly ash (20% CR)
10. refuse + 33% Clinch River fly ash (33% CR)
11. refuse + 13% limestone (13% Lime)
12. refuse + 13% limestone + topsoil
13. refuse + 5% rock phosphate (5% RP)
14. refuse + 5% rock phosphate + topsoil (5% RPTS)
15. refuse + 300 tons/1000 tons Westvaco fly ash surface applied.

These columns were run under unsaturated conditions and leached with 2.5 cm of a simulated rain each week. Refuse used in this experiment was about 4% total sulfur. The Clinch River Fly Ash (CR) is an alkaline ash with a pH of 11 and a CCE of about 10%. The Westvaco fly ash (WV) was collected at the same site that the WV fly ash in experiment 1. Leachates were collected and analyzed for pH, EC, Fe, Mn, SO<sub>4</sub>, and B regularly. Other elements (Ca, Mg, K, Na, Cu, Zn, Al, Ni, As, and Se) were monitored on a less frequent basis. One objective of this phase of the experiment was to provide data on the leachate quality generated by these treatments under tightly controlled laboratory conditions. Leaching of this phase began in March of 1992.

#### Nonalkaline Ash Study

In addition to the 45 columns in this study, four columns were packed with an acidic fly ash from the Celanese plant in Pearisburg, VA. These columns were packed with the same refuse used in the second column experiment. The mixing ratio was 20% by weight fly ash. This ash was quite light in weight and getting the refuse/ash blend to mix well and remain mixed was difficult. Two of the columns (20% ash + lime) were limed to their ABA (acid base accounting) acidity of 132 tons CaCO<sub>3</sub> per 1000 tons refuse or 13.2% limestone by weight. Leaching of these columns began in September of 1992.

### **Results and Discussion**

#### Preliminary Column Study

After over four years of weekly leaching the leachate from the ash amended columns remained at pH 8 with very low levels of Fe and Mn (Fig. 1, 2, 3). The leachates from the unamended refuse are pH 1.9 with very high levels of Fe, Mn, Al, Cu, Zn, and other toxic elements (Fig 1, 2, 3, Table 1). Close inspection of the data from the composite samples in Table 1 reveals that the refuse was intensely weathered by the acidity generated by pyrite oxidation. The levels of Ca and K dropped below our detection limits in the third composite which was taken after nearly three years of leaching. The levels of all elements tested declined during the four years of leaching. The quality of the leachates improved with time. There was a slight, but noticeable decrease in leachate pH in the 20% ash treatment due to the acidification of one of the three replicates, after -1000 days of leaching. The acidification process was quite rapid in this column. Leachate pH decreased from 8.1 to 4.1 in about 100 days (14 seven-day leaching cycles). The pH of the other two columns in this treatment remained at pH 8.1 for the duration of the experiment. The leachate pH from the 33% columns remained at 8.1 for the duration of the experiment.

Fly ash was very effective in controlling the effects of pyrite oxidation and acid generation. Both the 20% and 33% treatments were very effective, however the decline in pH of one of the 20% columns may indicate that the pyrite in that column had not been permanently arrested. Leachates from the ash treated columns contained higher levels of Na and K than the leachates from the unamended columns. The ash blends also had much lower EC values than those of the control columns at the peak of acid generation. In the last year the EC of the control columns declined to < 4 mmhos cm<sup>-1</sup>. There

are some fluctuations in the EC data due to stoppages in column leaching to simulate dry conditions (Figure 4). During these periods salts are precipitated and then these salts dissolve when leaching resumed, producing higher levels of soluble salts. Information on the solid phases found when these columns were dissected upon the completion of this experiment can be found in Stewart (1996).

### Second Generation Column Study

Leaching of this phase began in March of 1992 and ended in July of 1995. The 5% (5% WV) Westvaco ash mix maintained a basic pH through a few weeks but subsequently failed, and began generating an acidic leachate (Figure 5). The 10% (10% WV) Westvaco ash blend has maintained a pH near 8 for almost 40 weeks, but it also failed and began to produce acidic leachate. The 20% (20% WV) Westvaco ash blend maintained a pH near 8 for two years and then slowly acidified. The 33% (33% WV) Westvaco ash blend maintained a pH above 8 for over three years and had a correspondingly low level of leachate metals (Figure 5). When an ash blended column acidified, the elements in the ash were available to be leached in a low pH environment. This led to acid stripping of some elements from the fly ash and produced leachates which were enriched in some metals. When the 5% WV columns acidified they produced a leachate with twice as much Mn as the control columns. We assume that the added Mn came from the ash. The refuse used in this experiment was about 4% total sulfur and the unamended column leachate has a pH of 1.6 with about 15,000 mg kg<sup>-1</sup> Fe. The high concentration of elements in solution was reflected in the high EC values from these columns. The EC values do decrease with time but a large increase in EC was observed whenever a column acidified (Figure 6). The EC values plotted in order of fly ash addition once they acidify. The control having the highest EC, the 5% WV the next highest and so on. A more comprehensive analysis of the data from the early stages of this experiment is available in a thesis by Jackson (1993) and a paper by Jackson et al. (1993) and are also discussed in a dissertation by Stewart (1996).

The Clinch River Ash (CR) contained more alkalinity than the WV ash. The 20% CR columns maintained a pH of 9 for over three years. This was about half a pH unit above the leachates from the 33% CR columns. The lime treatment has maintained a pH of about 8 for the past three years, as expected. The 5% RP and 5% RPTS represent treatments that were bulk blended with rock phosphate. Rock phosphate was used by others (Spotts and Dollhopf, 1992) to control AMD by limiting Fe mobility due to Fe phosphate formation. In this case the rock phosphate seemed to control Fe somewhat but not completely. The pH values from the rock phosphate treated columns are < 4. The pH values from the topsoil treated rock phosphate columns (5% RPTS) were nearly identical to those of the 5% RP columns. In some of the other treatments the topsoil apparently lowered the hydraulic conductivity of the column material and the leaching waters had more time to dissolve weathering products in the column.

### Nonalkaline ash columns

We had expected these columns to acidify quickly and have high levels of metals leached from the ash under the acidic conditions present in the unlimed columns. Surprisingly, this did not happen. The unlimed columns acidified much more slowly than the control columns (Figure 7). The 5% WV ash (a much more alkaline ash than Celanese) columns in the second column experiment also acidified more quickly than these columns (Jackson et al. 1993). We believe that the ash in these columns slowed down the rate of water movement in these columns to the point where amorphous Fe compound formation is favored over Fe<sup>+3</sup> oxidizing the iron pyrite. This would keep the rate of pyrite oxidation low and the generation of acidity would also be slowed as observed. The unlimed Celanese ash columns had a pH profile similar to that of the rock phosphate treatments. Iron, Mn, and Al show trends that were much like those for the limed ash columns. Boron levels in these materials were a bit high. Other than low pH values and high B levels, there seem to be no apparent water quality problems with mixing this acidic fly ash with this very acidic refuse. The Celanese column results are important because acidic fly ashes will likely be used on or in refuse piles because of backhaul obligations. In this particular case the effects of the ash appear to be positive, however, other ashes and other refuse combinations may not share this finding.

## Conclusions

1. Alkaline fly ash can control the oxidation of pyrite in coal refuse if enough alkalinity is present. If enough alkalinity is not present the ash will act to delay the onset of acidification, but not prevent it from happening.
2. If pyrite oxidation occurs in ash amended mixtures the metals in the ash will be exposed to acid stripping and could result in higher levels of dissolved metals than would have been present in the unamended coal refuse.
3. A blend of nonalkaline fly ash and ground limestone may be effective in controlling acid mine drainage from coal refuse.

## Acknowledgments

We would like to thank the following for their support of this research project: Virginia MMRRRI (USDI) Grant # G1134251, The Powell River Project, The Virginia CIT, Westvaco, Elk Run Coal Company, Appalachian Power Company, Virginia Power,Consol, Hoechst Celanese.

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Table 1. Elemental content in composite leachate samples.

Sample	Control				20 % Ash				33 % Ash			
	257†	360‡	970§	1363¶	160#	360‡	970§	1363¶	160#	360‡	970§	1363¶
Element	mg kg <sup>-1</sup>											
Al	870	350	72.6	33.2	0.12	0.18	0.74	42	0.13	0.61	0.14	0.23
B	3.1	1.6	0.08	0.31	3.6	2.5	1.1	0.91	5.0	4.1	0.88	0.42
Ca	810	590	<0.1	3.34	300	433	542	651	370	450	489	188
Cr	0.87	0.33	nd	nd	0.01	0.01	nd	nd	0.01	0.53	nd	nd
Cu	16.6	5.1	0.96	0.49	0.01	0.06	0.02	0.25	0.01	0.01	0.02	0.034
Fe	7600	3900	348	104	3	0.13	0.14	0.52	0.03	1.4	0.31	0.10
K	0.84	0.44	<0.3	<0.3	36	41	51	63	44	50	44	25
Mg	371	149	54	27	54	103	93	61	62	111	51	11
Na	17.8	0.7	0.45	0.98	82	19	14	10	61	26	8.7	5.9
Ni	10.3	2	nd	nd	0.01	0.01	nd	nd	0.01	0.12	nd	nd
P	30	11	0.06	0.06	0.42	0.35	0.06	0.06	0.34	0.38	0.06	0.06
Pb	0.91	0.44	nd	nd	0.01	0.01	nd	nd	0.01	0.01	nd	nd
S	9246	4440	660	334	323	458	523	673	405	481	415	134
Si	123	79	nd	nd	16	15	nd	nd	13	15	nd	nd
Zn	25	3.8	0.84	0.50	0.04	0.09	0.03	4.0	0.04	0.08	0.03	0.004

† Data for sample 257 is from a composite sample from the Control treatment. Samples from day 66 to 191 were combined.

‡ Data for sample 360 is from a composite sample from each. Samples from day 304 to 413 were combined.

§ Data for sample 970 is from treatment composite samples, samples were combined by treatment from day 956 to 984.

¶ Data for sample 1363 mean values from samples taken on day 1363 of the experiment.

# Data for sample 160 is from a composite sample from within each ash treatment. Samples from day 126 to 195 were combined.

Figure 1. Mean leachate pH values. Error bars extend one standard deviation of the mean.

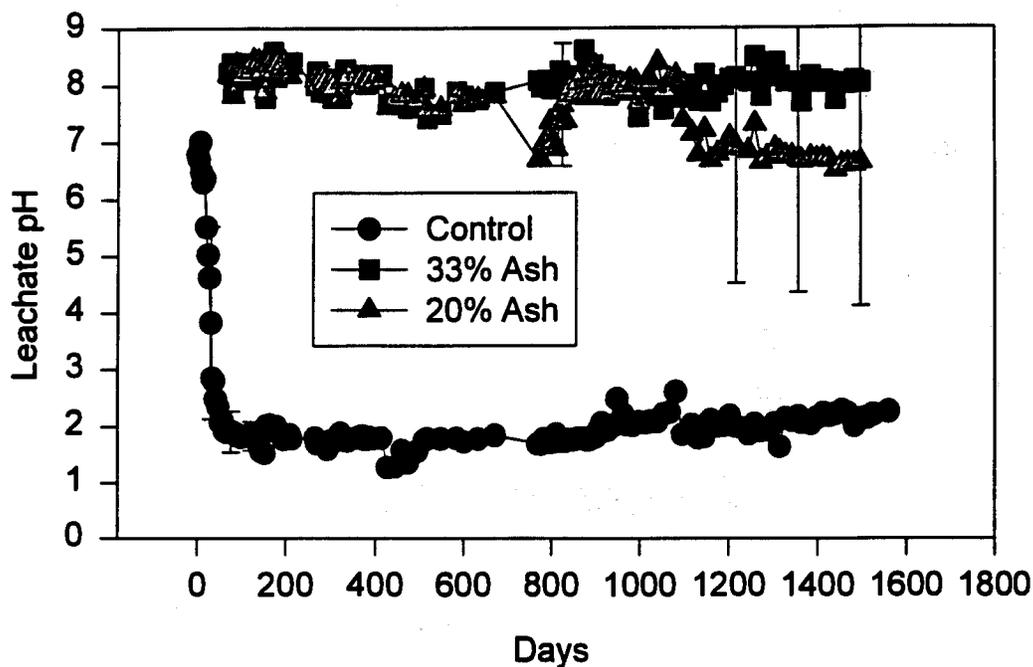


Figure 2. Mean column leachate Fe content. Error bars extend one standard deviation above and below the mean.

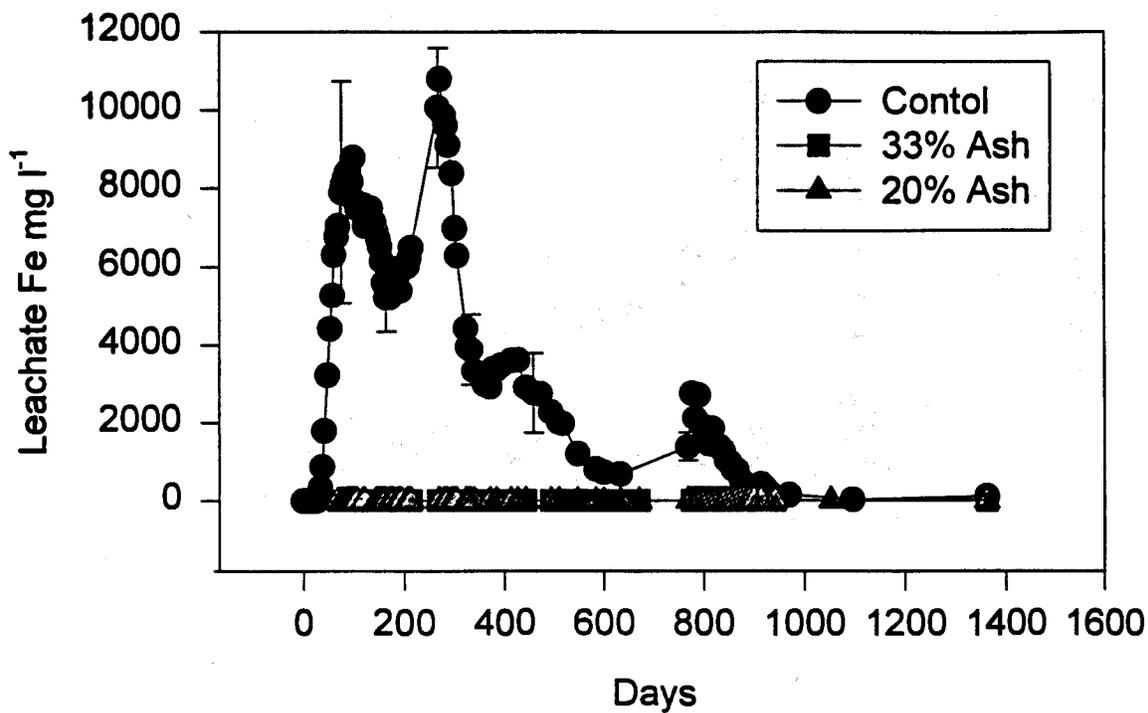


Figure 3. Mean leachate Mn content.

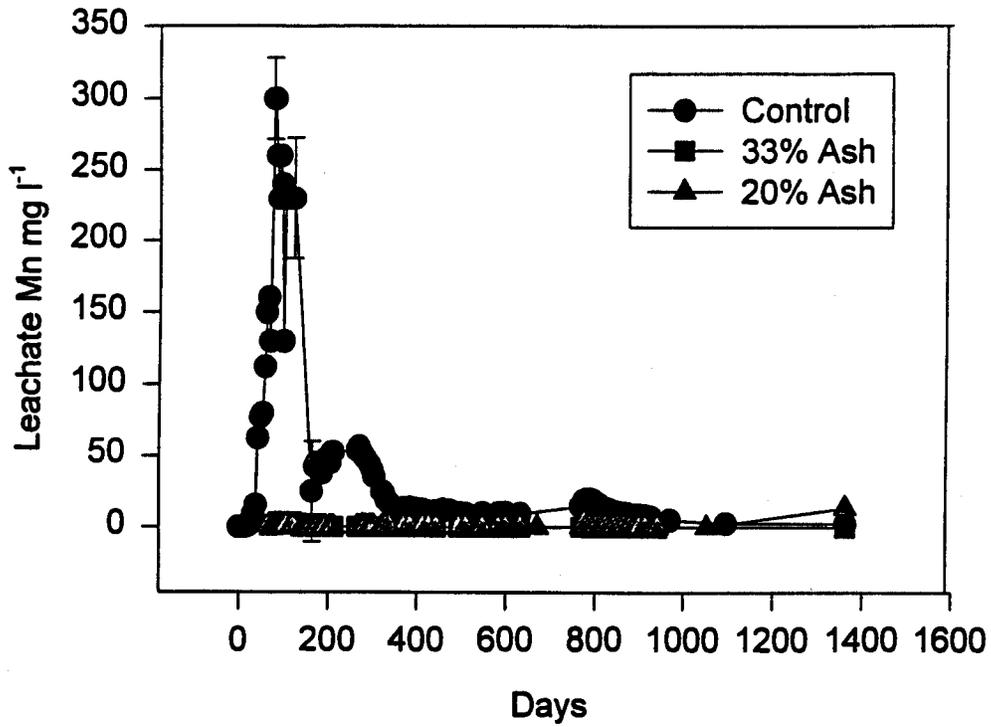


Figure 4. Mean column leachate EC values. Error bars extend one standard deviation above and below the mean.

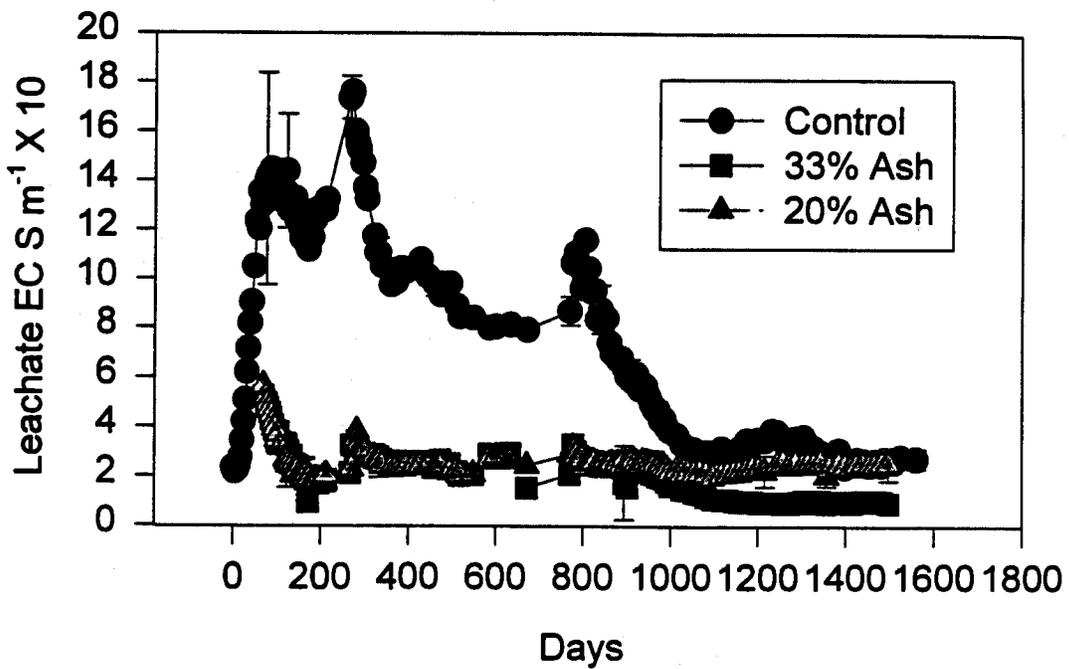


Figure 5. Mean pH leachate pH values from the WV ash treatments in the second generation column studies.

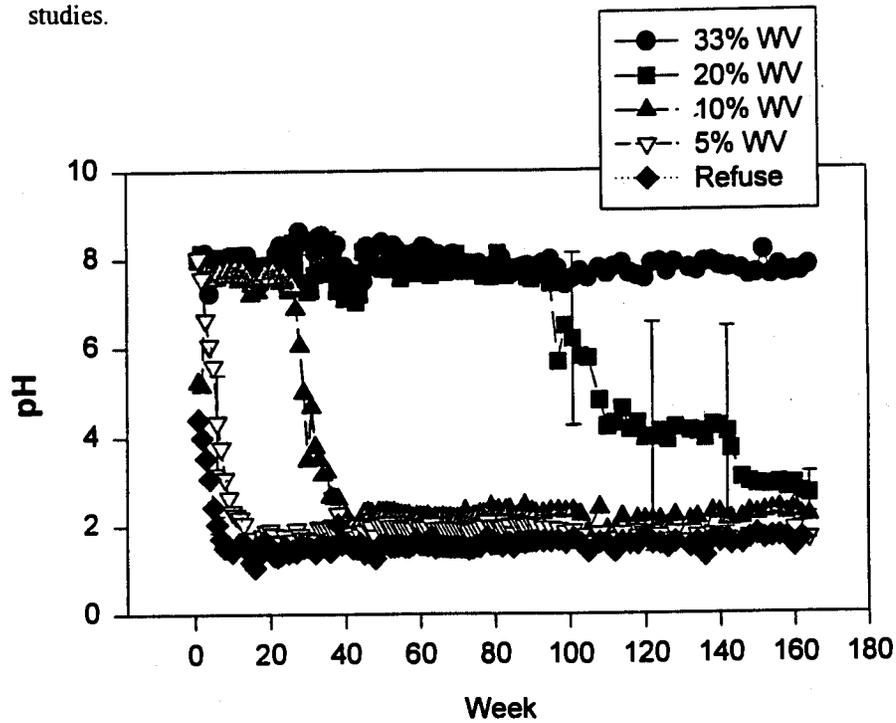


Figure 6. Mean leachate EC values from the WV ash treatments from the second generation.

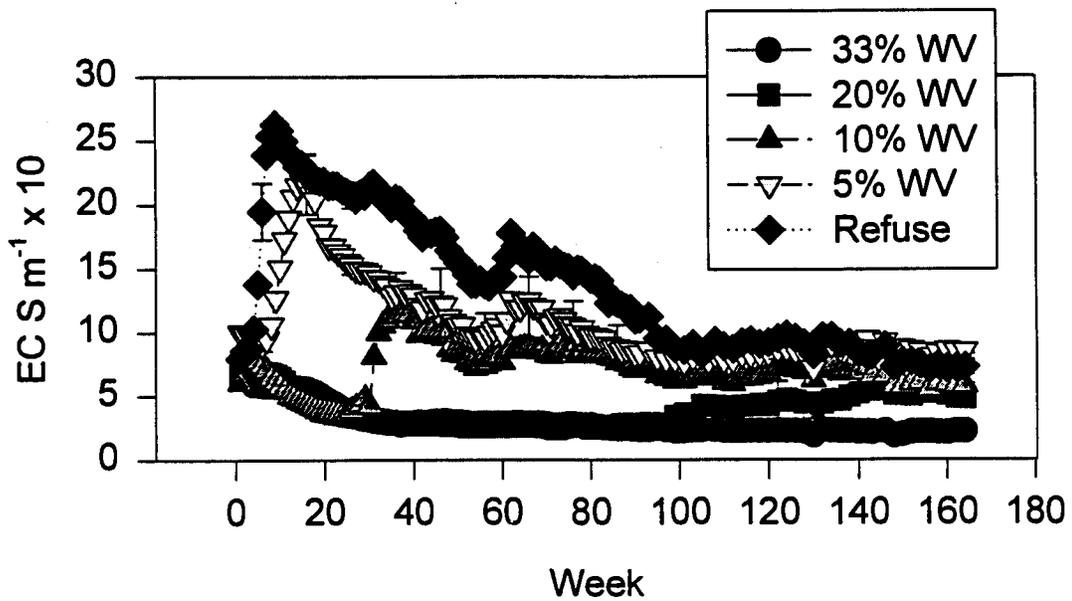
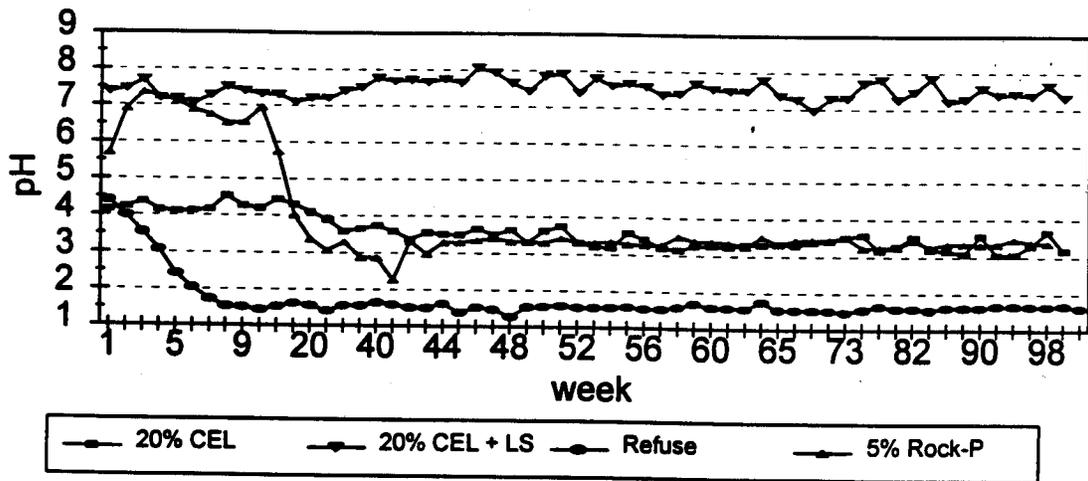


Figure 7. Changes in leachate for the non-alkaline ash columns. Data for Refuse and 5% Rock-P included for comparison.



## **APPENDIX 1: ADDITIONAL PAPERS**

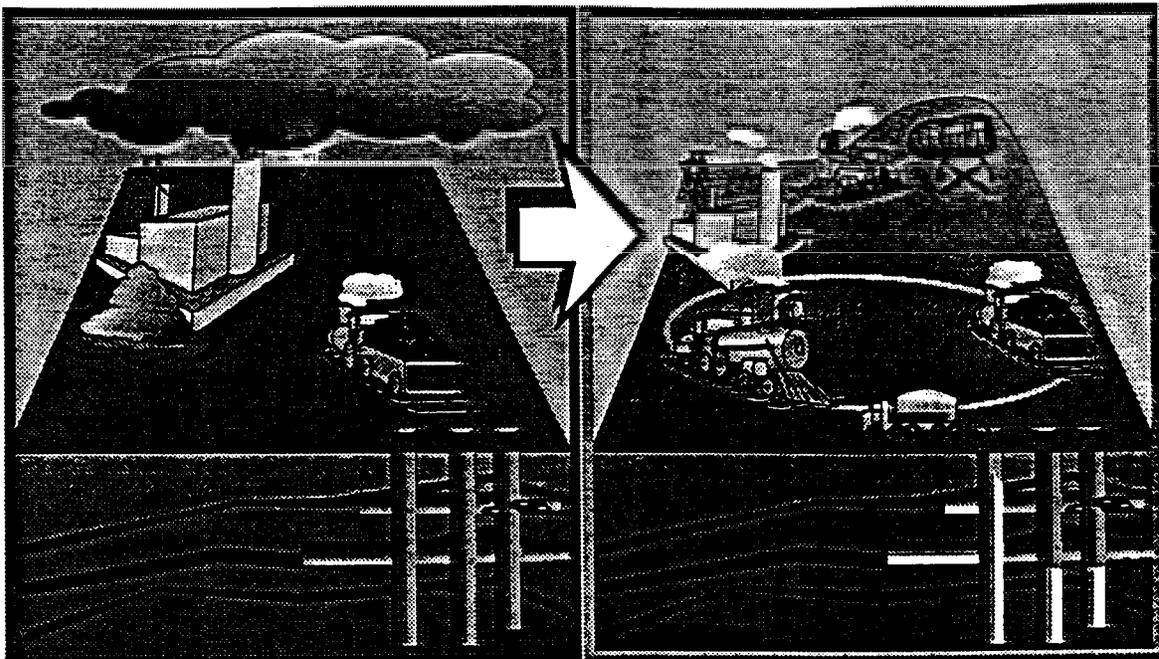
# AN OVERVIEW OF THE WESTERN MARYLAND COAL COMBUSTION BY-PRODUCTS/ACID MINE DRAINAGE INITIATIVE

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## Introduction

The Western Maryland Coal Combustion By-Products (CCB)/Acid Mine Drainage (AMD) Initiative (the Initiative) is a public-private partnership exploring the use of CCBs to eliminate AMD from Maryland's abandoned coal mines. This dynamic partnership will sponsor a series of large scale experiments and demonstrations addressing the engineering problems that characterize the beneficial application of CCBs to prevent acid formation on a scale that is consistent with the large quantity of these materials that will be produced by power plants in or near western Maryland. The initial demonstration is the filling and sealing of a small hand dug mine (the Frazee Mine) under approximately ninety feet of overburden on Winding Ridge near Friendsville, Maryland. The Maryland Department of Natural Resources (DNR) Power Plant Research Program (PPRP)'s partners in this initial demonstration include three coal companies, a power plant operator, an environmental consulting company, and the Maryland Department of the Environment Bureau of Mines (MDE). In addition, personnel of the former U.S. Bureau of Mines, now with the U.S. Department of Energy (DOE), have made a substantial contribution to the Winding Ridge Project. A second demonstration being planned for the Kempton mine complex will involve a partnership of PPRP with at least West Virginia interests, the Mettiki Coal Corporation, Buffalo Coal Company, and MDE. Subsequent demonstrations will focus on reducing the cost of materials handling and mine injection and solving the engineering problems characteristic of filling abandoned mines in Maryland. Partners are welcome to participate in one or more demonstrations at whatever level is consistent with their interests and resources. The Initiative is the flagship activity in Maryland's overall Ash Utilization Program, the goal of which is to promote beneficial use of all coal combustion by-products (see Figure 1). This presentation is an overview of Maryland's vision that AMD can be eliminated from the inventory of environmental issues the State must address.

Figure 1. The ultimate goal is transition into beneficial applications of all CCBs.

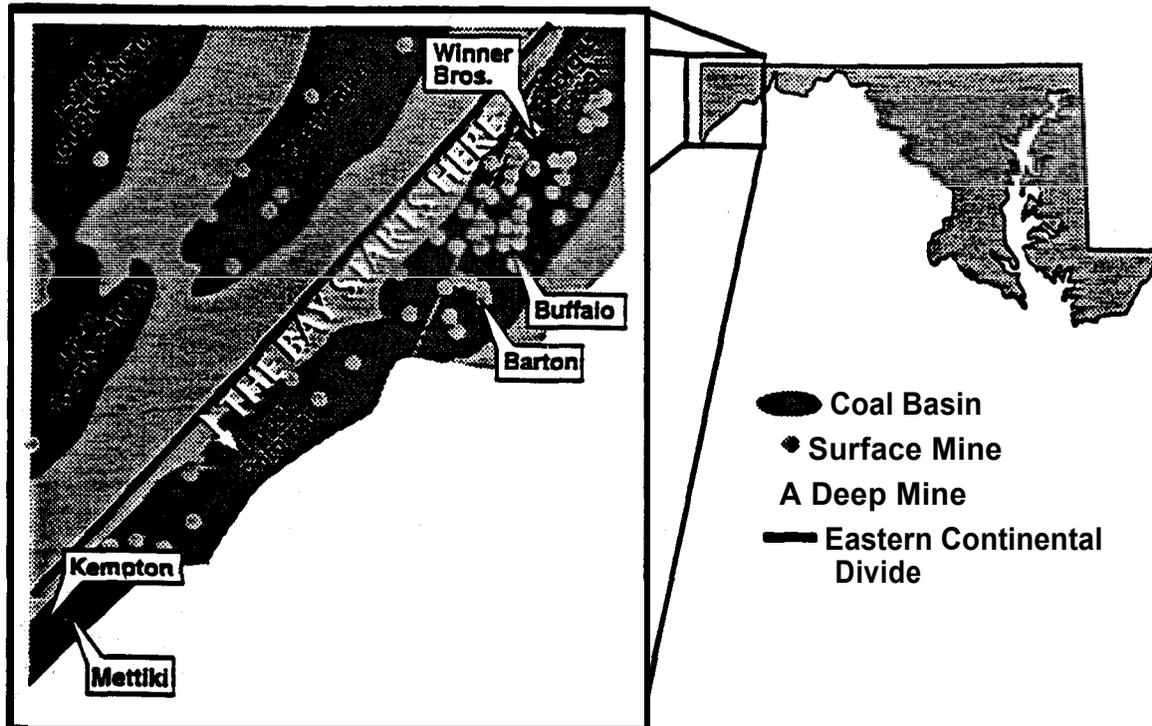


## AMD In Maryland

AMD is an old water quality problem in Maryland. It affects approximately 450 miles of western Maryland waterways, and dates to the earliest mines in Maryland starting in the 1840s. AMD is a legacy of coal mining in the last century and up through 1977, when mine reclamation laws were established. Summing Maryland coal production over the years before 1977 reveals that Maryland mountains have void space created by removal of a quarter billion tons of coal. This seems small if one thinks of it in terms that this entire historical production is equivalent to a current year's production in Wyoming. It is also small compared to that of our neighbors, West Virginia and Pennsylvania. Water quality, however, is very important to Maryland. Maryland's most produced and productive coal basins, the Upper Potomac and Georges Creek Basins (see Figure 2), form the very northwest edge of the Chesapeake Bay watershed. What happens here affects the entirety of the Nation's River (the Potomac River) and the watershed of the Nation's Treasure (the Chesapeake Bay). Maryland's interest is not just an environmental ethic. We have repeatedly demonstrated, such as in our Fish Passage Program, the very practical economic benefits of good environmental stewardship. Consistent with this experience we have subjected our vision of eliminating AMD in Maryland to the classical *Prudent Man Test*: 1) Do the resources exist to justify this activity?, 2) Does technology exist to make it economical?, and 3) Can markets be identified for the service?

PPRP has looked at each of these questions having the benefit of extensive background regarding our utility industry, our coal industry, and participation in numerous environmental investigations and programs. I will present an outline of our analysis of each of these above questions that is consistent with the time allowed for this presentation. You are invited to visit with us here or in Annapolis to discuss details of any specific area of interest.

Figure 2. Maryland coal basins and selected mines.



## Resources

The sources of CCBs near western Maryland are: 1) Mount Storm (pulverized coal plant, one scrubber in place, two planned), 2) North Branch (fluidized bed combustion (FBC) plant, not operating), 3) Warrior Run (FBC plant, under construction), 4) Morgantown Energy Associates (FBC plant, operating), and 5) Albright (source of fly ash). These sources are estimated to produce two to three million tons per year of CCBs. Even if a million tons per year is reserved for beneficial use in active mining, there will be adequate amounts of CCBs available to treat abandoned mines at a practical rate for the foreseeable future. We made a decision early in our planning to avoid using additives for economic reasons. We have not ruled them out but would prefer to look first at other waste products available to us from Maryland industries, such as waste from Westvaco's paper mill at Luke, Maryland, and waste from our lime, cement, and aluminum industries in the Maryland counties just east of our coal mines. These wastes may be good activators to get the engineering properties we seek with CCBs to fill and seal deep mines to prevent the formation of acid.

In addition to these material resources there is a need for detailed information regarding the impacted waterways. We are fortunate that PPRP has participated with other State Agencies in the past in extensive monitoring of our waterways. The Initiative is the beneficiary of extensive data from the following Programs: 1) Maryland Synoptic Stream Chemistry Survey, 2) Maryland Critical Loads Study, 3) Maryland Biological Stream Survey, 4) Western Maryland Stream Survey, 5) Acid Deposition in Maryland, 6) Fish Passage Program, 7) Study of Maryland Coal Industry, and 8) Warrior Run and other Ash Utilization Studies.

The ultimate resource is capital. This is a priority consideration due to having started the Initiative in a period of meager State and Federal budgets. We are starting with seed money from the Maryland Environmental Trust Fund. We welcome the shift in emphasis at the Corps of Engineers and the Environmental Protection Agency to water quality projects and acceptance of economic impact as justification for support of projects. Ultimately, as we move to full scale implementation this utilization of CCBs must be a viable economic activity for our coal producers who are positioned to provide much of the field work. Our power plant operators and neighboring power plant operators (and their ash brokers) must see treatment of abandoned mines as an economical way to utilize their CCBs, or in the case of mines that are more expensive to fill, as out-of-kind mitigation to compensate for acid deposition. Environmental groups and foundations should also take an interest in the Initiative as it offers a permanent cure to an onerous environmental problem.

## Technology

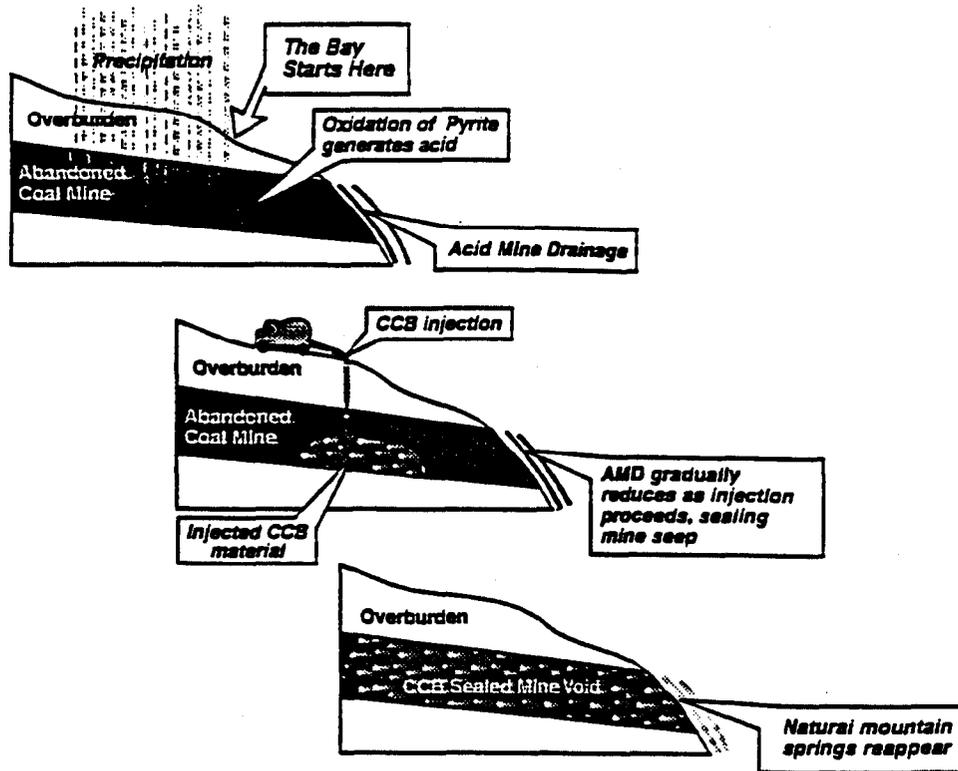
No textbook has yet been written on backfilling deep mines, and no engineering graduates are available who have taken Mine Filling 101. We look to the DOE Program at the University of West Virginia, Southern Illinois University, and the University of Kentucky as an active source of technology development. The historical program at Penn State is an important source of know-how. Other key projects include those of the Pennsylvania Department of Environmental Protection, American Electric Power, Indianapolis Power & Light, and the West Virginia Department of Environmental Protection.

We are interacting with these sources regularly and adapting what we learn to the specific civil engineering problems of filling and sealing abandoned mines in Maryland. Just as every mine was unique to the miners who made them, each mine has unique geologic and hydrogeologic conditions that must be understood to eliminate the formation of acid in them. That is the goal of the series of large scale experiments and demonstrations we are organizing under the Initiative. Specific experiments and demonstrations that are planned include:

- filling and sealing the Frazee Mine to demonstrate effectiveness of the concept (see Figure 3);
- filling and sealing a mine on the North Branch where streams have been modeled for economic and cost effectiveness studies;

- filling and sealing a mine in the Georges Creek Basin where AMD is highly variable;
- encapsulation of an area of intense acidification where it is not practical to fill an entire mine;
- selective filling of critical tunnels in the Kempton mine complex to restore the integrity of the individual watersheds it affects;
- tilling and sealing a mine in the unique Maryland ecosystem called The Glades; and
- backfilling a previously mined area to enhance remining where it will eliminate AMD.

Figure 3. Technical concept of the CCB/AMD Initiative - the Winding Ridge Project.



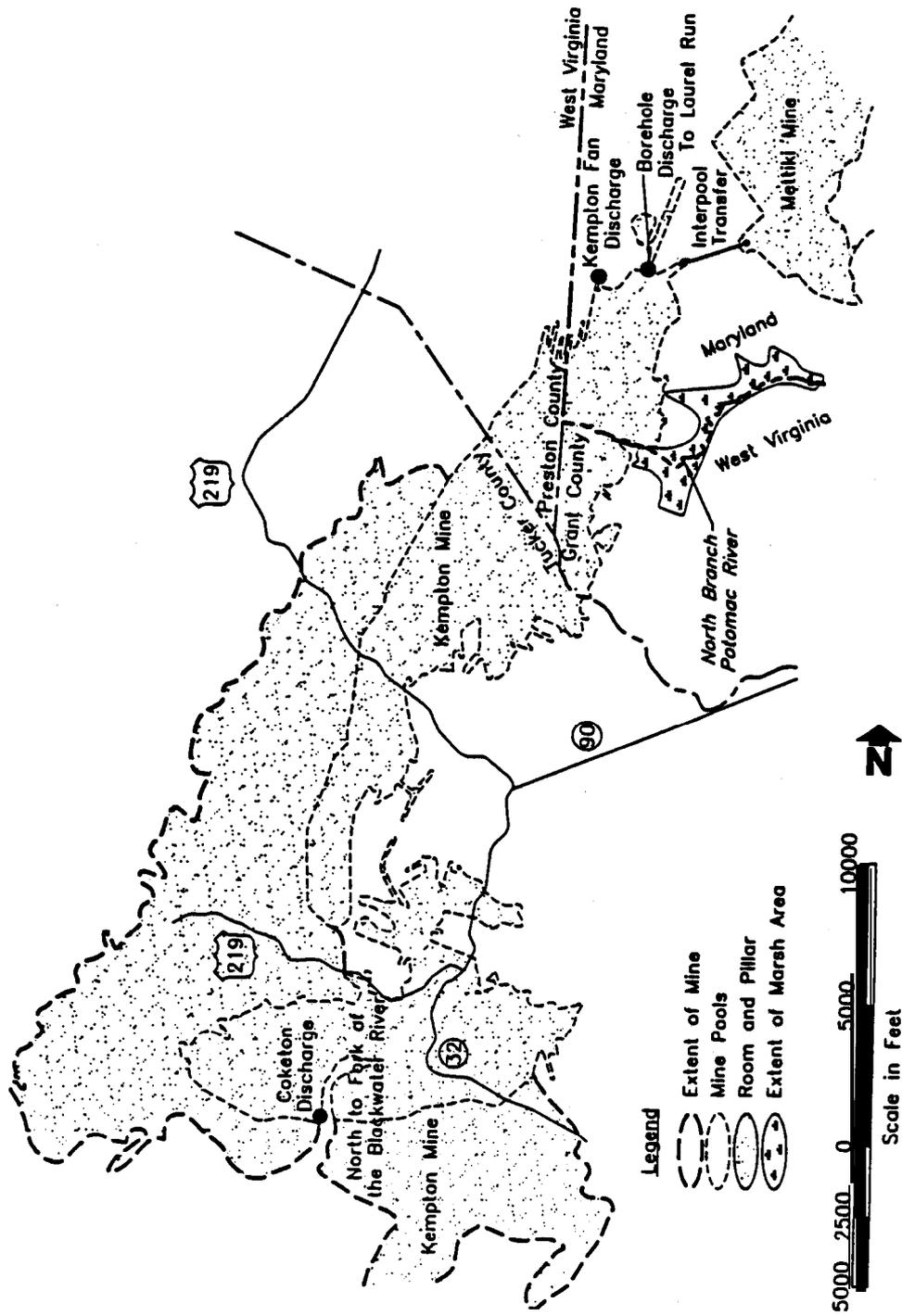
We also want to be in a position to put out an underground fire or stop major subsidence if the opportunity presents itself. We believe such demonstrations will establish a strong technical basis for utilization of CCBs to eliminate AMD in Maryland, demonstrate that costs can be reduced to be competitive with future landfilling costs, and provide the technology for elimination of AMD in all five of Maryland's coal basins.

### Market

The Maryland Bureau of Mines has provided PPRP with an inventory of 450 mines. There is space in these mines for all the CCBs our power plants are producing. Filling mines at the rate of one or two million tons of CCBs per year could go on for decades. We have a priority list of the 56 largest producers of acid for more careful study as candidates for our demonstrations. Two decades of activity at the one or two million ton per year rate will eliminate most significant sources of AMD in Maryland since many of our largest mines that produced from the *Big Seam* are not important sources of AMD. One large mine complex is an exception (the Kempton complex, see Figure 4), which we share with West Virginia. This six square mile, twelve mine complex mined the *Upper Freeport Coal* and now produces over 10 percent of the acid discharging into the North Branch of the Potomac River. Unfortunately, it appears to drain good water from the upper reaches of the North Branch and its extensive wetlands into

the mine pool. where it is contaminated with acid and flows out into Maryland's Laurel Run. We are determined to kill this AMD monster. Clearly there is a market for the service being developed.

Figure 4. Location of the Kempton mine complex in Garrett County, Maryland and, West Virginia.



## **A PRELIMINARY EVALUATION OF THE WINDING RIDGE DEMONSTRATION PROJECT**

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### **Introduction**

The Winding Ridge Project (the Project) is a small-scale demonstration of the beneficial application of alkaline coal combustion by-products (CCBs) to abate acid mine drainage (AMD) from a Maryland underground coal mine (the Frazee Mine). The Project is the first of its kind to be performed under the Western Maryland CCB/AMD Initiative (the Initiative), a partnership of government and industry exploring the use of CCBs to eliminate AMD in Maryland. The purpose of this paper is twofold:

- 1) present the status of Phase IV of the Project, which includes the mixing and injection of CCB grout at the Project site; and
- 2) discuss those issues identified by the Project team as key to the efficient operation and ultimate success of an underground injection project.

### **Phase Iv Status**

Phase IV of the Project commenced in July 1996 with the selection of DYNA Corporation (DYNA) as the mine injection contractor. By mid September, DYNA began mobilizing equipment to the site in preparation for mixing and injection. As of 7 October 1996, full-scale injection of alkaline CCB grout began. And looking ahead, injection is anticipated to cease by early November 1996.

As of the time of this conference, the Project team has injected 4,000 cubic yards of CCB grout into the Frazee Mine, consisting of 2,400 tons fluidized bed combustion (FBC) by-product, 800 tons pulverized coal combustion (PCC) Class F fly ash, 800 tons flue gas desulfurization (FGD) by-product, and 300,000 gallons of water pumped directly from the Frazee Mine pool. To date, the maximum daily grout injection has been 370 cubic yards. However, the typical daily injection total is lower, ranging from 275 to 300 cubic yards.

The CCB grout formula injected into the mine consists of 60% FBC by-product, 20% Class F fly ash, and 20% FGD by-product on a dry weight basis. Once mixed with mine water, the by-products account for approximately 45 to 50% of the total grout volume. Adherence to this grout mix formulation is ensured through the completion of daily batch calculations, which take into account the moisture contents of each of the by-products prior to mixing. Moisture contents of the FBC, Class F fly ash, and FGD by-products are generally 8-10%, 25%, and 30%, respectively.

The freshness of the FBC by-product is crucial to the strength of the resulting grout mixture, as determined by laboratory-scale tests completed by DYNA in late August. As a result, the Project team has used only FBC by-product that is less than one day old in order to maximize the free lime content of the injected grout mixture. This practice has resulted in 14-day unconfined compressive strengths on the order of 100 pounds per square inch (psi), and anticipated 28-day strengths of at least 250 psi.

The 60/20/20 grout formulation also exhibits good flowability, with field spread test results ranging from 7 to 9 inches. In fact, borehole camera logging successfully documented the flow of grout for distances of at least 100 feet, given a 3% slope and a 3-foot-high mine void. The grout was observed to move through even the smallest of crevices, which are abundant in the Frazee Mine due to its severely collapsed nature. Nonetheless, it was also observed that a break in injection activities, however short.

will ultimately limit the flow distances achievable by the grout. As a result, continuous injection is most desirable because it appears to maximize grout flow distances.

The 60/20/20 grout formulation has certainly worked well with the piston pump and steel pipe injection configuration employed by DYNA. The Project team has been able to pump the grout over distances of at least 750 feet to injection boreholes uphill of the batch plant. The steel pipe is moved from borehole to borehole during injection activities as necessary, while the batch plant and piston pump remain stationary at the lower end of the site.

### **Key Field Operation Issues**

As field activities proceed, we learn more about how to successfully execute an underground mine injection project. Over the past month, the Project team has continued to make observations and recommendations regarding the operation of equipment and handling of CCBs. Some of the recommendations have been implemented immediately, while others cannot be addressed until the next mine injection project is conducted. Just as important, however, is the constant evolution of our understanding of the Frazee Mine geometry, based on grout take and observation borehole monitoring during injection. Each of these key issues is discussed below as they relate to the Winding Ridge Project.

#### **Equipment Reliability and Mechanical Difficulties**

All equipment used at the site has been subjected to a relatively harsh work environment, including varying levels of dust, low pH mine water, and high pH grout mixtures. These factors are expected to take their toll on mixing and injection equipment over the course of a large-scale injection project.

In addition to the harsh work environment, the everyday use of this equipment affects its reliability over the long term and requires that some maintenance be conducted during the injection program. For example, DYNA has already repaired the transmission on the grout mixer and has arranged for maintenance on the Loadrite weighing system, which is used on the front end loader to measure CCB quantities. The best way to combat these potential production delays is to assure that key spare parts are available at Project site, and that backup methods for completing certain injection-related tasks (e.g., the weighing of CCBs using the Loadrite system) are available to the Project team.

Mechanical difficulties have also been identified at Winding Ridge. These include: 1) the construction and diameter of injection casing; 2) problems associated with the accumulator box and gate; and 3) the handling of CCBs laid on a gravelly, unpaved surface. Each of these is discussed in turn below.

Six-inch diameter steel casing is being used for injection at Winding Ridge. Each casing length is ten feet, and is joined with circular, steel clamps. Smaller diameter flexible rubber hose and steel reducer pipe is placed into the injection borehole to complete the injection line. This configuration has caused difficulties for two reasons: 1) the use of rigid casing increases the amount of time required to move from one injection borehole to another; and 2) the diameter of the flexible hose and reducer pipe is not necessarily conducive to injection boreholes that are less than six inches in diameter. The Project team has mobilized as many lengths of steel casing and extra flexible rubber hose as possible to make injection moves as quick as possible, and a smaller diameter reducer pipe was constructed to facilitate access to the four-inch diameter injection boreholes.

The accumulator box is a rectangular reservoir used to temporarily hold grout that has been discharged from the mixer but not yet released into the piston pump hopper. The longer the grout sits in this accumulator box, the greater the tendency for fly ash particles in the grout to settle out of the mixture. This affects the ability of the accumulator gate to effectively discharge the grout into the

hopper, as the settled particles back up against the gate and prevent the smooth flow of grout. The Project team regularly cleans the accumulator box to prevent such collection of fines.

Each of the three CCBs used for the Project are stored in bins underlain by an FBC/gravel surface that was compacted and leveled prior to use. However, because a front end loader is used to transfer by-products to the grout mixer, some of the FBC/gravel surface tends to be gathered up with the CCBs. This causes difficulty in the mixing and injection process because large gravel pieces can collect in the accumulator box or hopper, slowly clogging the injection system. The Project team has decreased the depth to which the front end loader operator scoops the CCBs, but this limits the amount of CCBs recoverable for mixing and injection. The Project team has also continued to clean the accumulator box and place a wire screen (or “grizzly”) over the piston pump hopper to assure that the amount of gravel pieces flowing through the injection system is kept to a minimum.

### Material Issues

Various material problems have been identified by the Project team over the course of injection, some of which are related to the as-received properties of the CCBs and some of which are associated with CCB truck delivery. CCB moisture and free lime contents are of particular concern, as they directly affect the efficiency of the mixing and injection procedure.

Fit and foremost is the fugitive dust issue that exists at the Project site due to the relatively dry nature of the FBC by-product. For this reason, any personnel working in the CCB handling and storage area is required to wear full-face air-purifying respirators. All remaining personnel working in and around the mixing and injection area typically wear half-face air-purifying respirators. The mixer operator has opted to wear a full-face respirator on particularly dusty days, as the CCBs are dumped into the mixer directly in front of him. The Project team has observed that the FBC by-product is completely unworkable if it is received at less than 4% moisture.

Another concern is the 75-foot distance required for bottom dump trailers to drop the FBC by-product. As the trailers drop the by-product, they can easily become stuck in the material. This decreases the efficiency of the grout mixing process because the front end loader must be used to pull the trailer away from the drop area.

As discussed in the Phase IV status section of this report, the FBC by-product has to be received and used within twenty four hours of generation to maintain its free lime content. Older FBC by-products tend to absorb moisture from the air, forming chunks that settle in the accumulator box or clog the piston pump hopper. The use of a “grizzly”, as discussed above, has prevented most of these chunks from entering the hopper.

The FGD and Class F fly ash materials also have difficulties associated with their moisture contents. Each has a tendency to stick inside the bottom of the dump trucks used to transport them to the Project site. When this occurs, the drivers must shovel out the remaining by-products manually prior to leaving the site.

Finally, an ongoing material issue is the settlement of solids from the grout prior to injection. Solids can settle in the accumulator box, as discussed in the previous subsection, or they can slowly accumulate inside the steel pipeline. Solids have been observed to settle when the mixing and injection of grout is not a continuous operation; that is, when a batch of grout has been mixed but is not immediately transferred from the accumulator box to the hopper and through the injection lines to the injection borehole. The accumulation of solids in the pipeline requires daily cleaning, as the injection activities at Winding Ridge are not a twenty-four hour operation. However, during the course of the work day, the Project team does attempt to minimize the mixing time and maximize grout injection rates to alleviate this problem.

### Mine Geometry and Characterization

The availability of a preexisting mine map is preferred for underground injection projects because it allows the Project team to focus on the grout injection sequence. However, many of us working in abandoned underground coal mines do not have that luxury, and have to rely on anecdotal and exploratory borehole drilling information to construct a reasonably accurate mine map prior to planning an injection program. In either case, a clear understanding of the mine geometry is paramount prior to injection activities.

Once the mine geometry has been delineated, the Project team must determine the location and extent of submerged, collapsed, and weathered areas in the mine. The existence of mine pavement debris, whether it be roof fall or material left by the miners as they abandoned the tunnels, can also play an important role in an injection program, depending upon the flowability of the grout.

Prior to implementation of an injection program, the Winding Ridge Project team had developed a detailed mine map based on field data, complete with interpretations of collapsed and submerged areas. As injection progresses, however, we continue to learn that the Frazee Mine geometry is different from our original interpretation, as grout takes and observation borehole monitoring tell us there exists more void space in the Frazee Mine than we were originally aware. Based on these field observations, we mobilized a drilling rig and completed a total of 17 additional exploratory boreholes to refine our interpretation of the mine geometry, as well as to provide additional injection boreholes in the lower elevations of the mine. Even so, the viability of these additional injection boreholes has been limited due to the weathered nature of the bedrock overburden and the degree of collapse and submergence in the mine. The existence of mine pavement debris may also be a factor limiting the grout takes in many of these injection boreholes.

## APPENDIX 2: RECORDED DISCUSSIONS

Edited by Kimery C. Vories  
USDI Office of Surface Mining

The following is the edited discussions that took place at the end of each presentation and at the end of the each session. The actual comments have been edited to translate the verbal discussion into a format that more effectively communicates the information exchanged into a written format. The organization follows the same progression as that which took place at the forum.

### Session I: Coal Combustion By-Product Characterization

1. Sampling Methods Dr. Terry Brown, Western Research Institute, Laramie, Wyoming.

*Regulatory Question:* If the variability of the material is as great as you are suggesting in your presentation, how would it be possible to monitor the differences in material as it goes to the disposal site, truck load by truck load and distributed in various different strata at the disposal site? What is the solution to the sampling problems in the field that are further complicated by this additional operational variability?

*Answer #1:* You are going to have variability. You need to determine what the range of variability will be for the material you are using. Based on the range of variability of the CCB material you should be able to design the disposal facility to handle it.

*Answer #2:* When you are doing a research project and you want to have a high level of confidence in your numbers, then the kinds of variability that Dr. Brown mentioned in his presentation becomes a real issue. When it comes to the use of these materials in a real world application, the bulk chemical properties of the ash, even if it varies several percent, aren't that important in the use of the material. If you know the basic bulk chemical characteristics of the material, you can get successful application and not be as concerned with the specific sampling protocol. My comment is not directed to the trace element concentration but to the bulk chemical constituents such as calcium, sulfur, and silica. These are of lesser importance in terms of environmental impact such as what is leachable. These bulk chemical constituents have a major importance in terms of the actual engineering properties of the ash, such as how it will handle when you mix it with water. When you start compacting samples, the variability in mineralogy may change by 5 percent for lime or anhydrite. The influence of this on the structural fill might be a difference in the amount of ettrugite or gypsum that forms. This will not significantly impact the permeability anymore than you would expect when compacting a natural soil material. This level of variability is inherent in all construction fill materials when you work with huge quantities of material compared to a researcher who works with 5 grams or less of the same material. Yes, variability is important and sampling is important, but it plays a greater role in research projects than in actual field applications.

*Regulatory Question:* You suggested that a publication was coming out about the different types of testing methods. Would this publication suggest that you establish a baseline instead of having so much diversity in sampling methods? Who is doing that and when would it be available?

*Answer:* A draft publication is now out on sampling heterogenous types of materials. Susan Sorini at WRI is working on developing the standard sample. The coal ash association is involved with this effort. More specific details will be provided in the final paper provided in this publication.

*Research Question:* Should we be talking about what size of bulk samples we should be collecting rather than the type of sampling that Dr. Brown is talking about? What type of variability of bulk sampling is critical for use in engineering design contrasted with the academic assessment of the exact chemical composition of the CCB material?

*Answer:* The specific application is a very important factor in determining the appropriate sampling methods. For example, the use of class C fly ash (high calcium fly ash) in concrete has a specific sampling method. This method requires a bulk sampling process where a composite sample is collected. The sample consists of several subsets of samples that are collected from every truck load of fly ash that leaves the power plant. Eventually they end up with a composite sample that represents 400 tons of material. After conducting more extensive testing on that material, they have found that a composite sample averages out some of the important chemical information related to this use. This testing would suggest that particular truck loads of material should not have been used in this application. The cement and concrete industry is finding that in certain applications, such as high performance concrete or even for standard concrete, they should not use a composite sample because the process of averaging hides important information. The ultimate question is, do you have the information, produced through sampling and chemical analysis, that is most useful for the application you are planning?

2. Leaching Tests: Commonly Used Methods, Examples of Applications to Coal Combustion By-Products, and needs for the next generation. Susan S. Sorini, Western Research Institute, Laramie, Wyoming Paper Presented by Dr. Terry Brown

*Research Question:* Because of the variability of results noted in your presentation, which gives better leachate results, available tests or lysimeter tests?

*Answer:* The lysimeter values were much higher than we obtained from the other tests.

*Regulatory Question:* Do you recommend a particular sampling or analysis method for testing high pH materials?

*Answer #1:* A lot of the CCB materials have high pH values, in the range of pH 9-12. When you use a TCLP test, you modify that pH to a lower value. In doing so, you are making the elements that are relatively soluble at that high pH relatively insoluble.

*Answer #2:* Concerning high pH CCBs, I don't think any of the standard tests address secondary mineral phase formation. When you are trying to analyze for trace element mobility in these high pH ashes, be sure that what you are leaching is what is going to be leached in the actual application in the field. In some cases, where these ashes react with the water, that is going to require a long term leaching. There are some minerals that form, ettringite being a major one, that have the ability to complex and chemically fix certain trace elements in ash such as Boron, Selenium, Arsenic, Vanadium, and Chromium. If you leach ash with an 18 hour test you will often obtain very different results than from a 30 or 60 day leaching test. If you are really interested in what is going to happen to leachates in the field, the current experimental data suggests that these longer tests are necessary.

*Regulatory Question:* Unless you are disposing of CCB ash in an acidic environment, would the majority of leachate tests even be appropriate in terms of what is going to take place in the field?

*Answer #1:* Most leaching methods that were presented here do not give a representative measure of what will occur in the field. We need to look at these materials in the long term and how this effects the solubility relationships. We have been looking for a relatively simple method that will give us information on a chemically complex situation. A uniform standard testing method, however, does give us a way to make comparisons between different CCB materials.

*Answer #2:* At the University of North Dakota, we have developed a test that has been submitted to ASTM. Hopefully this method should address these 'concerns for CCB materials. It involves leaching under environmental conditions that are representative of disposal conditions. It also has a long term component built into it.

Industry Question: What type of testing do you recommend to address the long term aspect of leaching? We have conducted tests where it took three months to get the third pore volume through.

Answer: I would not recommend column leaching under any conditions. With respect to long term leaching, and you are looking at a material that will undergo changes on hydration, you want to look at the material long enough to determine the effect of those changes. We recommend that you sample at 18 hours, sample at 30 days, and if necessary sample at 60 days in order to evaluate the trend. Since it is usually impossible to determine when the concentration changes will achieve an equilibrium, we want to determine if the concentrations of trace elements are going up or down over time? You need to carry the test out long enough to see if that is happening, how long you carry on the test after that depends on what you are trying to learn. We have had tests that have been ongoing for over 7 years.

Industry Question: CCB materials have been classified as non-hazardous by the USEPA. All of this concern about leachate testing seems to be backward.

*Answer # 1:* I think we would call it environmental responsibility. Although most CCB materials are fairly benign, that is not a universal statement. The purpose of leaching tests should not be to determine how toxic the material is because most are non-toxic. It is a precaution that the specific material you are using is not going to cause any environmental problems. There are some CCB materials that do have constituents that can under the right conditions leach.

*Answer #2* When the US EPA ruled on CCB materials being non-hazardous, they left it up to the States as to how they wanted to handle it as a solid waste. The State has to address citizen concerns to insure that it is being used safely and that it won't have a negative impact on the environment. When a product is labeled as a waste there tends to be a prejudice against them that normal commercial materials do not experience. Even when you take a waste product and turn it into a commercial material the product is still under the same regulatory requirements of the product as a waste. It is an unfair situation that results in an unfair playing field for commercialized CCB products. Until people become more comfortable with the nature of these materials, we are going to have to continue looking at leachate tests and chemical analysis. Although a lot of knowledge about these materials has been accumulated by professionals working in the field, it is apparent that this knowledge has not been effectively communicated to the public.

*Public Question:* I do not understand how we can be talking about comfort levels when we are talking about materials that often have Uranium, Thorium, and other radionucleotides in them. I have not heard any remark about testing the radioactivity of these materials.

*Answer #1:* Although we are talking about testing CCB materials, if you apply the same tests to cement, you are going to find the same type of problems and yet no one questions the safety of using cement.

*Answer #2:* If you tested the natural soil materials outside this building, you would find approximately the same amount of radioactive materials that you find in CCB materials. The radioactivity of CCB materials has been tested and it is not a problem.

*Regulatory, Statement #1:* The determination by the US EPA that CCB materials are non-hazardous, does not make it a non-toxic material. There are some situations where it would be toxic. These situations have to be evaluated on a case by case basis. The surface mining regulations would normally consider anything with a pH above 9 to be potentially toxic and many CCB materials have a pH in excess of 9.

*Regulatory Statement #2:* Concerning the US EPA determination that CCB materials are non-hazardous, the rulemaking in 1993 related very narrowly to the four large volume wastes generated at coal fired utilities. The US EPA is in the process of completing its regulatory determination by April of 1998 on "remaining wastes." With respect to beneficial reuse there was a brief statement that the US EPA is

comfortable with beneficial reuse when handled in an environmentally safe manner. They are in the process of revisiting beneficial reuse from a “remaining waste” standpoint. The data that is being presented at this meeting still has a lot of relevance from a regulatory standpoint particularly at the Federal level.

**Public Question:** We have looked at 37 different leaching tests for disposal of CCBs at surface coal mines and all of the tests have indicated that the primary drinking water standards have been exceeded for one or more constituents and most for several. The pH of all of these samples have been between 10 and 13. The corrosivity cut off under the Resource Conservation and Recovery Act (RCRA) for determining that a waste is hazardous is 12.5. If this were any other waste produced by industry, it would go to a hazardous waste landfill. The unfairness is, that if it is produced by an electric utility, it can go to mine in Indiana without a liner or a viable ground water monitoring system. The unfairness is the politically motivated exemption of CCBs produced by electric utilities from the hazardous waste requirements of RCRA. Where is the unfairness to beneficial reuse of CCBs, when in Indiana the State Solid Waste program exempts CCBs from its requirements when the material is considered a beneficial reuse or when it is disposed of on a surface coal mine?

*Answer #1:* Speaking as a person who is actively working to find ways to beneficially reuse these materials, if we told cement producers that they had to apply leachate tests to their materials because they utilized CCB materials in their product it would not be accepted because “cement” is considered sacred as a commercial material. If you would test Portland cement for pH you would find that it has a pH of 12.5. A hydrated lime that is commercially used in agriculture will have a pH of 12.5. Although the high pH of some CCB materials may affect the paint on trucks used to haul it or the dozer cleats used to grade it, after the material has been placed in a disposal area its chemistry begins to change and in a very short period of time our tests show that the pH returns to a nontoxic, noncorrosive range of 7-7.5. The formation of minerals in that material over time changes its pH. There are a lot of things that happen to the CCB material after it is placed in the environment that tend to make it more benign. The materials you are talking about have exceeded the drinking water standards by 5 to 25 times. In order to be classified as a hazardous waste, it would have to exceed the drinking water standard by 100 times or more.

*Answer #2:* You need to understand the difference between pH and the total amount of alkalinity and alkaline capacity. Just because you have a material with a pH of 12.5, you may not have a material that has the capacity to produce large amounts of alkalinity.

*Research Statement:* Care should be taken in comparing CCB materials to cement. Portland cement is used to make concrete, which is a solid material, as opposed to CCB materials which are a powdered material. When it comes to the stability of a material, the most important consideration is the ratio of its surface area to its particle size or volume. Concrete, as a solid material, has a surface area that is relatively insignificant compared to a material that is a powder in terms of its potential to generate leachate. In this context, a comparison of cement to CCB material is not a fair comparison.

3. Bulk Chemical and Mineralogical Characteristics of Coal Combustion By-Products. Jodie Tishmack, Purdue University, West Lafayette. Indiana

*Regulatory Question:* When utilizing CCB materials as a soil component, have you tested the plant materials produced to determine if elements like aluminum or other trace elements are being accumulated at toxic levels“?

*Answer #1:* We have done testing on total metals and leachable metals of each of the materials utilized to create this artificial soil, including the CCB material. We are also trying to determine what these leachate characteristics will be over time. We haven’t seen anything with trace metals that we are concerned about. We are closely monitoring nitrates and sulfate from this material because of their greater potential impact to groundwater quality.

Concerning the materials agronomic effects, the trace elements found in the CCB materials are plant micronutrients. We suspect that some of the increased plant growth we are experiencing may be due to providing micronutrients that have become depleted from natural soil materials. We are pursuing plans now to expand our project to an ash embankment where we will use a subsoil cover coat then place a layer of synthetic topsoil in order to revegetate the area.

Answer #2: We have been using PFBC ashes to treat very acid soils (pH of around 2) and comparing that with calcium carbonate applications alone in the green house. We are seeing an increased plant growth of 10 to 20 percent with the ash material compared to treatments with calcium carbonate alone. We are attributing this difference in plant growth to the presence of micronutrients available in the ash materials that are not available in the calcium carbonate or the acid soils.

*Regulatory Question:* On your fill experiment what were the lift thicknesses and how much compaction were you doing?

Answer: The lift thickness started at about 12 inches but has been increased to about 18 inches as we have gained experience with the material. Based on our experience gained over the last 2 years, we have varied the lift thickness, level of compaction, and addition of water. We have a target of about 70-80 pounds per cubic foot of compaction.

In the lab we discovered that some of the testing methods had to be modified to give accurate results on the compaction curves when working with CCB materials. The lab normally puts the sample in an oven at 105 degrees centigrade and measures how much free water is given off. At this temperature some of the ettrugite and gypsum that has formed in the CCB material will dehydrate. This water that was bound up in the ettrugite and gypsum crystals will register as free water. Since density is a function of wet weight divided by 1 plus the moisture content, you overestimate your water content. This results in an underestimation of the dry density. As a result, we have now reduced our oven temperature to between 55 to 60 degrees centigrade. This does not dehydrate the ettrugite and gypsum and gives us a much more accurate compaction density figure.

In conclusion, we have found that building with CCB ash fill material requires much less quality control than building with natural soil materials. We get a very good fill material without having to specify things like plus or minus 5 percent of the moisture or plus or minus 2 percent of the dry density. We have allowed the contractor latitude to use his experience in building with fill to determine how much compaction needs to be applied. We will have a final report on the results by the spring of 1997.

*Regulatory Question:* Have you placed any of these fill materials in areas that could be flooded or in contact with ground water?

Answer: No.

4. Engineering/Regulatory David Hassett, Director of Applied Chemistry, Energy and Environmental Research Center, Grand Forks, North Dakota

*Regulatory Question:* Concerning overburden testing on surface coal mines, how do we take existing testing systems for analysis of CCB materials and relate it to data already generated in a SMCRA permit to predict impacts to water quality and plant growth? The concern being how should this be incorporated into mine reclamation planning'?

Answer #1: The question may be too complex to answer here. One thing that should be understood about laboratory data, is that laboratory testing does not simulate the natural environment. There are no laboratory tests that I am aware of that are going to tell you what concentrations of leachate will result when the CCB material is placed in a disposal area. What the laboratory tests will tell you are general

things (such as, for a given quantity of CCBs, what is the potential for it to leach a given trace element). An important thing to remember, when evaluating trace elements, is that toxicity is a function of concentration and not a function of identity. From this, I can give you an estimate of how much of the total amount available would be likely to leach out. I can't tell you how long it will take, the liquid to solid ratio, or the actual field concentrations that will result. I can give you an estimate of the general potential for any of the trace elements to reach concentrations that would be considered toxic or hazardous.

In conclusion, based on most analyses of CCB ash materials, I can say that there is no potential for these materials to generate hazardous concentrations of trace elements. Most CCB ash materials have very little total volumes of trace elements. In most of these materials, the trace elements are not in a form that is readily available for leaching. Some of the materials, that do have potentially toxic concentrations of trace elements that leach readily, also form ettringite and in a very short period of time, geologically speaking (a few months), tend to tie up these elements and become self remediating. Also when you talk about disposal into a mine, the leachate potential does not end at the border of the mine. We can not predict how the natural hydrogeologic conditions will alter the chemistry of the leachate. All of the elements that exist on the mine site following reclamation and disposal of CCB materials, existed on the mine site prior to disturbance. You have not introduced any new materials. You have only changed their forms. The question is, whether you have changed the form in a beneficial or a harmful way. That is the question we are trying to answer.

*Answer #2:* I am not sure if you are going to be able to use a lot of the data that is in a SMCRA permit for this type of evaluation. An example would be acid/base accounting data. Acid/base accounting only gives you an indication of potential acidity rather than what will actually occur in the field. Also, different labs use different methods of analysis which limits the usefulness of this information for comparison with sites other than the site it was collected on. We have tried to predict what would happen when you mix CCB ash material in a soil. We have used an EQ geochemical computer model that was developed at the Lawrence laboratory. I am not sure if these models give you very much information, however, because of the lack of a high quality data input.

*Regulatory Question:* Most of the experience with CCB materials concerning disposal has shown that there is little reason for environmental concerns when the disposal area has been properly designed. My question is, whether the States should change their emphasis on permitting of CCB disposal from utilizing leachate tests, that try to predict environmental impact, to putting more emphasis on proper design of the disposal area'?

*Answer:* I would agree that priorities should be changed, but think that some leachate testing will still be necessary. Most, though not all, field tests have shown that CCB ash materials are benign. In one case in North Dakota the natural ground water did not meet drinking water standards but the leachate coming from the CCB ash material did. I think that the need now is to have more laboratory studies correlated with field studies.

*Regulatory Question:* Based on the information presented in this session, it appears that comparing the testing of high pH CCB ash to that of Portland cement is a fair comparison.

*Answer #1:* Making the comparison of high pH CCB ash to Portland cement is a fair comparison, however what is not fair is the standards and stringency of testing to which CCB ash materials are held. The high pH characteristic of CCB ash materials is one its best attributes. In order to form ettringite, you have to be between the pH range of 11.5 to 12.5. This is the pH you get when you mix lime with water, As a result of the clean air standards placed on coal fired power plants, we are now finding that virtually all of the CCB materials being generated are now ettringite formers.

*Answer #2:* Concerning leachate from CCB materials, the surface area is a very important factor. In solid-liquid relationships, the surface area is not just an important factor. it is the only factor. If you have

a large concrete block, the surface area is negligible when compared to the same amount of material in a powder form.

*Public Question:* How do you distinguish between coal combustion by-product materials that are utilized in some type of economic product and coal combustion waste materials that are not valuable and are disposed of? My understanding is that, in Illinois, a coal combustion by-product can not be taken back to the mine site, but in Indiana everything is regarded as a coal combustion waste. What is the difference between CCBs and CCWs?

Answer: No substantive difference. It is just a different name for the same material.

*Industry Question:* Could Jodi Tishmack tell us more about her work with creating an artificial soil from CCB materials? I think that it is this type of research that will remove a lot of the public fears and uncertainties about CCB materials.

Answer: I am using bottom ash and fly ash from the fluidized bed unit and the stoker and mixing it with plant residues. We will be publishing the results soon. We will also have information on ground water studies done in association with these artificial soil experiments.

*Regulatory Question:* What is the reactivity of the CCB ash material when placed at a surface mine under oxygen rich conditions, as compared to being placed in an underground mine in conditions devoid of oxygen?

Answer: The oxygen conditions are really not important when placing scrubber sludge materials.

*Regulatory Question:* Will the properties of CCB ash materials, when placed in a fill, break down over time?

Answer: Although we really don't know the long term situation, most indications are that the materials will last for a long time. Most studies are fairly recent and do not address the time factor. Because you do not have clay materials in CCBs, you do not have the settlement problems that you would expect utilizing natural soil materials. Permeability may increase slightly (from 10 to the minus 7 to 10 to the minus 5) and the strength of the material may be slightly reduced (from 1500 pounds per square inch to 800), compared to a natural soil material that would only have about 200 pounds per square inch of strength. Relatively speaking the fill from CCB materials is still much stronger over the long term than a fill with natural soil material.

*Regulatory Question:* What are the environmental advantages or disadvantages of CCB materials in disposal areas related to the submergence of the material in ground water?

Answer: The chemical reactions you have with CCB materials will happen whether you have a large amount of water available or only a little water. If the CCB material has cementing properties it will be come a large concrete block if it is in contact with water. If you have a CCB ash material produced by eastern bituminous coal, it will not form a concrete block unless you have added a source of lime to achieve the cementing properties. Those CCB materials that have had lime added such as scrubber sludge would have this cementing characteristic.

*Public Question:* Is the quality of the low grade concrete produced by the CCB material dependent upon the amount of water added in the design of the fill?

Answer: Yes this is true. However, the till produced by CCB material that does not develop into a low grade concrete is still many times stronger than a fill made of natural soil material.

## Session II: Site Characterization

1. Western Perspective J. Matthew Tanner, Environmental Compliance Coordinator, Texas Utilities Services, Inc., Dallas

*Regulatory Question:* Has Texas Utilities, in their experience with this material, conducted any economic studies to determine how much could be saved as a result of things like reduced compaction requirements? A knowledge of how savings could result from the use of these materials would be useful.

*Answer:* We don't have that kind of information,

*Question:* You said your disposal costs were in the range of \$15-18 million. Could you relate this to a cost per ton of material disposed or a cost per kilowatt hour of generation?

*Answer:* We don't have any numbers for that, however as a percentage of the total cost of electrical generation, it would be a small amount. Disposal costs at the plant would be about \$1.50 per yard of material disposed.

*Question:* You have used CCB bottom ash materials for short term ballast on railroad spurs, is it possible to use the material for long term ballast applications?

*Answer:* Our understanding is that it will not hold up under long term use because the material is too soft. Our bottom ash comes from the burning of lignite coal which is very soft compared to other coals.

2. Mid-Western Perspective Dr. Robert Darmody, University of Illinois, Department of Natural Resources and Environmental Sciences, Urbana

*Question:* Could you expand on your comment that CCB fly ash minerals are more reactive than older minerals? How long a period of time are you referring to?

*Answer:* The CCB ash materials have no water associated with them. When placed in a till they hydrate, generate heat, take on carbon dioxide, possibly cement, and weather rather rapidly. This is quite different from natural soil materials that are the result of thousands of years of weathering and do not change much when moved around.

*Question:* Could you expand on your comment that some soils in Illinois are deficient in some minerals? Which elements are usually deficient?

*Answer:* Some Illinois soils show a response to the addition of boron where alfalfa is the crop being grown. Generally older soils are prone to have more nutrient mineral deficiencies.

3. Eastern Perspective Barry Stewart, American Coal Ash Association, Alexandria, Virginia

*Question:* Is the change in water holding capacity that you have observed a long or short term phenomenon? Is the water available to plants?

*Answer:* It should be a long term property. As the CCB material weathers, the water holding capacity may actually increase. The water is available to plants.

*Question:* Could you expand on concerns about Boron, Cadmium, and Selenium concentrations increasing relative to surface mining reclamation?

*Answer:* The overall concentration of the elements will increase. Boron will probably dissipate quickly because it leaches very fast. Some of the other metals may increase on a whole soil basis.

*Question:* If Boron leaches does it decontaminate the soil but contaminate the water?

*Answer:* Some of the Boron will precipitate but some of it is attenuated by the soil as it goes to the ground water.

*Public Question:* Do high Boron levels have an adverse impact on crop growth?

*Answer:* They can.

### **Session III: Regulatory Requirements**

#### 1. Indiana Mike Sponsler, Director, Division of Reclamation

*Public Question:* You referred to a list of 6 sites out of 500 as identified by the US EPA as being a problem in EPA's determination that CCB materials were not hazardous. Did that list include the Michigan City and Bailey sites in Indiana?

*Answer:* My slide showed those two sites. The situation there is that they found migration down gradient but not off site. There was no attenuation of trace elements to the soils because it was very sandy. At the Bailey site, they had other industrial wastes as a factor, due to its proximity to a heavily industrialized part of Gary, Indiana.

*Public Question:* Are most slurry ponds in Indiana, that contain large amounts of CCB materials, outfitted with ground water monitoring wells? It is our understanding that there is very little ground water monitoring going on at most sites where large CCB slurry ponds are located.

*Answer:* It is my understanding that this is not required. I believe the power industry is sampling them for their own information. This would be a requirement if the disposal activity was located on a coal mine in Indiana.

*Public Question:* By referring to the US EPA report on CCB materials, are you saying that the US EPA classification of hazardous under RCRA has anything to do with the determination of "toxic forming" under SMCRA?

*Answer:* What I am saying, is that it is a material we felt we could manage. Concerning toxicity, SMCRA requires that you provide special handling in order to protect the hydrologic balance. The Indiana program requires this type of handling for toxic materials.

*Public Question:* What about the other attributes of CCB materials, such as high or low pH, high hydroxide, or flocculent concentrations that may be toxic to fish or aquatic life?

*Answer:* If you look at the US EPA report you do not find any mention of damage to living things. Taking a laboratory leachate result and assuming that living things are going to be exposed to those concentrations is no more realistic than making the same assumption concerning a compliance sample of a sewage lagoon. The question is, what conditions are going to occur after the water gets off site. Until the water gets off site it is part of the treatment system. The important thing to note from the US EPA study is that very little high concentration leachate was migrating off site.

*Public Question:* Many of the States surrounding Indiana have separate laws pertaining to CCB materials. Indiana has memorandum 92-1, which has been created by the Indiana Department of Natural Resources. If there is a case where water is contaminated by CCB materials, what recourse do citizens of Indiana have with respect to damages?

Answer: The adjacent State of Illinois also does not have any specific laws concerning CCB materials. The content of memorandum 92-1 was a product of the requirements related to protecting the hydrologic balance under the Surface Mining Control and Reclamation Act of 1977. The law in Indiana then would be the State equivalent to SMCRA.

2. Kentucky Gary Hahn, Department of Mines, Frankfort

*Regulatory Question:* In Kentucky, you require CCB placement to be 4 feet above the seasonal high water table established after mining. Is that based on information in the applicants permitting package related to the probable hydrologic consequences to determine the seasonal water table? It is my understanding that it can take years for the actual water table to be reestablished.

Answer: It is important to identify the final ground water level because we want to keep the materials out of the ground water. We try to use good technical scientific information.

*Academic Question:* Are low volume wastes defined by reference to US EPA documentation or is it defined by the State?

Answer: Coal combustion by-products means fly ash, bottom ash, scrubber sludge, and waste from fluidized bed combustion produced by the combustion of coal. Coal combustion by-products do not include boiler slag and residue from refuse derived fuels such as municipal solid wastes, tires, and solvents.

*Industry Question:* Does Kentucky have any limitations on the amount of CCB materials that can be placed back in a surface coal mine?

Answer: The limit is, the tonnage of CCB materials placed in a surface mine can not exceed the tonnage of coal removed from a specific permit area.

*Question:* Concerning Kentucky's requirement that CCB material be placed above the water table, do you have any specific data that shows a difference between the wet placement versus a dry placement?

Answer: This is just what we have in the law. There is a concern about the volumes that must ultimately be disposed, and how much can be disposed of in underground mines.

3. Pennsylvania Nevin Strock, Chief, Surface Mine Permit Section

*Regulatory Question:* In Pennsylvania, is there any way to know, after the mine and CCB disposal are gone from the scene, that later land owners will know that CCB materials were disposed of on their property'?

Answer: The CCB ash disposal must be recorded with the county recorder of deeds.

*Public Question:* There must the CCB ash material be placed relative to the ground water table?

Answer: It must be placed a minimum of 4 feet above the premining seasonal ground water table.

*Public Question:* In your ground water monitoring requirements, do you have a standard for water quality, that if exceeded, would require Pennsylvania to do anything?

Answer: In Pennsylvania, there are trigger levels based on ground water parameters. If those levels are exceeded that would require an assessment and remediation.

*Question:* Concerning constraints placed on the fill structure, why does Pennsylvania have requirements

for the level of compaction and the maximum lift thickness?

*Answer:* The primary reason concerns the final stability of the site. Pennsylvania is currently reevaluating this and other requirements to determine what the need is. The State has not experienced any stability problems with CCB materials.

4. New Mexico Monte Anderson, Hydrogeologist, Mining and Minerals Department

*Public Question:* Does New Mexico require ground water monitoring of CCB disposal sites and would the State be required to do anything if certain levels of contaminants were exceeded?

*Answer:* There is ground water monitoring at all sites. If New Mexico ground water standards were exceeded, State action would be required.

*Regulatory Question:* Is there anything that would trigger additional CCB material chemical analysis after the initial permit approval process?

*Answer #1:* In Pennsylvania, there is a minimum of one analysis every 6 months and may require quarterly monitoring if the need arises. Indiana requires quarterly analysis and may require additional analysis if a supplier were changed. If significant changes in the materials were demonstrated, then the permittee would be required to apply for a significant permit revision.

*Answer #2:* Missouri has three programs that deal with CCB materials. These are Land Reclamation, Solid Waste Management, and Water Pollution Control. The Land Reclamation program does not regulate CCB material directly but looks at those aspects of CCB disposal that may ultimately impact successful reclamation such as approximate original contour, grading, revegetation, and timeliness of reclamation. The Solid Waste Management program regulates CCB disposal. This would include exemptions for CCB materials used for a beneficial use or its use for reclamation where there is not a public health hazard created. Special surface and ground water monitoring is required. Although Missouri mines have historically disposed of CCB materials, currently no active mines are disposing of this material.

*Industry Question:* How many sites in Pennsylvania have received CCB materials? Have any of these sites exceeded trigger levels for corrective action? What is the total tonnage of materials being disposed of?

*Answer:* Pennsylvania has 70 active sites that since 1986 have utilized CCB materials beneficially as a fill material or as a soil additive. We haven't had any problems, with the exception of one site with sulfate. Pennsylvania is currently working on the compiling and analysis of all of its' data on CCB material monitoring in order to evaluate long term effects. Many of the sites were permitted back in the late 1980s. The tonnage of material disposed of has been gradually increasing since 1986 and was 6 million tons in 1995.

*Public Question:* What are the requirements of Kentucky and Missouri to take corrective actions if water quality standards are exceeded due to CCB materials'?

*Answer:* Kentucky would reevaluate the monitoring program and possibly require additional monitoring sites and could potentially stop the disposal of the CCB material. The critical standards would be the drinking water standards. In Missouri, the water must be suitable for its intended use. In most cases you are not dealing with well defined aquifers that have extremely low hydrologic conductivity and in most cases there is no current use of the ground water. The surface mining requirements would require the operator to replace water supplies that became contaminated. At the time of final bond release, it would also be possible to deny the release if the water was no longer suitable for its intended use. In most cases, however this is unlikely due to the lack of water use in the areas where coal is mined.

Question: Two States allow CCB disposal on the pit floor and two States require it to be 4 feet above the water table. What is the reason for the differences?

Answer: When New Mexico required placement on the pit floor it was with the knowledge it was already above the water table. In other situations we require the material to be above the water table. In Pennsylvania, we are trying to avoid contact with water movement along the high wall and along the pit floor. Indiana does not have any requirements related to water tables. The reason being that the US EPA study was on sites that were mostly in contact with water, usually in flood plains and sand and gravel aquifers. If you have high pH materials we would expect the crystal formation and concrete like characteristics of the material when associated with water contact to immobilize the chemical constituents. These studies would indicate that water contact with CCB materials is not a problem.

Question: What happens when an operator would request to place a CCB material in association with an acidic environment on a mine site?

Answer: Potentially the operator would be asked to revise the permit or it could be denied if problems with potential toxicity could be expected to occur.

*Regulatory Question:* It is my understanding that the Kentucky program does not accept any CCB material where the leachate analysis indicates that RCRA standards have been exceeded. Does Kentucky actually use drinking water standards or RCRA standards as its trigger levels for monitoring ground water adjacent to CCB disposal sites?

Answer: The Kentucky program is quite new in this area. Kentucky has only had one permit approved for CCB disposal and disposal has not yet begun. As such, we can not really address what measures Kentucky would take in the event of circumstances that have never happened.

#### **Session1 IV: Design/Engineering/Planning**

1. Assessment of environmental impacts including health and safety Gary Brendell, GAI Consultants, Monroeville, Pennsylvania

*Engineering Question:* Have you had any experience with the placement of structural CCB material fill in cool wet seasons, and if so, what are your recommendations?

Answer: CCB ash material has been placed under all types of weather conditions. Cool is not as much of an issue as cold. We have had situations where it was so cold that water in the ash would freeze and then you don't get adequate compaction. In this case, we were able to bring CCB ash materials directly from the power plant while it was still hot so that it could be placed and compacted before it had time to cool down and freeze. In cases where the material gets too wet, you again have problems with getting adequate compaction. If this is the case, you may need to shut the job down until the material can dry out or bring fresh dry material in that can be mixed with the material on site so that you can get the optimum density for compaction. Things do go better in the summer.

*Regulatory Question:* Has your firm actually done some of the risk assessment procedures that you have recommended in your talk including the long term laboratory tests?

Answer: We have not done any of the long term laboratory tests. In the current regulatory environment, we have run the leaching tests based on site specific State recommendations.

*Engineering Question:* What type of dust control measures do you use'?

Answer: We use water trucks 98 percent of the time. If CCB ash is going to be exposed for a long

period of time, we might cover it with bottom ash to prevent the lighter material from being blown around.

**Question:** Of the fill materials you have used, do you prefer to use CCB ash till or do you prefer some other till material? How would you rank CCB ash as a fill material?

**Answer:** CCB fly ash compares favorably with many soil materials. There are some soils that you would prefer to work with if they were available. The advantage to CCB fly ash is that it is available in bulk quantity and can reduce or eliminate the cut and fill operation expense. A good example would be that, in Pennsylvania, there is a lot of rock and highway construction which requires a lot of blasting to level the grade and generate the fill materials. If you knew ahead of time you could get 300,000 tons of CCB fly ash, you could avoid all of that blasting. As long as you can build a till that meets the construction design specifications, it does not matter that it is not the ultimate till material. The economic advantage of CCB fly ash is primarily a function of the haul distance from the power plant.

2. Materials handling including dust control Paul Petzrick, Maryland DNR, Annapolis, Maryland

**Engineering Question:** What was the mixture of CCB material you were using?

**Answer:** The mixture we used consisted of 60 percent Fluidized Bed Combustion Ash, 20 percent class F fly ash, and 20 percent FGD material. We then added water to get a moisture range of 47 to 53 percent.

3. Design and Management of Coal Combustion By-Product Mine Backhaul Placement Areas, Bill Giles, Freeman United Coal Co., Farmersville, Illinois

**Industry Question:** Do you have any information on transportation of this material by barge and truck?

**Answer:** I am not aware of any situation where it has been handled with barges. Most of my experience has been with rail transportation and then loaded into haul trucks. It would seem, however that the technology of handling cement could be applied to handling most CCB materials.

4. Planning and Design for CCB Utilization in Abandoned Mined Land Settings: A Case Study John Gasper, ATC Environmental Consultants, Indianapolis, Indiana

**Regulatory Question:** What is the additional cost involved with creating the POZO-TEC product from CCB ash material?

**Answer:** The product came to us at no cost. The cost was incurred by the power plant. The benefit came from its superior structural properties and its ability to tie up metals. The power plant considered this a good trade off to having an uncontrolled sloppy fill.

**Regulatory Question:** Could you expand on the relationship of moisture content to design considerations?

**Answer #1:** As received moisture content varies considerably depending upon whether it is fresh or has been preconditioned. The more reactive CCB ash materials require larger amounts of water in order to get the right compaction characteristics. Class F ash materials do not require as much water as do other ash materials. Some of the physical characteristics change as the material hydrates. Initial hydration causes the material to break down like quick lime. Additional hydration will cause heat to be generated as the lime is converted to slake lime. Moisture will be driven off by the heat, requiring additional water inputs.

**Answer #2:** Concerning moisture content, it is important to note that at less than 4 percent moisture the

FBC material becomes virtually unworkable. At less than 4 percent moisture the material will suck itself right out of the bucket of a front end loader. Our FBC material would not mix at less than 47 percent moisture. It would not become a homogeneous material. At a moisture content greater than 53 percent, it suddenly became slop. The moisture content is a case by case requirement depending upon the material used and the application.

Question: Does the SGLP test have any disadvantages or costs relative to other tests?

**Answer:** No.

Question: What material handling methods are used to mix the POZO-TEC material?

Answer: This material is generated by the power plant utilizing hoppers to put the quick lime in the mix. The sludge is blended in belt lines which and is discharged as POZO-TEC in a pile at the end of the belt line.

Question: Is there any way to arrive at a representative unit weight for the material?

Answer: There is no good way. The only thing you can do is measure the in place density.

*Academic Question:* Dr. Hassett, you pointed out that column leaching experiments should not be considered as a leaching procedure. Could you comment on this?

*Answer:* When you look at an ash monofill, it is easy to visualize it as a column leaching phenomena that would occur in nature. It probably does not work that way because most of these materials are fairly impermeable. Because of this, water spends a lot of time reacting with the material. A column leaching experiment in the laboratory has a column of material where you run liquids through in order to allow for a collection of leachate at a fairly fast rate of pore volume exchange. This rarely occurs in nature. The other thing that happens is that the results are frequently misinterpreted. The column may be leached with a progression of different pH level fluids, assuming that the results reflect a particular level of acid leaching. Instead, the ash material is reacting with the leaching fluid over a wide range of pH levels. The only way it can be evaluated is to section the column after the experiment and see what is happening mineralogically section by section. Batch leaching experiments give you absolute control over what is happening. You can do a leaching at specific pH levels. You need the data from several batch leaching experiments in order to interpret what is happening in the column concerning pH, concentration, and fluids. Also the rate of fluid flow is so high in most column leaching tests that the mineralogical reactions that occur in the column do not occur in nature. In order to duplicate what would occur in nature you would have to use a rate of one pore volume every 60 to 90 days.

*Academic Question:* Dr. Bradley Paul is a proponent of column leaching tests. Could you provide a response to Dr. Hassett's concerns?

*Answer:* I would agree with a lot of what Dr. Hassett said about column leaching experiments, particularly in regard to the rate of fluid flow through the column. The ASTM column test has been standardized and dictates that you use a pore volume per day. There are other column experiments where the fluid is allowed to percolate through the column under the influence of gravity and get some of the slower reactions. I like the column leaching experiment rather than the batch experiments because you do not get 20 parts of liquid to one part of solid in the field. Although column leaching is not a perfect simulation of what happens in the field, a properly run column experiment is a much closer simulation of what is happening in the field than a batch leaching experiment. If you want to understand everything that is happening in a column, then you have to have the type of information recommended by Dr. Hassett. The column leaching experiment will give you results that are defensibly close to field conditions. It will not give you every mineralogical detail. The column leaching tests are useful for

engineering applications. We have been very successful using open percolation columns without using high rates of water flow in combination with computer simulation to get very accurate predictions of what has occurred in the field.

*Question:* What is the relative utility of impounded ash versus dry ash material?

*Answer #1:* In regards to class F fly ash materials, both can be used. Impounded ash may need to be dredged and stockpiled in order to reduce the moisture content. From an environmental point of view, any leachable constituents of the impounded ash may have already leached out prior to placement in a structural fill. We have found that impounded ash material water quality is near drinking water standards. An additional problem with some impounded material is that it may have been codisposed with bottom ash materials where differential settling will take place. This presents problems when you are trying to maintain a uniform quality of material for the fill operation. It is best to handle impounded material when the weather is warm and dry. When using FGD filter cake, the high moisture content can cause it to freeze up in the truck beds during the winter. The practical limit for hauling impounded ash in the winter is 20 degrees Fahrenheit. Otherwise, it freezes in the truck beds. Also, Flue Gas Desulfurization sludge is not a construction material; it is a construction nightmare.

*Answer #2:* Our experience has been that within two days of dredging the impounded material, the water content was low enough that the material can be handled. As a practical guide, we used the observation that if the material pumped out ahead of where you were driving on it, the moisture content was too high. The only way to determine this was actually working with the material.

*Question:* Could you comment on types of compaction equipment to use in the field?

*Answer:* Compaction criteria depends upon use. In general, rubber tired equipment works better than tracked equipment, vibratory rollers are the only way, sheep's foot rollers do not work at all. Heavy rollers that can compact to 18 inches are preferable. Light vibratory rollers do not compact more than 12 inches.

*Academic Comment:* Leaching tests are a dynamic test. In nature, our underground water quality was more in a static condition. When we placed a camera down the bore hole for 400 feet, in order to look at the abandoned underground mine works, we found that the water had stratified in this mine which had been abandoned for 45 years. Whenever the camera would touch something like a mine support timber, it would generate an enormous cloud of sediment. It suggests that hydrologic conditions occurring 400 feet above were not effecting the water in the mine. I think that we need a specific ASTM test developed that would represent this static condition.

#### **Session V: Environment: Land And Water**

1. Bituminous Fly Ash Chemical Properties and Influence on Water Quality Dr. Bill Evangelou, Agronomy Department, University of Kentucky at Lexington.

*Question:* Would the acid generated from a normal application of fertilizer on CCB ash be enough to begin leaching the CCB material?

*Answer:* A normal application of fertilizer is usually enough to begin leaching metals from the CCB ash material.

2. Ground Water Quality Dr. Bradley Paul, Mining and Engineering Department, Southern Illinois University at Carbondale

*Public Question:* What is the potential for the formation of colloids or flocculent from the attenuation of high pH CCB ash and resulting potential toxicity to fish or other aquatic life?

*Answer:* We did monitor the water at two sites and found no such problems. Although any neutralization of acid mine drainage has the potential to produce chemicals that could be damaging to aquatic life, acid mine drainage by itself is also toxic to aquatic life.

3. Coal Combustion Residues as Soil Amendments: Surface Coal Mining Dr. Ron Korcak, Agricultural Research Service, Beltsville, Maryland

*Question:* You said that calcium sulfite mixed with soil produced sulfur dioxide which is toxic to plants. Before that could happen, wouldn't calcium sulfite when exposed to air convert to calcium sulfate, also called gypsum and is a plant nutrient?

*Answer:* If the CCB material is allowed to mix with air sufficiently, prior to placement in the soil, this is the case. It is only when it has been placed prior to mixing with air that sulfur dioxide is created in the soil. I do not have any data on the rates of conversion, but that data should be available at the ARS office in Beckley, West Virginia.

4. Public Concerns Regarding the Management of Coal Combustion Wastes Tom Fitzgerald, Kentucky Resources Council, Inc., Frankfort, Kentucky.

*Academic Comment:* If people are concerned about radionucleotides in CCB ash materials, a good source of information would be publications by Bob Finkleman of the USGS and a book by Dals Swain called "Trace Elements in Coal." With respect to the Oak Ridge article on the subject, that article is responsible to science what Jeffery Dahlmer was to freedom of expression. In general, a good way to look at radionucleotides is to do a bulk analysis of the CCB ash to determine if there is anything there to leach.

*Public Question:* What percentage of the coal combustion waste produced in Kentucky is reused?

*Answer:* Kentucky encourages the beneficial reuse of CCB materials and requires the same sort of material characterization related to environmental concerns as materials that are land filled. Although we don't have any numbers for Kentucky, nationwide we know that about 25 percent of the CCB materials have been reused for the last 10 years.

*Public Comment:* A recent paper presented to the Indiana Academy of Sciences outlined water quality problems in Grant County, Indiana due to oil and gas drilling over 100 years ago. Current coal mine applications suggest that they will improve the environment by creating a pool of ground water that can be used in the future. Now the mines are applying for permits to dispose of CCB materials in these same areas. Much of the current discussion concerning CCB disposal on mine sites revolves around what exactly is happening with the chemistry of these materials and what is going to be the water quality situation 1, 5, or 10 years in the future. Are we setting up problems for future generations because of generalizations being made about these materials which may not be true on a site specific basis?

*Regulatory Comment:* Based on recent conversations with the heads of the Indiana and Kentucky geologic surveys, radionucleotides are not a problem in the Illinois coal basin or in the Kentucky coals.

*Industry Question:* Dr. Paul could you comment on the use of acid/base accounting to evaluate the application of CCB ash materials to amend an acid mine drainage situation?

*Answer # 1:* The procedure most frequently used usually evaluates the sulfur and iron of the spoil material, its pyrite content, and its total potential to generate acidity. This is compared with the ability of the carbonates of the mix to neutralize the acidity. Based on this result, it is usually recommended that carbonates be added to achieve a safety factor of 2 units of alkalinity to 1 unit of acidity or sometimes a 4 to 1 safety factor. Application rates derived from this method are not thought to result in situations where acid mine drainage would occur. I have used acid/base accounting when the project involved

mixing of CCB materials with mine spoil. I have not used acid/base accounting when I am using the CCB material to provide a an impermeable layer over acid-forming materials.

*Answer #2:* Acid/base accounting is a perfect test for a CCB ash that has no heavy metals in it. The test will determine how much alkalinity it has and how much surface neutralization it can produce. Many States require you to multiply this amount or potential neutralization capacity by 5 to 20 times to provide an actual application rate for the CCB ash material. However, pH has absolutely nothing to do with the release of a metal like cadmium. The reactions that regulate the release of these metals is more difficult to predict. If you try to use CCBs to neutralize an acid spoil with a lot of iron, the neutralization will cause the iron to be released. If you use CCBs to neutralize an acid spoil without iron, the neutralization will cause the heavy metals in the CCB materials to be released. Acid-base accounting would not be an adequate test if the CCB materials contain heavy metals.

*Regulatory Question:* Could you comment on the differences between the field results indicated by Dr. Paul's work and the laboratory results of Dr. Evangelou's work?

*Answer #1:* I see no conflict between the work of Dr. Evangelou in the lab and the work we have done in the field. The analysis we performed was very limited because we were only trying to get site specific results. Our analysis, under the pH and environmental conditions of that site, would be in agreement with the results that Dr. Evangelou would get if he made the tests in the lab under the same set of environmental factors. The work of Dr. Evangelou in the lab is doing testing over a full range of pH values and testing in the presence of other salts to see if the metals would desorb under certain conditions. This is very important to a good fundamental chemical analysis. In an applied field study, we are only looking at one set of environmental conditions that would exist unchanged for hundreds of years.

*Answer #2:* It is very easy for inexperienced people to look at fundamental chemical data and misinterpret it. The lab data and the field data are in agreement. The laboratory tests can tell you what will happen to the CCB ash material after it has had maximum exposure to carbon dioxide. In the field, you have diffusion limitations and barriers. If you see in the field the pH stabilizing at pH 12 and it will take 2 years, it is because the carbon dioxide is not available to react with it. All of this has to be integrated with kinetics. If you put CCB ash materials in soil, soil and CCB ash do not titrate much differently. In fact, soil is not a good buffer. It buffers itself at pH 5 and pH 7. In a Midwestern climate, the farmer must lime every 4 to 6 years and, if he is raising tobacco, every 2 years. The reason is, because the soils do not have any buffering capacity. Most crops need to be grown at a pH of 6. In the same way, CCB ash materials have little buffering capacity and their neutralization ability is quickly exhausted.

*Public Question:* The environmental concern would be the mobilization of heavy metals from the CCB materials and the movement of these at potentially toxic concentrations in the surrounding water systems. What are the chances that these CCB materials could result in the mobilization of potentially toxic concentrations of heavy metals in off site water systems?

*Answer #1:* During the 1994 legislative session in Kentucky, a representative of TVA indicated that migration off site was not a concern for their ash ponds. When I questioned this point, I was provided with three pages of literature that documented contamination outside of the disposal area. This documentation will be provided as part of the final publication. This literature would suggest that if you have an area that is flooded you may have a problem with contamination versus an area that is high and dry or has an impermeable cap.

*Answer #2:* If you take any agricultural soil and you put it in a column and start leaching, it will turn acid even though leached with distilled deionized water, Eventually it will start leaching metals such as aluminum. So under these conditions, natural soil itself is toxic. CCB ash material is no different. Some would make that the argument that the soil is a given, you just need to manage it, and the **only** way

to manage it is to raise the pH to an acceptable level. Every soil has a unique capacity to store heavy metals. When you add CCB ash materials that contain heavy metals to the soil, in the long run, if you keep adding CCB ash materials or other refuse materials to the soil, you will eventually saturate this capacity and heavy metals will be leached from the soil. Even if the soils are actively managed to maintain an optimum pH of 6.5, continued input of heavy metal containing soil amendments such as CCB materials or sewage sludge will result in the potential for releasing heavy metals.

*Answer #3:* From an engineering and geological perspective, no mineral, rock, or coal ash will last forever. Eventually everything is going to break down and the elements will be transported via natural forces in the environment. The question is not whether these minerals will be reintroduced into the environment, but the rate at which they are reintroduced. Based on my experience with CCBs from the Illinois coal basin, there are very few metals present in levels that could be toxic. I have found an initial high leaching profile that tapers off very quickly. Whether or not you will get a significant contaminant plume in ground water, is a combination of the concentration level of the contaminant and the duration of the contaminant level. Based on the studies we have performed, we are not generating the type of long duration flush necessary to produce a significant contaminant plume. You also need to consider, that on the mine site, the soils have a lot of attenuation capacity. At one site we did leach boron and molybdenum. Within 15 meters of the disposal site, the boron made it to the monitoring well, the molybdenum did not.

*Regulatory Question:* If I had the situation as a regulator where I had the current speakers as the experts that would evaluate a permit to dispose of CCB materials on a mine site, I would not have any problem with the speaker's ability to determine the applications suitability. Is the expertise represented by the speakers at the this forum available as a technical guide to regulatory permitters for their use in approving permit applications?

*Answer #1:* No it is not, and that is precisely what needs to be developed. Typically, State regulators dealing with coal mining look at iron, manganese, pH, acidity, alkalinity, and neutralization potential of the overlying strata and will not gather baseline data or characterize that data on the full range of metals that are of concern. These metals are concentrated and more available in the CCB materials and are being placed back in an environment that is more hydrologically accessible and permeable than existed prior to mining. It is my hope that this type of guidance would be a result of the forum because there is a great deal of difference in how each State is managing and characterizing CCBs. Although Dr. Paul's data shows a decrease in metals over time, the situation I have experience with has shown an increase in metals over time. Someone should determine what are the proper tests for each situation. Should the States be using the long term tests advocated by the researchers in North Dakota in conjunction with short term tests? The States are not currently providing these long term tests. In some cases in Illinois, the ground water table will not be restored prior to the end of the 5 year liability period following coal mine reclamation. In this case, ground water contamination may not be detectable at the time of bond release. In this case, a much closer look should be taken of the characterization of the material and the validity of modeling the reestablishment of the hydrologic regime. State regulators are not currently looking at the impact of CCB disposal on the long term impact of surface coal mining to the hydrologic balance of the area.

*Answer #2:* From an agricultural perspective, I have dealt with a number of waste products including CCBs. No matter what type of waste I am dealing with, the first thing I request is a total chemical analysis. I usually look at that analysis as it relates to trace elements that I assume will ultimately be available to the environment. That is what we tried to do in our manual on land application of Fluidized Bed Combustion materials. In these flow diagrams we have maximum loading rates for the different metals. This addresses the concern that, in 100 years, the soil will still be utilizable for agricultural purposes.

*Answer #3:* There are some CCB ashes that are no problem to use as soil amendments. The question is, when they do show some level of heavy metal concentration, should you use them in a situation where

they have the potential to contaminate the water of vegetation. One of the things that should be looked into is the classification of CCB materials. For example, if I have a silica based CCB ash that contains arsenic, I will not put it on an agricultural soil because I know the arsenic will be released. If I had an iron oxide CCB ash with the same amount of arsenic, I would be less hesitant to apply it to an agricultural soil. So far, we have not really addressed these differences in basic CCB chemistry in any systematic way that could be utilized in evaluating their suitability for different environmentally related applications. Our analysis has been based on its content rather than on its reactivity. A lot of work remains in order to classify these materials to determine its suitability for different types of disposal and use.

*Regulatory Comment:* I would strongly disagree with any type of a checklist mentality in connection with producing a guidance document. Currently, we have a number of States that have developed the guidance for implementing these programs in their State that meets their specific conditions. If we try to develop a checklist for a one size fits all program, we will end up with a very dissatisfied customer base including the citizens that live near the coal mines. We have already seen four or five different how to CCB programs in the U.S. We should not lump these together because of the variety of conditions experienced by the different States. A State like Pennsylvania, with a lot of acid mine drainage, may need to do something very different from a State in the Illinois coal basin that has very little acid mine drainage.

*Answer:* I don't think anyone here is saying that you should develop a one size fits all type of guidance document or program. There are certain things that should be done in all cases, such as adequate characterization of the CCB material and the fate and transport of that material in the environment. A lot of the questions that should be asked are new to people conducting these types of permit review.

*Regulatory Comment:* We have been discussing a lot of tests that concern what may or may not be leached by the CCB materials. These are not tests that will tell you whether or not to approve a permit application. In most cases, the question is how to manage the material, which depends upon site specific factors such as climate, hydrogeology, topography, and land use. You have to look at what is in it, where is it going, and how are you going to manage it.

*Public Comment:* In Indiana, the citizens believe that an adequate evaluation of the fate, transport modeling, and characterization of wastes is not being done. This is not a need for a checklist, but for minimum safeguards that delineate what is required by SMCRA when coal mines are used for disposal areas. This is something that the citizen's feel that the framers of SMCRA did not envision.

*Industry Comment:* Texas has had a CCB program in place for over 25 years. It covers a lot of the questions that have been asked here. It is a very stringent process that requires a lot of modeling and characterization such as we have been discussing. My experience with our utility that burns 32 million tons of coal per year, is that no contamination has ever left any of the land fills where the CCB materials have been placed. The electric power research institute (EPRI) has spent over \$20 million in CCB research that should be accessed in any future work in this area.

*Academic Comment:* Concerning comments made about regional environmental differences, I would like to give an example. If you took a truck load of CCB ash containing boron to California, and tell a farmer I would like to put this on your field as a boron soil amendment, he will chase you away with a shotgun. This is because he knows that boron will kill his crops. The reason is that there is no rainfall in California. and boron has built up in the soils. At about 2 ppm of boron in the soil water, boron becomes toxic to plants. In the Midwest, however, there is no boron problem in the soils and some soils have boron deficiencies. You have a different problem with heavy metals because they are chemically bound in a reversible fashion. If you have heavy metals in the CCB ash material, then it is very difficult to predict the potential release of these metals into the environment in terms of concentration and under what set of conditions a release would be expected to take place. If the CCB ash material does not contain heavy metals, then this is not a problem, but some do. Someone needs to systematically evaluate

the CCB ash characteristics and the environmental conditions under which that material could be expected to exist. For example, if you grow tobacco on CCB ash amended soils and the soil pH drops to 4 every time you fertilize it, then you will flush out any heavy metals in the CCB ash materials. For this reason, research scientists are hesitant to make general recommendations for the agricultural application of CCB ash materials as soil amendments. In order to evaluate its potential usefulness as an agricultural amendment, you would need to know what is in it, where will it be used, what will be grown on it, how will it be managed, and what are the long term consequences of this application.

*Public Comment:* We do not feel that an adequate risk assessment of disposal of CCBs at surface coal mines has been demonstrated. The Federal and State regulators need to develop definite regulatory criteria for CCB disposal to adequately protect water resources and water users from contamination.

## Session VI: Monitoring And Evaluation

1. Coal Combustion By-Products and Contaminant Transport in Ground Water Edward Mehnert, Illinois State Geological Survey, Urbana, Illinois

No questions.

2. Geochemical Modeling & Impact Assessment Dr. Gary Dreher, Illinois State Geological Survey, Urbana, Illinois

*Academic Question:* One of the limitations of these models is the use of them by amateurs. These models assume that you have physical mixtures of crystals. But if you wet a heterogeneous mass of crystals and then dry them and run the model again, that model will have lost all of its ability to predict anything because the minerals have become mixtures of minerals and the delta "gs" have changed. That is a big limitation for these models.

*Answer:* I agree. Models are not for the amateur. You have to know a lot of chemistry and mineralogy before you can use it or understand what it is telling you.

*Academic Question:* The models that you have talked about are based on natural systems. None of the models that I am aware of take into account things that happen in alkaline CCB material. This would include the formation of ettringite monophase and subsequent formation of tomasite, all of which decompose into very sorptive materials like aluminum oxide hydroxides. These kind of phases are responsible for the solution chemistry and concentrations of arsenic, boron, chrome, molybdenum, selenium, sulfur, and vanadium. Do you know if anyone is trying that data inputted into these models? Also when you look at CCB ash material, this is composed of 60 to 80 percent amorphous material that is not crystalline. I don't think we know anything about how these amorphous materials behave in solution. Is anything being done to adjust the models accordingly so they will work with CCB ash materials?

*Answer:* These models are limited to crystalline phases and will not work with amorphous materials. I do not know of any work to solve that problem. You have a problem in the lack of thermodynamic data and a lack of defined mineralogy.

3. Instrumentation Dr. Steve Esling, Geology Department, Southern Illinois University at

*Regulator?/ Question:* Did you use a neutron meter? It is able to go to much greater depths.

*Answer:* That is a useful instrument for monitoring volumetric moisture content, but it requires a licensed operator that we did not have. Neutron meters can take readings in a bore hole that is already cased. The time domain reflectometer we used becomes impractical below a depth of one meter.

*Academic Comment:* These systems are great for collecting water samples but they have great

limitations for analysis of water solutions. One of the problems in analyzing alkaline environments is the partial pressure of carbon dioxide. A man named Suarez at the Selenium Laboratory of the Federal Station of the University of Riverside in California has developed an instrument that can be used to maintain a constant partial pressure of carbon dioxide while removing solutions.

*Public Question:* Could you comment on what an appropriate positioning of monitoring wells relative to a CCB material disposal sites, the length of time for monitoring once an equilibrium has been achieved, and how long a time that might be?

*Answer:* At one site, we finally got a boron reading in a down gradient monitoring well 15 meters from the disposal site. There was a significant attenuation from 100 parts per million in the disposal site to 10 ppm at the monitoring site. At this point, I do not think we have seen the concentration of boron peak yet at this site. We are just seeing the outer edge of the plume coming through. The movement through these CCB materials and the mine spoil is very slow. We have monitoring wells no more than 15 meters from the disposal site where it took a year for the water from the disposal site to reach the well. The modeling would suggest that we may have to wait much longer to see the maximum concentration of pollutants that would occur at that monitoring well. It depends upon what the overall hydrologic conductivity of the material is. I would recommend that a couple of down gradient monitoring wells be placed as close to the disposal area as possible. It will be years before you pick up anything in monitoring wells 20 to 40 meters from the disposal site. You need to have monitoring wells at several distances down gradient. The only way you will ever be able to figure out the porosity is to be able to take readings in more than one monitoring well. Although research with CCBs has been occurring for some time, one thing that is still missing is good field data due to the length of time necessary to get good data.

*Public Comment:* A concern for citizens is that we are not finding, in permit applications, information on what the effects of CCB disposal will be to the down gradient water quality after the mine site reaches a hydrologic equilibrium. Because of the extent of mine dewatering that occurs during mining, there is a cone of depression that will take years to reach equilibrium. In the permit applications, there is no information as to the time when hydrologic equilibrium will be reached and when the monitoring wells will be providing information on potential contaminant concentrations from the disposal sites. In the Illinois coal basin, there seems to be agreement from all parties that the reclamation bond can be released prior to ever getting an actual reading of potential pollutant levels from monitoring wells installed down gradient from CCB disposal areas. Although monitoring wells can be located in the CCB ash materials directly, we do not believe that this data is representative of what will occur down gradient or ultimately off site from the disposal and mine site.

*Academic Question:* If there are as many required assumptions in modeling as you have suggested, what is the point of modeling?

*Answer #1:* The model should bracket the problem and suggest what you might see in a field situation. In terms of a mine situation in Indiana, where they are pumping out a lot of ground water, I can assume a water level in the mine and based on the geology put in a hydrologic conductivity value and give you a quick number like 5 years. If you give me better (more site specific) information, we will conduct field testing, I use "MOD FLOW," I put in a layered situation, I add some more complexity to the model, and I may be able to tell you that it will be 3.5 years. If we determine that fractured flow is occurring rather than porous flow then we could use a model for that.

*Answer #2:* In the case of chemical equilibrium modeling, we are at the state of the art. The next step is chemical kinetics, which is a big step. There is not a lot of data available for the kinds of things we need to look at. A chemical kinetics model (if and when it is developed) would be a lot more realistic because it would not have to assume a chemical equilibrium.

*Academic Question:* In the laboratory, I am trying to study as many ions together as possible in order to see how they behave in the presence of other ions. For example, you take a simple ion like potassium

and you can estimate a constant rate of diffusion. Then you add ammonium and that estimate is no longer valid. If you add another more reactive ion, such as calcium, the estimate of the constant rate of diffusion is lost altogether. Based on this, I question the monitoring of 20 ions simultaneously. Some of these are potentially determining ions that modify surfaces. In this case, you would need 10 times as many differential equations on the chemical component as you would on the transport component. In essence, the water transport component is very simple by comparison. The chemistry component becomes almost non solvable in the sense that it would any way be realistic. Trying to look at arsenic and iron together would be an impossibility.

*Answer:* There are going to be some things that are nearly impossible to model. There are models available that link ground water flow with equilibrium chemistry but you do need the constants. Research has been put together to look at some of the important ones but perhaps not for CCB materials.

### Session VII: Case Studies

1. Engineering Design of the Injection of Alkaline CCB to Abate AMD Paul Petzrick, Maryland  
Department of Natural Resources Power Plant Assessment Division, Annapolis, Maryland

No questions.

2. Fluid Placement of Fixated Scrubber Sludge to Reduce Surface Subsidence and to Abate Acid Mine Drainage in Abandoned Underground Coal Mines R. James Meiers, Indianapolis Power and Light, Indiana

*Engineering Question:* How did you determine how much grout to put in each hole?

*Answer:* We would experience high pressure. While we were injecting in one bore hole, the material would flow out and fill a room, then the pressure would build up as the room filled. The pressure would go up to 300 to 400 psi and then drop off to 0 psi. What had occurred was the grout had now started flowing into another room. We shut down when we were maintaining 500 to 600 psi.

*Regulatory Question:* You stated that you were doing this for subsidence control. Are you conducting monitoring for subsidence for more than 1 year?

*Answer:* Based on the compressive strengths that have been met and the documentation on the amount of void that has been tilled, the contractor has assumed that the subsidence has been eliminated in this area. One hundred psi should be more than adequate strength to reduce subsidence. The ground water monitoring is also over and these are the final results.

*Academic Question:* You stated that the CCB material was produced from an inhibited oxygen cycle. From that, I assume that it was placed as sulfite rather than sulfate. However, most of your ground water monitoring was for sulfate. Did you do any sulfite monitoring?

*Answer:* The leachate testing we did conduct found that the material leached sulfate not sulfite.

3. Use of Stabilized FGD Material for Reclamation of Acidic Mine Lands Shan Mafi, American Electric Power, Columbus, Ohio

*Academic Comment:* Your work has shown that alkalinity plays a major role in controlling the apparent production of acid mine drainage. Considering what we understand about the process that drives pyrite oxidation, just because acid mine drainage is not currently occurring as a result of your treatment, that does not mean that you have turned off the pyrite oxidation mechanism. If you look at the pyrite oxidation processes, you find that at pH 3 oxidation increases because of microbial oxidation and at pH 5 oxidation declines and as the hydroxide increases the pyrite oxidation increases. When the bicarbonate

increases, the oxidation of pyrite doubles. You will not see this in your data because you have 1500 ppm sulfate. That tells me you are dealing with gypsum. What you are observing is the solubility of gypsum going into your water. All of these reactions are surface driven reactions. Eventually you may find, in 10 to 20 years or so, that you will have to treat the area again because all of you alkalinity has been coated with iron oxides. This means that the performance of your system may decline over time.

*Answer:* We are going to continue to monitor the pond as long as it exists because Ohio DNR has plans to continue using FBC materials for reclamation and will receive an impermeable cap within the next year. Our plan was to stop the acid mine drainage as a result of the surface water. I think that by placing a cap with this type of permeability we have been able to do that. What we have not been able to do is stop the acid mine drainage that may result from exposure to ground water. If we stop the recharge from the surface, we expect decreasing levels of oxidation and a lowering of the ground water table with time.

*Engineering Question:* What advantage was gained by adding cement kiln dust?

*Answer:* We added lime kiln dust to increase the strength of the FGD material. If you increased the strength to around 400 psi and exposed it to the elements, then freeze thaw action would not impact it. For the pond liner and the channel we wanted to increase the strength. Lime kiln dust was the most economical option for achieving this strength requirement.

4. Characterizing Ash Composition and (versus) Projecting Environmental Impacts for Purposes of Permitting CCB Disposal: Two Approaches Chuck Norris, Geo/Hydro Inc., Denver, CO

*Industry Question:* Although there are 10 to 15 monitoring wells at the Prides Creek site in the Midwest, looking at your study area in New Mexico you did not install one monitoring well even though there may be perched water tables or intermittent ground water in the area. Concerning your call for responsibility in site characterization, there was no attempt to obtain permeabilities or porosities in the study that you ran. Not even the climatological data was from the site. This seems contradictory to me.

*Answer:* The mine in New Mexico involves the mining of a ridge between two drainages and all of the mining is to occur above the drainages. There had not been any ground water found as a part of all of the exploration drilling on the site. The closest ground water where the company was able to construct a well was 2 to 2.5 miles away. There just isn't any ground water on the ridge in the premining condition that would permit sampling. This is why we conducted leaching of the spoil material in order to establish that any ground water that occurred on the ridge after mining would be similar to the ground water we found a couple of miles away. There was no known premining ground water on the site. The climatological data that was available was used. You don't have 20 to 30 years of weather data in the Raton basin. So you use the closest weather data that is available.

5. Baker Soil Test Development and Field Case Studies Provide Theory and Data Showing that Plants don't Grow in Soils, Dale E. Baker, Land Management Decisions, Inc. State College, Pennsylvania

*Academic Question:* At the beginning of your talk, you pointed out that looks can be deceiving by showing a slide where everything looked well but you stated that there were deficiencies. At the end of your presentation you showed us sites where plants grew well when you amended all of these materials with sludge. But then you didn't show us the nutrient content of the plants growing on these sites.

*Answer:* We have analyzed them and the nutrient content is as it should be.

*Industry Question:* Could you address how the Baker Soil Test is used for heavy metals?

*Answer:* The Baker soil test uses a complexer that mimics soil adsorption properties so that I could characterize it with constants. The chelator diethylamine, triamine, pentaacetic acid (DTPA) was chosen for doing that. This reflects the adsorption properties of the soil.

6. Leachate Quality from Coarse Coal Refuse Mixed with Coal Fly Ash: Effects of Ash Blending Rates  
Dr. Barry R. Stewart, Virginia Tech CSES, Blacksburg, Virginia

**No questions.**

## APPENDIX 3: RESULTS OF WORK GROUPS

The following comments were the products of small work groups of 15 to 20 people based on interest and experience. The discussions reflect the thinking of people in the groups at the time of the forum but may not represent any particular consensus or plan of action.

### **Session I: Coal Combustion By-Product Characterization**

A summary of the discussion of the group was as follows:

The TCLP test probably should not be used to characterize CCB ash materials for disposal on surface coal mines. The synthetic ground water leaching procedure appears to be a better procedure for predicting what will come out of CCB materials under a surface coal mining situation. The critical aspect of that test is that we need to understand the ground water system at the site and be correlated properly to the test. This procedure requires long term (60 day) leaching. It is important that tests be conducted for a long period of time because of the changes these materials undergo.

If the leachate products released by the synthetic ground water leaching procedure exceed the RCRA standards, then that CCB material should probably not be disposed of on surface mines.

If we do use SGLP, it is probably as good as most of the other overburden tests that we use such as acid/base accounting, ammonium bicarbonate, DTPA, and total element analysis in predicting water quality.

### **Session II: Site Characterization**

The main concerns discussed were related to hydrology.

The preconditions for the permit sites should be characterized when the original permit is being prepared. If they are not, any right to dispose of CCB's should be forfeited.

There was a great concern with the long-term effects to the groundwater.  
There was a desire to have the precondition site characterization information made more readily available to the public.

There was an interest about what strata or zones had to be identified in the site characterization.

One of the participants would like to see water tested by specific strata or zones.  
Another felt that the existing water testing method was appropriate.

There was an interest about how long the water quality should be tested.

One of the participants would like the water quality tested for at least nine months throughout three different seasons.  
Six months is the minimum time required for testing water quality.

A possible solution for the concerns is to have interaction between all the different communities involved with the hope of arriving at a resolution.

### **Session III: Regulatory Requirements**

No conclusions were arrived at by the work group. A list of issues that were developed by the work group is as follows:

- The role of SMCRA concerning waste disposal on the mine site.
- Regulatory uncertainty
- Duplicative regulations
- Utility deregulation
- Public participation
- Bonding authority
- Interstate transfer
- Recycling barriers
- Federal regulatory standards for both permitting and performance
- Ground water monitoring and trigger levels for recycling and disposal
- Waste characterization
- Clarify the difference between coal combustion waste (CCW) and coal combustion by-product (CCB)
- Cofueling
- Risk/cost benefit analysis

#### **Session IV: Design/Engineering/Planning**

The discussion was subdivided under four categories: 1) Planning including sampling, site characterization, site planning; 2) designing the utilization project; 3) materials handling; and 4) post placement studies.

##### Planning:

1. Planning must be site specific for the specific CCBs to be utilized or managed.
2. Meaningful leaching tests need to be developed to assess the field leaching potential of the CCBs. The use of TCLP for leaching tests is counterproductive to the beneficial use of CCBs.
3. Sampling protocols based on observed variability and for different management options need to be developed.
4. Develop simple field tests to indicate the variability of CCBs. This work is currently being done at SIUC.

Items number 2 and 3 should be developed within the next couple of years. In order to do item number 3 we need to develop a database on the variability of engineering and environmental characteristics of CCBs. Some work has been done by EPRI. This information should be collected, synthesized, and used to develop the initial sampling protocols.

##### Site Characterization:

The process is very site specific. Controlled performance experiments to account for host geology, geochemistry, and hydrology must be done. The results of the leaching tests are not in agreement with what we are experiencing in the field. We should also be collecting more data on the field environmental impacts on ongoing projects. Develop predictive empirical models that can be used by industry in the near term.

##### Site Planning:

We need to establish the relationships between CCBs placement location and ground water resource location. Should CCBs be placed above or below the water table? This should be a high priority in order to provide a higher level of comfort to the regulatory agencies. We need to study the short and long term hydrologic conductivities of the environments where CCBs are placed. Management of CCBs needs to be an integral part of the process. Interaction between CCBs and the environment need to be considered.

### Design of the uroiect area:

The structural stability issues are the most critical. We need to know how applicable existing technologies are to CCBs management. What are the appropriate tests that need to be conducted. What are the appropriate stability analysis tests? Long term durability studies are very important. Liquefaction potential tests should be used in seismically active areas. The beneficial use of CCBs is at a disadvantage because of the regulated nature of surface coal mines.

### Materials Handling:

Dust control is the most import issue. Occupational health and safety associated with handling the materials. Cost effective back haul transport system. Can we come up with less expensive ways of mixing than pug mills. Identify more efficient compaction equipment. What are more efficient ways for preconditioning FBC by-products?

### Post placement studies:

We need to establish minimum requirements for cover around structural fills and embankments so that vegetation can be established.

What are the mineralogical changes in CCBs when managed in the near surface materials?

What is the trace element take up by vegetation, and can we establish vegetation for the long term?

What are the near term and long term changes in engineering and hydrologic properties of CCBs?

## **Session V: Environment: Land And Water**

The results of this discussion focused on five main issues or concerns as follows:

### Agriculture:

What are the long term effects of repeated applications of CCBs as a soil amendment, especially as it relates to biological accumulators such as selenium?

### Hydrology:

We need better information on the adequacy of monitoring wells and modeling efforts to predict the long term effects to water supply. What is the role of monitoring data to ultimate bond or liability release? What would constitute appropriate mitigation of potential contamination?

### Guidance for surface mining permit review and approval:

What is the best science available for evaluation of CCB disposal or beneficial use at the mine site? Could such guidance be developed to account for most differences related to differing types of CCB materials, climate, hydro geologic environments; and disposal method

### Acidic spoil treatment:

What are the long term effects of: (1) the injection of CCB materials into underground mines, (2) its use as a liming agent for acidic spoil; or (3) its use as a clay cap in connection with acidic spoils?

Communication with the public:

What are the best methods for communicating the results of CCB technical information that would indicate that disposal can be done safely and that beneficial use is to be promoted?

**Session VI: Monitoring And Evaluation**

No two CCB materials are alike and no two CCB disposal sites are alike.

CCB materials suitable for one application may not be suitable for others.

A classification system that would rate application suitability is needed.

Soil properties of the CCB materials need to be evaluated as well as the geochemical properties. This should be compared to a similar evaluation of the native soils at the site.

Reasons for monitoring in the vadose zone are: (1) early detection of problems when these materials are used for impermeable liners or caps for evidence of failure; (2) monitoring the effects of the material on soil water, (3) data collected in the vadose zone can assist in improving existing empirical **models**.

Are we paying enough attention to surface water monitoring?

Where should monitoring wells be located? The needs of researchers are different from that of regulators. Should you use long screens or short screens? Are you trying to determine three dimensional flow and delivery of a particular contaminant at a particular point in your flow system? Are you just trying to gather contaminant information in general?

How far should monitoring wells be located from disposal sites? This information currently exists. You can use the literature values for the material properties of the soils and regional data on ground water gradients. This should give you a reasonably good estimate of how far monitoring wells need to be located in order to detect contamination in a reasonable time or prior to bond release.

How long do you need monitoring?

If you are monitoring, how do you determine that contamination has occurred? We need to get involved with newer US EPA statistics for evaluating down gradient contamination.

We need to do post audits of monitoring sites where models have been used to verify model results in the field.

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