Coolside Waste Management Research

Project No. DE-AC21-MC91MC28162

Quarterly Technical Progress Report

April 1, 1993 to June 30, 1993

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Resource Applications and Waste Management

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for

COOLSIDE WASTE MANAGEMENT RESEARCH

Technical Progress Report

Contract No: DE-AC21-91-MC8162

Report Period: April 1, 1993 to April 30, 1993

Statement of Project Objectives

Produce sufficient information on the physical and chemical nature of Coolside waste to design and construct physically stable and environmentally safe landfills.

Summary of Progress for Period

A study focused on the formation mechanism of ettringite crystals in FGD - waste materials is reported. Ettringite crystals form in Coolside, FBC, and AFBC derived wastes. The degree of swelling in FGD-derived waste can be correlated to the amounts of ettringite crystals present. It was observed that ettringite forms on mineral surfaces and inside pore space. Under a confining pressure ettringite formed only within the available pore space. At higher packing densities of the FGD materials less ettringite was observed to form. Monitoring of swell continued on Coolside and FBC hydrated ash remolded in CBR molds under a variety of conditions.

Subtask 2.2 Chemical Characterization of the Waste

Characterization of Mineralogical Reactions That Cause Swelling of FGD Waste Mixtures

Project Objective - Produce sufficient information on the mineralogy and mineralogical transformations of dry FGD by-products and the formation mechanism of the mineral ettringite to predict swelling characteristics of FGD-derived materials.

Introduction

Reactions controlling the formation, composition and disintegration of ettringite are critical in determining the overall stability and strength of cements and concretes derived from dry-flue gas desulfurization wastes. These wastes typically consist primarily of fly ash, along with, CaSO_3 , and CaSO_4 and unreacted $\text{Ca}(\text{OH})_2$. The sulfites and sulfates in these materials react with the portlandite ($\text{Ca}(\text{OH})_2$) along with the glassy aluminosilicate portion of the fly ash to form calcium sulfo-aluminate minerals. Ettringite, the most important of these, is the main contributor to the compressive strength development of the FGD waste mixtures. Excessive ettringite formation causes first lateral and horizontal swelling of the concrete which often leads to destructive crack formation. It has been shown that the quantity of ettringite formed and compressive strength of the FGD waste mixtures reach a maximum until ettringite begins to disintegrate. Because the formation mechanisms of ettringite are not entirely understood, swelling in FGD derived products is difficult to predict.

This study focused on the formation and disintegration mechanism of ettringite in FGD waste mixtures with varying contents of aluminum (hydr)oxides, and calcium (hydr)oxides of the starting materials. Mineralogical transformations were documented in X-ray diffraction and scanning electron microscope (SEM) observations of the materials.

Experimental Approach

To determine the cause of swelling in FGD waste mixtures, X-ray diffraction analyses were performed on Coolside, FBC (received from Wormser Development Company), and AFBC (received from an oil company) materials before and after swelling as monitored by the Kentucky Transportation Center.

Dry flue gas desulfurization wastes typically swell at a given time. This swelling indicates that mineralogical reactions may have occurred, thereby causing the expansion of the FGD derived materials. The utilization of FGD waste materials in

engineering applications can only be successful if the amount and, ultimately the rate of the swelling can be accurately predicted. Research into the swelling characteristics of by-products from coal fired power plants was documented in previous technical progress reports (see January 93 report and February 93 report). In this study X-ray diffraction work was performed on precisely the same materials that were earlier analyzed for: (1) total amount of swelling and; (2) rate of swelling.

Sample Materials:

Coolside:

Coolside Run #2 (ash as received)

Coolside Run #2 / 12.57 lb surcharge / 99 Days

Coolside Run #2 / 2.5 lb surcharge / 100 Days

Pilot Plant 1 in Laboratory Column 19

Pilot Plant 2 in Laboratory Column 20

Pilot Plant 3 in Laboratory Column 21

Coolside 1000 in Laboratory Column 9 / High Density: 69 lb/f³ / 36 % Moisture

Coolside 1000 in Laboratory Column 10 / Medium Density: 65 lb/f³ / 45 % Moisture

Coolside 1000 in Laboratory Column 11 / Low Density: 49 lb/f³ / 41 % Moisture

FBC:

FBC (ash as received)

FBC Non-hydrated #1; #2; #3; #4

FBC Hydrated

FBC Pellets

AFBC

AFBC (ash as received)

AFBC ash (7 %) mixed with soil: Field experimental site #2

AFBC ash (7 %) mixed with soil: Field experimental site #18

Experimental Methods

X-ray diffraction (XRD) patterns of the samples were obtained from randomly-oriented powder mounts using CuK α radiation. Diffraction patterns were recorded from 6 to 60 2θ with step interval of $0.2^\circ 2\theta$ and a counting time of 6 seconds per step.

Scanning electron microscopic (SEM) examination of the FGD derived mixtures, using a Hitachi S-2700 (magnification up to $\times 10^4$), allowed a comparison of the morphological features.

XRD - Analyses

Table 1 lists the mineral phases observed in the FGD waste materials.

Table 1 Mineralogical Composition in FGD Waste Mixtures

	P	C	A	Q	G	M	Cl	E	MO
Coolside #2	x	x	x	x	x			< X	
Coolside #2 12.57 lb surcharge/ 99 days		x	x	x			x		X
Coolside #2 2.5 lb surcharge / 100 days		x	x	x			x		X
Pilot Plant 1 (Column Lysimeter 19)		x	x	x	x	x			X
Pilot Plant 2 (Column Lysimeter 20)		x	x	x	x	x			X
Pilot Plant 3 (Column Lysimeter 21)		x	x	x	x	x			X
Coolside 1000 (Column Lysimeter 9)		x	x	x	x	x			X
Coolside 1000 (Column Lysimeter 10)		x	x	x	x	x			X
Coolside 1000 (Column Lysimeter 11)		x	x	x	x	x			X
FBD ash as received	x		x	x	x	x		< X	
FBC Non-hydrated #1	x	x	x			x		X	
FBC Non-hydrated #2	x	x	x			x		X	
FBC Non-hydrated #3	x	x	x			x		X	
FBC Non-hydrated #4	x	x	x			x		X	
FBC Pellets	x	x	x			x		< X	
AFBC Ash as received	x	x	x	x					x
AFBC Ash + Soil in Field Site #2		x	x	x	x	x		x	X
AFBC Ash + Soil in Field Site #18		x	x	x	x	x		x	X

P = portlandite; C = Calcium Carbonate; A = anhydrite; Q = quartz; G = gypsum; M = mullite; Cl = clay;

E = ettringite; MO = magnesium oxide

x = occurrence <x = very minor occurrence

Ettringite

Leaching of a mixture of fly ash and calcium-based scrubber waste results in the formation of an ettringite structure phase. Scrubber ash adds sulfate and calcium to a high-pH, high-Na, high-Al solution which results from fly ash - water reactions. This combination is apparently ideal for ettringite formation.

Ettringite is a calcium aluminum hydroxy-hydrate mineral. It is both an individual mineral with the formula $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$ and the group name for a series of chemically analogous isostructural compounds. The ettringite structure is shown in Figure 1.

Previous studies indicate that ettringite formation could be enhanced through the addition of the proper amounts of aluminum and/or sulfate. For example, sulfate is thought of as the limiting factor in ash derived from low ash sulfur coals.

Coolside Material

XRD analyses of Coolside # 2 (ash as received) indicates that no ettringite occurs in the raw mixture (Figure 2a). Portlandite ($\text{Ca}(\text{OH})_2$), calcium carbonate (CaCO_3), anhydrite (CaSO_4), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$), and quartz (SiO_2) are the main ingredients observed. After 100 days and 2.5 lb surcharge, massive amounts of ettringite formed in the sample (Figure 2c). At 12.57 lb surcharge after 99 days, ettringite formed in the Coolside #2, but the amount was less than in the sample that was exposed to lower surcharge (Figure 2b) for approximately the same amount of time. The sample that had more ettringite also showed greater swell characteristics. In both aged samples, ettringite crystals appear to have formed on mineral surfaces as well as in the available pore space. In case of the higher surcharge, more ettringite formed in interstitial parts. These findings may indicate that the formation mechanism of ettringite (formation either occurs on mineral

surfaces or in pore space) could be controlled by the amount of pressure exerted on the FGD waste sample.

Coolside #2 sample was further sub-divided into four samples (by KTC) which were tested for their swell characteristics as a function of time. Investigations included: (i) varying surcharge and, (ii) aged or non-aged samples (Table 2). The swell characteristics of the Coolside #2 material are illustrated in Figure 3 a-d.

TABLE 2

<u>Coolside #2 **</u>		
<u>NO AGE TIME</u>	#2-1 1.09 kg surcharge	CaO + Ca(OH) ₂ present
	#2-2 5.60 kg surcharge	
<hr/>		
<u>7 DAYS AGE TIME</u>	#2-3 1.19 kg surcharge	Ca(OH) ₂ present
	#2-4 5.70 kg surcharge	

** Mineralogical Composition of Coolside #2 is given in Table 1

In this study, XRD-analyses were prepared for the four Coolside #2 samples before surcharge was applied. The aged samples were observed to have much more portlandite (Ca(OH)₂) present, while the non-aged samples have some lime (CaO) present.

The four Coolside #2 samples are still swelling. As soon as the swelling stops, samples will be X-rayed and investigated using SEM applications to determine how much and where ettringite crystals formed.

Figure 4 compares three XRD patterns for the Coolside 1000 samples packed with high density (69 lb/f^3), medium density (65 lb/f^3), and low density (49 lb/f^3) in column lysimeters 9, 10 and 11, respectively. The results clearly demonstrate that the Coolside 1000 sample with the highest packed density has the smallest amount of ettringite present.

Pilot Plant samples # 1, #2, and #3 located in laboratory column lysimeters 19, 20, and 21, respectively, were separated from the columns, dried, and prepared for XRD-analyses (Figure 5). Representative samples were taken from the top, middle and bottom of the columns for comparative purposes. The semi-quantitative XRD analyses of the samples indicate that the largest amount of ettringite crystals formed in the Pilot Plant sample #3 (Figure 5c), which was characterized by the lowest packed density (49 lb/f^3) of the three samples under investigation.

Figure 6 compares the XRD patterns for the Pilot Plant sample #2 that were taken from the top, middle, and bottom from column lysimeter 20. The results indicate that ettringite crystals appear to be highly concentrated in the middle zone of the column lysimeter, while the top and bottom samples have less ettringite crystals. Samples taken from the top and bottom of the lysimeter have approximately the same amounts of ettringite present. It is not clear at this time what caused the enrichment in ettringite crystals in the middle zone of the column lysimeter, however, it is speculated at this time that leaching from top, and availability of water may have caused this enrichment pattern.

The results observed for the Coolside 1000 sample and Pilot Plant sample from column lysimeters indicate that FGD waste samples exposed to high packing density, or exposed to higher surcharge, always result in less ettringite formation than those with low packing densities.

FBC Samples

XRD analyses of the FBC residue (as received) indicate the presence of portlandite, anhydrite, gypsum, quartz, and a negligible amount of ettringite (Figure 7).

Figure 8 compares the XRD pattern for the non-hydrated FBC ash with that of the hydrated FBC ash. The non-hydrated sample contains large amounts of calcium oxide (CaO), while in the hydrated sample portlandite (Ca(OH)_2) dominates. During hydration, the majority of anhydrite was converted to gypsum (Figure 8). The hydration process furthermore resulted in the formation of ettringite crystals (Figure 8b), which are shown in the SEM image of Figure 9.

Pellets were produced from the FBC ash (by CONSOL). XRD analyses of the pellets are shown in Figure 10, indicating that the pellets are very similar in their mineral composition compared to the hydrated FBC ash. The amount of ettringite crystals present in the pellets was very minor.

Small amounts of hemi-hydrate ($\text{CaSO}_4 \cdot 0.5 \text{H}_2\text{O}$) were present in the pellets which was determined in XRD analyses of powder samples prepared from the "raw" pellets (Figure 11). After the pellets were submerged in water (with a standing water pressure of 50 -70 pounds), large amounts of hemi-hydrate crystals formed particularly at the surfaces of the pellets (Figure 11). The hemi-hydrate crystals occur as white, needle shaped crystals which are often large enough to be recognized on the pellet surfaces. The hemi-hydrate crystals were separated from the pellet surface and the XRD pattern of these crystals is indicated in Figure 11c. SEM observation of the hemi-hydrate (bassanite) showed that almost all crystals are characterized by abundant crack formation at the crystal surfaces (Figure 12). Portlandite was also observed on the crystal surfaces (Figure 13).

The growth of hemi-hydrate crystals must have affected the strength of the pellets. This is based on SEM observations of a polished surface prepared from a hydrated pellet after dissecting the pellet in half. SEM observations indicate the presence of numerous cracks throughout the pellet interior (Figure 14 and 15) which are most likely responsible for the low strength of the pellets. The number of cracks and size of cracks increased immensely after the samples were submitted to the soundness test.

After these results were discussed with Dr. Milton Wu from CONSOL, who prepared pellets

at lower curing temperatures to avoid the formation of hemi-hydrate crystals. CONSOL reported that pellets formed at lower curing temperatures after addition of ~ 10 weight percent silica dust passed the soundness test. XRD observations of this type of pellets indicate the absence of hemi-hydrate crystals. Furthermore, SEM investigations of the same samples showed much less crack development in the samples.

AFBC Material

Results of ettringite formation in soil mixtures obtained from field experiments using AFBC ash are compared in this report to ettringite in Coolside samples and FBC samples to help investigating the formation mechanism of the ettringite crystals. The AFBC ash was supplied by Ashland Oil. The ash sample was mixed with soil (7 wt % AFBC ash) and placed above untreated subgrade in experimental sections (tested by the Kentucky Transportation Center for road base purposes). The mineral phases in the ash were identified and are summarized in Table 1. Ettringite was not present in the ash (Figure 16). After approximately six years, core samples were taken from the field experimental site #2 and site #18. XRD analyses of the soil-ash mixture are shown in Figure 17, indicating that ettringite crystals had formed at site #2 (Figure 17a) and site #18 (Figure 17b). The soil-ash mixture was then observed in the SEM (Figure 18, 19) to identify the spatial relationship between ettringite crystals and mineral phases present in the soil. Ettringite crystals appear to form both on mineral surfaces and inside available pore space. These results are very similar to those observed for ettringite formation in Coolside column lysimeters described earlier.

The addition of water to AFBC ash resulted in the formation of large white crystals which were identified as calcium carbonate and typically resulted in the formation of a thin calcium carbonate crust on top of the ash - water mixture. Although the results of the XRD analyses of this crusty material indicated the presence of only calcite (CaCO_3), SEM observations suggest that based on the crystal morphology aragonite (CaCO_3 polymorph of calcite) crystallized first and was transformed into the calcite structure. The formation of a calcium carbonate-enriched crust was also observed when water was added to FBC residue.

Subtask 2.3 Geotechnical Characterization of the Waste

Swell Tests

Monitoring of swell continued on the following samples: Coolside pilot plant run #2 and on a FBC hydrated ash remolded near 95% of standard maximum dry density and optimum moisture content. The samples were remolded in CBR molds (6 inch diameter, 4.584 " height) and swell was monitored under the following conditions:

approximately 12.5 lb. surcharge, no age time

approximately 2.5 lb. surcharge, no age time

approximately 12.5 lb. surcharge, 7 days age time

approximately 2.5 lb. surcharge, 7 days age time

Time of aging represents the amount of time before the samples were placed in water. Aged specimens were sealed at room temperature to prevent moisture loss before placement into the water tank.

Swell tests were also initiated on non-hydrated FBC specimens remolded near 95% of standard density and optimum water content in CBR molds. Swell is being monitored with aging and surcharge conditions similar to those of hydrated FBC ash and Coolside #2. Results, to date, of swell tests are presented in Figures 21 -23.

CBR Tests

CBR tests were performed on three Coolside #2 samples which were subjected to long-term swell. Results from these tests, performed on samples in which swell had ceased, are located in Table 3.

Table 3. Results from CBR Tests, Coolside Run # 2.

Age Time (Days)	Surcharge Weight (Pounds)	Soaking Time (Days)	CBR
0	12.42	115	36.3
7	2.50	100	50.0
7	12.57	99	143.8

Work planned for next month

Monitoring of swell will continue on FBC ash and Coolside run #2 samples. Testing will be continued on synthetic FBC ash aggregate for possible use in a bituminous concrete application.

Figure 5 Comparison of XRD patterns of (a) Pilot Plant #1 from column lysimeter 19; (b) Pilot Plant #2 from column lysimeter 20 and; (c) Pilot Plant #3 from column lysimeter 21. All XRD patterns show two major ettringite peaks. The largest amount of ettringite was observed in column lysimeter 21, which was characterized by the lowest packing density.

Figure 6 Comparison of XRD pattern of Pilot Plant #2 samples from column lysimeter 20 (a) Top Zone, (b) Middle Zone and, (c) Bottom Zone. Ettringite crystals appear to be enriched in all zones however, the middle zone has the highest ettringite concentration.

Figure 7 XRD Pattern

FBC Ash Non-Hydrated

FBC Ash Hydrated

Figure 8 XRD Pattern of (a) non-hydrated FBC ash. No ettringite crystals are observed (b) hydrated FBC ash with ettringite crystals present

Figure 9

SEM microphotograph illustrating FBC ash after addition of water. Needle shaped ettringite crystals grow on mineral surfaces. The FBC ash was not compacted and ettringite crystals were able to grow without tension from neighboring mineral phases. Ettringite crystals appear to grow in a randomly oriented fashion, forming a complex network of intergrowing crystals. The largest ettringite needles in this FBC sample are approximately 15 microns long.

Figure 10 XRD Pattern of

Figure 11 Comparison of XRD pattern of (a) FBC pellets before hydration, (b) FBC pellets after hydration for 14 days (50-60 pounds water pressure). Minor amounts of hemi-hydrate (bassanite) formed inside hydrated FBC pellets. (c) XRD pattern of hemi-hydrate crystals that were concentrated at hydrated FBC pellet surfaces.

Figure 12

SEM microphotograph of hemi-hydrate (bassanite) crystals. The hemi-hydrate crystals grow on the surfaces of the FBC-pellets after the pellets were submerged for 14 days in water (with 50-60 pounds of water pressure). Crystals of various sizes are observed. Most hemi-hydrate crystals are characterized by abundant cracks which occur on the mineral surface.

Figure 13

SEM microphotograph of a single hemi-hydrate (bassanite) crystal. The crystal surface shows multiple fractures and cracks. At some areas along the hemi-hydrate crystal surface portlandite (Ca(OH)_2) crystals occur in small agglomerations.

Figure 14

SEM microphotograph of FBC pellet interior. The sample consists of a multitude of micron-sized mineral agglomerations of portlandite and anhydrite. The agglomerations are typically surrounded by a thin precipitation layer consisting of calcium carbonate (in the SEM photo represented by a white rim around granular mineral agglomerations). At 70 times magnification large cracks are recognized throughout the pellet interior.

Figure 15

450 times magnification of FBC pellet interior. The SEM image illustrates the presence of small cracks that typically surround mineral agglomerations

Figure 16

AFBC Ash (as received)

NO SMOOTHING

Figure 17 XRD pattern of AFBC ash - soil mixtures (a) AFBC ash (7 wt%) mixed in soil at experimental field site #2 (b) AFBC ash (7 wt%) mixed in soil at experimental field site #18. XRD pattern indicate that ettringite crystals formed at both field sites.

Figure 18

SEM microphotograph of soil - AFBCash mixture from field experimental site #2. Needle like ettringite crystals occur intergrown with the clay minerals and sand. The box in the left side photo includes the ettringite crystals which are enlarged at the right side photo. Ettringite crystals appear to grow inside pores and on mineral surfaces

Figure 19

SEM microphotograph of ettringite crystals that grow on mineral surfaces in soil - AFBC ash mixtures from experimental field site #2

Figure 20

White Crystal Agglomerations Separated from Soil - Ash Mixture

Figure 21 Swell Versus Time, Coolside Run #2 CBR Samples.

Figure 22 Swell Versus Time, FBC Ash CBR Samples.

Figure 23 Swell Versus Time, FBC Ash (Non-Hydrated) CBR Samples.

COOLSIDE WASTE MANAGEMENT RESEARCH

Technical Progress Report

Contract No: DE-AC21-91-MC8162

Report Period: May 1, 1993 to May 31, 1993

Statement of Project Objectives

Produce sufficient information on the physical and chemical nature of Coolside waste to design and construct physically stable and environmentally safe landfills.

Summary of Progress for Period

All samples collected from the Coolside desulfurization process including the Edgewater demonstration runs and the CONSOL pilot test runs are summarized and tabulated in this report. An attempt to interpret these results is also made. A master list of samples collected from the Coolside Edgewater plant demonstration runs and the CONSOL pilot plant test runs was prepared. An operating log from the Edgewater Coolside Process Demonstration Topical Report was summarized for the Coolside demonstration runs.

Analysis of the Coolside solid waste materials was completed. Samples were characterized for their major, minor and trace element concentrations by several analytical methods. The concentrations of major and minor elements of 264 individual barrels obtained from the Coolside Edgewater Plant demonstration runs were determined. Large variations in most of the elements were observed which indicate that the Coolside waste is very heterogenous although the wastes were quite homogeneous within the same barrel. The concentration ranges between two layers of samples were all within one sigma of the average value.

From the operating logs, mechanical problems were found to affect the elemental concentrations of the Coolside materials. The concentration of Na varied with the NaOH feed rate. Na dropped when the pump quit but increased again when the pump was back in service. A similar trend for Ca and Fe was observed. As the pump rate of hydrated lime dropped, the concentration of Ca in the sample decreased.

Also, when the solids recycle line plugged, the ash content, i.e. concentrations of Fe and Al in the Coolside samples, dropped. Mechanical problems also affected the SO₂ capture efficiency. As the concentration of promoter and hydrated lime increased in the duct, an increase in the SO₂ capture efficiency was reflected in the sulfur content of the samples. Analysis for carbon, hydrogen and nitrogen concentrations indicated a wide range of carbon content in these materials.

A wide range of concentration values were observed for most of the minor and trace elements. The elemental concentrations of hydrated limes showed there were no significant amount of trace elements present in the hydrated lime except some fluorine and strontium. Positive correlations were observed between the concentrations of Ca and F, and Ca and Sr. There was also a strong positive correlation between both Na and Ca with halogens (Br and F) which is related to capture of the corresponding hydrogen halides. Monitoring of swell continued on Coolside and FBC hydrated ash remolded in CBR molds under a variety of conditions.

Task 2 - Chemical and Geotechnical Characterization

Subtask 2.1 - Sample Collection

In order to avoid any confusion and duplication of analysis that we had performed up to date, we prepared a master list of all samples collected from the Coolside Edgewater plant demonstration runs and the CONSOL pilot plant test runs. [Appendices A & B] This list described the Coolside operation conditions (Ca/S ratio, Na/Ca ratio, and mode of process), sampling dates, sample numbering system, and sources of hydrated lime, coal and fly ash used during each run of Coolside desulfurization process. We also summarized the operating log from the Edgewater Coolside Process Demonstration Topical Report¹ for the Coolside demonstration runs [Appendix C]. This log provided a detailed description of the equipment operations and operating problems encountered during the runs which helped us to interpret some of the results obtained from the Coolside waste samples.

Subtask 2.2 - Chemical and Mineralogic Analysis of the Materials

The analysis of the Coolside solid waste materials had been completed and tabulated. The Coolside samples were characterized for their major, minor and trace element concentrations by several analytical methods which included proton-induced gamma-ray and X-ray emission analysis (PIGE/PIXE), X-ray fluorescence, direct current plasma/inductively coupled plasma atomic emission, and cold vapor atomic absorption techniques. Sulfur, carbon, hydrogen and nitrogen were determined by the ASTM methods. Selected samples were analyzed for mineralogical composition by X-ray diffraction and scanning electron microscope. The sampling protocols for each analytical technique used have been described in previous technical reports and an annual report.

The concentrations of major and minor elements of individual barrel obtained from the Coolside Edgewater Plant demonstration runs are given in Table I. A total of 264 samples from the Demonstration Runs 1, 2 and 3 were analyzed by PIGE and PIXE. The typical detection limit of the Coolside waste samples obtained by PIGE and PIXE is given in Table II. For trace elements, the detection limits are in tens of ppm. Since a critical absorber (10 μm thick Cr foil) and a 356 μm thick mylar film were used to reduce iron X-rays signal and bremsstrahlung, respectively, the detection limits for elements like iron, potassium, and calcium are in hundreds of ppm range. The overall average concentrations of major, minor and trace elements in these samples from each run and all runs are given in Table III. The data from different runs are compared by showing the histograms of individual element from each run. [Figure 1] From Figure 1, we observe large variations in most of the elements which indicate that, as one would expect, the Coolside waste is a very heterogenous material. For this reason, it is important to investigate the composition of a large number of samples in order to obtain a reasonable estimate of the elemental composition of the composite waste in the field and laboratory lysimeters.

The results of PIGE/PIXE sample preparation procedures are given in Table IV. The results showed the sample and graphite mixture was very uniform in a given mixing process. The standard deviations were less than 5% for most of the elements. The homogeneity of samples within the same sample vial and within the sample barrel

(Barrel # 42) is given in Tables V-a and V-b. We found the Coolside wastes were quite homogeneous within the same barrel, but larger variations existed within the same vial. We observed there was not much difference between Layer # 1 (42-1x) and Layer # 2 (42-2x) samples (Table V-a). The concentration ranges between two layers of samples were all within one sigma of the average value. For this reason, we only analyzed one sample from each barrel. Although this did not necessarily represent the average elemental concentrations of each barrel, a total of 264 barrels of Coolside solid waste material was analyzed.

In previous reports, we had indicated that the elemental concentrations of the Coolside materials varied with time. This was based on the assumption that the representative barrel numbers corresponded to the time of operations. An effort was made to correlate the operation conditions and the elemental concentrations to see if the wide ranges in concentration values were due to statistical analysis, or due to the variations in feedstock, or the difference in the capture efficiencies of the elements had a role. We summarized the operation conditions and the daily operating logs from the Edgewater Coolside Process Demonstration Topical Report¹ [Appendices A & C]. This information provided a detailed description of the equipment operations and operating problems encountered during the demonstration runs which helped us to explain the variations observed in the Coolside materials.

The concentration of the major elements (e.g. Na, Ca, Fe, and S) of 264 Coolside waste samples from Runs 1 to 3 are plotted against the barrel number (# 28 to 434) in Figures 2 to 5. The mechanical problems encountered during the Coolside operations are also labelled along the time axis (barrel number). From the operating logs, we found that, some mechanical problems such as keeping up the pump pressure for deliveries of sodium hydroxide, hydrated lime, and recycled solid occurred during the demonstration runs. Sometimes the recycled solids delivery pipes were plugged due to chunks of fused ash clinker materials. All of these mechanical problems did result in affecting the elemental concentrations of the Coolside materials. In Figure 2, the concentration of Na in the Coolside materials clearly varied with the pump pressure of the NaOH pump. When the NaOH pump lost its pressure, we

observed a clear drop in sodium concentration (at the end of Run 1 and during the Run 2). When the NaOH pump was back in service, the concentration of Na increased (at the beginning of Run 3). We noticed a similar trend for Ca and Fe in Figures 3 and 4, where the concentrations of Ca and Fe varied greatly with the barrel number. As the pump pressure of hydrated lime dropped, the concentration of Ca in the sample also decreased. When the recycled solid pipes were plugged, the ash content, i.e. concentrations of Fe and Al in the Coolside samples dropped.

These mechanical problems also affected the SO₂ capture efficiency. We observed the concentration of S varied greatly with time. The average concentration of sulfur in the Coolside samples was 1.87 ± 0.35 % which ranged from 1.10 % to 2.72 %. The variations in Na, Ca and S concentrations showed a similar trend during Run 1 (Barrel # 28- 176). There was no surprise, when the amount of promoter and hydrated lime increased in the duct work, the SO₂ capture efficiency also increased. This was reflected in the sulfur content of these samples. In the sulfur plot (Figure 5), a zig-zag pattern of S concentration in the samples were observed for Run 3. Although the NaOH pump pressure was kept fairly constant during this period of time, there were some mechanical problems encountered in maintaining flow from the hydrated lime and recycled solid feeding pumps. In Ca plot (Figure 3), a similar trend was also observed. However an inverse trend was observed for Ca and Fe in the samples from Run 3.

We analyzed a total of 25 samples from the Coolside demonstration runs for carbon, hydrogen and nitrogen concentrations by the ASTM methods. A wide range of carbon content in these materials was observed. The Coolside samples has an average carbon content of 8.54 ± 1.43 %, which lies within a range of 6.12 % to 11.98 %. The difference in carbon content was also observed by looking at the color of samples. The colors of the samples were range from light grey to greyish black. One of the possible explanations for this variation is the incomplete coal combustion due to the temperature change in the boiler. Another possible explanation might simply be the dilution effect. We had observed a similar effect for Fe or Al with calcium earlier. If more hydrated lime was injected into the duct work, the percent

of carbon in the waste would decrease. We can rule out the possible difference in samples which were collected from different ESP units, and only ESP # 2 was in service during the runs.

Therefore we can conclude that, the concentrations of major elements in the Coolside samples varied with time. It is clear that, these variations were mainly due to the mechanical problems (i.e. feedstock variations), and were not due to the chemistry of Coolside process with the exception of sulfur.

The results of the PIXE/PIGE analysis of 264 Coolside waste samples from Runs 1, 2 and 3 (Barrels # 28 to 434) are given in Table III. A wide range of concentration values were observed for most of the minor and trace elements. Due to lack of information on the original feedstock (e.g. coal, recycled solid, and sodium hydroxide solution), it is very difficult to do a mass balance of elements in the feedstock and the waste materials. To overcome this problem, we did interelemental correlations, and tried to interpret the results and hypothesize the possible chemistry of the Coolside process. Before attempting to interpret this data, we obtained some information on the feedstock materials for the Coolside Process from the Edgewater Coolside Process Demonstration Topical Report¹. It provided information regarding the concentrations of major elements only in the feed coal, hydrated lime, ESP hopper ash, recycled solids, and turning vane deposit samples. This information was not very useful in term of interpreting the trace element data obtained from the Coolside waste samples. Table VI gives the major elemental concentrations of feed coal, hydrated lime, ESP hopper ash, recycled solids, and turning vane deposit samples. By comparing these data with the average concentrations of the Coolside waste (Table I), we found the Coolside waste, ESP hopper ash, and recycled solids all had a very similar composition. The concentrations of Na, Ca, Fe, and Al are almost the same. The concentrations of Na and Ca these recycled solids and Coolside samples were much higher than the feed coal.

Table VII gives the elemental concentrations of hydrated limes used in the Edgewater Coolside demonstration runs and the CONSOL pilot test runs. Black River Hydrated Lime was used during the Edgewater Coolside demonstration runs and the

CONSOL pilot test runs 1, 2 and 4. Mississippi hydrated lime was used during the Advanced Coolside Process (pilot test run 3). Clearly, there were no significant amount of trace elements present in the hydrated lime except some fluorine and strontium. We observed positive correlations between the concentrations of Ca and F, and Ca and Sr.

Table VIII gives the Pearson's correlation coefficients of element pairs whose concentrations clearly varied with time during the Edgewater Coolside demonstration runs. The Pearson's correlation coefficient is a measure of the closeness of relationship (linear) between two variables. It is defined as

$$\text{Pearson's Correlation: } r = \Sigma XY / (NS_x S_y)$$

where X and Y are the values of variables X and Y

N is the number of samples

S_x and S_y are the standard deviations of X and Y

Table VIII shows some examples of elemental pairs which were significantly correlated at 99% confidence interval (p-value < 0.01). A positive correlation coefficient means that, as concentration of one element increases, the concentration of the other element also increases too. This type of positive relationship was observed for elemental pairs like Na-S, Na-Br, Na-F, Ca-S, Ca-F, Ca-Sr, and Al-Fe. Negative correlations were observed for elemental pairs Ca-Fe, Fe-S, and Fe-Sr. We had mentioned earlier, the dilution effect of hydrated lime (i.e. Ca and Sr) clearly affected the ash content, i.e. Fe, Al in the Coolside samples. Another way to examine the relationships between different elements by doing is to plot scatter plots. Figures 6 to 8 are the scatter plots of some elemental pairs. We can clearly observed the "source" contribution effect of elemental pairs, e.g. Al-Fe and Ca-Sr in Figure 6.

One of the interesting observations of our study is that we observed strong positive correlations between both Na and Ca with halogens (Br and F) (Figure 7). We believe that, chlorine is also strongly correlated with Na and Ca in the Coolside solid waste samples. At the present time, our PIGE/PIXE system is not designed to

determine chlorine directly. An improvement on the system design will enable us to determine elements from Na to Cl directly by PIXE analysis. We obtained the chlorine information from the leaching data which was acquired from the field lysimeters and laboratory column experiments. The data showed high levels of chloride and bromide were leached out from the Coolside waste samples. It was reasonable to conclude that the Coolside waste samples also contained high levels of Cl though we did not analyze for its concentrations in the solid samples. When we compare the elemental concentrations of Coolside solid waste (Table IV) with the average Appalachian fly ash samples (Table IX), high levels of As, Br, F, Ca, Na, Zn and Pb (possibly S, Cl) were observed in the Coolside samples. In a normal coal combustion process without any scrubbing system, the extremely volatile elements like F, Cl, Br and Hg are usually present in the gas phase. The concentrations of these elements are extremely low in the normal fly ash samples. When the halogens are released from the coal, they are likely to form acids, e.g. HF, HCl, and HBr. During the Coolside desulfurization process, we added alkaline reactants, i.e. NaOH and $\text{Ca}(\text{OH})_2$ into the flue gas stream. Acid-base reactions were occurring during the Coolside process, where HF, HCl, HBr and possibly H_2SO_4 reacted with bases and formed salts. We conclude that, the Coolside process not only captures SO_2 in the flue gas stream and also capture the volatile elements like halogens (i.e. F, Cl and Br).

There were high levels of As, Zn and Pb found in the Coolside solid waste when we compared it to the average Appalachian fly ash samples. We do not know the source of these elements and do not have an explanation for the high levels of these elements without gathering more information on the feed coal. Table X gives the average and range of elemental concentrations in Appalachian coal and U.S. bituminous coal found in the literature. The concentrations of trace elements in coal are greatly depended on the source of coal. Currently we are trying to obtain more information on the types and sources of coals used during the Edgewater demonstration runs. Figure 8 and Table VIII show a strong positive correlation among highly volatile elements like As, Zn, Se, and Pb. The concentrations of these elements in the Coolside samples were high compared to the average fly ash samples. A

further review of the literature might be able to give a better understanding of the possible role of Coolside process in enhanced the capture of these volatile elements.

One of the ways to understand the chemistry of the Coolside materials is to calculate the enrichment factors of the elements with respect to the parent materials (feedstock). Since we do not have any trace element information on the parent coal, we chose to compare the Coolside materials with respect to the crustal abundance. The enrichment of element X relative to average crustal material is given as:

$$EF_{crustal} = \frac{[X]_{ash}/[A]_{ash}}{[X]_{crustal}/[A]_{crustal}}$$

where EF = Enrichment factor

[X] = Concentration of element X in ash or crustal material

The enrichment factors of elements in the Coolside materials with respect to the crustal abundance are given in Table XI. These are also compared to the enrichment factors of elements in the average Appalachian fly ash samples. From Table XI, we observed both Coolside waste and Appalachian fly ash samples had extremely large EF's for As and Se, where Mn was depleted compared to the crustal abundance in both samples. The Coolside materials also had much higher EF's for As, Br, Zn, and Pb.

The results of the Coolside samples obtained from the CONSOL pilot test runs are given in Table XII. The elemental concentrations of the parent fly ash materials (Avon Lake fly ash) used in the test runs, and the control fly ash (Trans Ash) and Ottawa sand used in field lysimeters are given in Table XIII. Some of the LIMB waste samples results are given in Table XIV. Next month we will try to interpret some of these pilot test run results.

Subtask 2.3 Geotechnical Characterization of the Waste

Swell Tests

Monitoring of swell continued on the following samples: Coolside pilot plant run #2,

FBC ash (hydrated and nonhydrated). All samples were remolded near 95% of standard maximum dry density and optimum moisture content. The samples were remolded in CBR molds (6 inch diameter, 4.584 " height) and swell was monitored under the following conditions:

approximately 12.5 lb. surcharge, no age time

approximately 2.5 lb. surcharge, no age time

approximately 12.5 lb. surcharge, 7 days age time

approximately 2.5 lb. surcharge, 7 days age time

Time of aging represents the amount of time before the samples were placed in water. Aged specimens were sealed at room temperature to prevent moisture loss before placement into the water tank.

Swell tests were also initiated on two samples of FBC pellets. The pellets were loosely placed in CBR molds. Surcharge weights (2.5 and 12.5 pounds) were placed on the samples prior to saturating in water. Results, to date, of swell tests are presented in Figures 9 through 12.

Unconfined Compressive Strength

Unconfined compressive strength tests were performed on hydrated FBC ash samples remolded near ninety five percent of standard maximum dry density and optimum moisture content. The samples were tested after aging for various times. After remolding the samples were sealed in airtight containers and aged. The samples gained strength with aging as shown in Figure 13.

References

1. McCoy, D. C., Scandrol, R. O., Statnick, R. M., Stouffer, M. R., Winschel, R. A., Withum, J. A., Wu, M. M. and Yoon, H., "The Edgewater Coolside Process Demonstration", a topical report, (CONSOL, Inc., Pittsburgh, PA 15129), February 1992, Appendix C.

APPENDIX A
Master List of Coolside Solid Waste Samples

I. Edgewater Demonstration Runs:

A. Coolside Operations

Location: Ohio Edison's Edgewater Power Plant, Lorain, OH
105 Mwe Unit 4, Boiler 13 utility boiler, No. 2 ESP

Date:

Run 1: Feb 8-10, 1990, 26 tons (170 drums @ 300 lbs each)
Run 2: Feb 13, 1990, 18 tons
Run 3: Feb 14-16, 1990, 21 tons

Operations:

Recycle Mode using recycle sorbent along with hydrated lime G (Black River Hydrated Lime, Carntown, KY (Dravo Lime Co.)) with sodium additive at 25°F approach to adiabatic saturation. The average SO₂ removal is about ~ 26%

Feedstock:

Average sulfur content in coal: 1.47 ± 0.12 % (compliance Ohio coal)

Ca/S ratio = ~2.0

(fresh hydrated lime provided 0.7 to 0.8 fresh Ca/S molar ratio and the recycle sorbent provided an available Ca/S of 0.5 to 0.7 in the form of unreacted

Ca(OH)₂)

Na/Ca ratio = 0.2

B. Sample Information

Storage Location: South Broadway Warehouse

Sampling Date: 7-9-91, 7-10-91

Total number: 345 vials @ ~200 g each

Run 1	Drums # 1-170, 1001-1069, 2000-2023
Run 2	Drums # 171-293
Run 3	Drums # 294-433, 4000-4011
Composite A	Drums # 42, 52, 45, 80, 122
Composite B	Drums # 344, 377, 434, 397, 401
1000-series	Drums # 1040, 1030, 1042
300-series	Drums # 339, 387, 362

II. Pilot Test Runs:

Parent Materials:

Cleveland Electric Illuminating Company (CEI) Avon Lake Plant Unit #9
(feed coal: medium-sulfur Ohio coal)

Operations: (see Pilot Test Runs information Sheet)

Sample Information: (see Pilot Test Runs Information Sheet)

Test 1: Jan 7-9, 92, Standard once-through with Na additive

Test 2: Jan 10-15, 92, Recycle mode with Na additive

Test 3: Jan 15-22, 92 (?), Advanced Coolside mode without Na additive

Test 4: Jan 23, 92, Once-through without Na additive

III. LIMB:

FBC hydrated samples

FBC non-hydrated samples

FBC pellets

AFBC samples

IV. Control Ash

Commercial available fly ash used in Field Lysimeter # 4

APPENDIX B
Brief Summary of Pilot Plant Production of Coolside Waste Samples¹

I. Operation Conditions:

Pilot Plant Site: CONSOL's 0.1 MWe Coolside pilot plant

Date of Operations: Test 1: Jan 7-9, 92
Test 2: Jan 10-15, 92
Test 3: Jan 15-22, 92 (?)
Test 4: Jan 23, 92

Test 1: Standard once-through with Na additive

Ca/S mol ratio = 2.08 Na/Ca mol ratio = 0.19
lb recycle/lb lime = 0
SO₂ Removal = 78 % Sorbent Utilization = 34 %

Test 2: Recycle mode with Na additive

(Baghouse solids were recycled on a semi-continuous basis, the baghouse ash was collected and returned periodically to the recycle feeder in batches.)

Ca/S mol ratio = 1.25 Na/Ca mol ratio = 0.21
lb recycle/lb lime = 2.9
SO₂ Removal = 72 % Sorbent Utilization = 52 %

Test 3: Advanced Coolside mode without Na additive

(Fly ash was mixed with the spent sorbent first before injected into the duct work.)

Average fresh Ca/S ratio: 1.2 No sodium additive
SO₂ Removal = 73-97 % Sorbent Utilization = 49-61 %

Test 4: Once-through without Na additive

Ca/S mol ratio = 2.42 Na/Ca mol ratio = 0
lb recycle/lb lime = 0
SO₂ Removal = 60 % Sorbent Utilization = 25 %

II. Materials and Process:

Hydrated Lime: Black River hydrated lime, Carntown, KY (Dravo Lime Co.)
- used in Pilot Test Runs 1, 2, 4 and Coolside Edgewater
Demonstration Run

Mississippi hydrated lime, St. Genevieve, MO (Mississippi Lime
Co.)
- used in Pilot Test Run 3 (Adv. Coolside mode)

Fly Ash: Cleveland Electric Illuminating Company (CEI) Avon Lake Plant Unit
#9
(feed coal: medium-sulfur Ohio coal)

Flue Gas: Flue gas composition consists of CO₂, H₂O, SO₂, and fly ash.
The inlet flue gas conditions can be matched to the flue gas
conditions downstream of the air preheater in a coal-fired boiler (burning a
medium sulfur Ohio coal).

Process:

Flue gas composition and condition was controlled to simulate that which would be produced by burning a medium sulfur Ohio coal. Hydrated lime is injected into the flue gas at the top of humidifier. The amount of water spray controls the humidifier exit gas temperature for the desired approach to saturation. A water-soluble additive such as NaOH can be fed as aqueous solution into the humidification water stream.

- 1) SO₂ Content: 2000 ppmv (dry basis)
Fly ash / S ratio = 4.0 lb/lb
- 2) Temperature: 300°F at the inlet of flue gas
25°F approach to adiabatic saturation

¹Based on the "OCDO Coolside Waste Management Project Milestone Report for Phase 3 Pilot Plant Production of Coolside Waste Samples," (Stouffer, M. R., Wu, M. M., and Rosenhoover, W. A., CONSOL, Inc., June 9, 1992).

APPENDIX C
Operating Log Summary

2/8 Two recycle solids injector lines developed plugs which were cleared

2/9 Recycle solids flow was lost through 5 of the 9 feed lines from the distribution bottle. Clinker material in the recycled ash solids plugged the 2" diameter feed line block valves.

Had problems maintaining ESP energization during the day.

2/10 At 12:40 hrs, the sodium additive feed was lost due to low pump discharge pressure.

At 16:49 hrs, the sodium additive pump tripped off.

2/11 Attempts to add packing to the sodium additive pump failed to stop shaft leakage. (pump failure)

The recycle solid feed was lost for a while at 16:30 hrs due to clinker material jamming the feed valve at the pneumatic conveying line inlet.

2/12 The recycle feed system was down from 00:55 hrs to 01:21 hrs, jamming in the rotary feed valve. The recycle solids feed lines continually plugged at the distribution bottle.

Sodium pump was placed back in service at 20:36 hrs.

2/13 Coolside Operating condition: $Ca/S = 0.75$ $Na/Ca = 0.185$, 20°F approach, and 4,000- 8,000 lb/hr recycle solids.

2/14 Maintained operating conditions

2/15 At 02:00 hrs, the hydrated lime feed was lost due to the plugging of a feeder vent line.

Between 11:00 - 11:37 hrs, the hydrated lime feed was off again.

At 14:49 hrs, the sodium additive feed pump was readjusted due to low pressure.

2/16 Conducted a 5-hour test at the same operation as above, except 17°F approach

Conducted a 4-hour test at 19°F approach, with recycle solid only no sodium additive and no fresh hydrated lime.

Table I

Elemental Concentrations

Page 1

Concentrations of Major and Minor Elements in Coolside Solid Waste Samples

Barrel #	Na, %	Al, %	K, %	Ca, %	Ti, %	Fe, %	S, %	C, %	H, %	N, %
28	0.91	12.80	1.49	8.24	0.43	7.33	2.21	7.56	0.18	0.18
32	0.85	13.59	1.65	7.36	0.49	8.20	1.61	8.11	0.13	0.18
36	0.89	12.75	1.47	8.13	0.42	7.74	1.64			
37	0.86	11.98	1.39	8.16	0.42	7.22	1.79			
39	0.90	13.12	1.50	8.29	0.44	7.73	1.76			
40	0.82	12.21	1.54	7.89	0.44	7.65	1.66			
41	0.80	11.51	1.42	7.70	0.42	7.34	1.76			
42-11	0.79	11.80	1.38	8.02	0.44	8.27	1.53			
42-12	0.78	12.48	1.37	7.61	0.42	7.68	1.47			
42-13	0.76	11.65	1.37	7.68	0.44	8.16	1.50			
42-14	0.84	12.95	1.47	7.82	0.46	8.94	1.53			
42-15	0.79	13.04	1.44	8.11	0.45	8.32	1.52			
42-16	0.88	12.11	1.41	8.10	0.46	8.15	1.50			
42-21	1.09	13.15	1.54	9.79	0.46	8.20	1.53			
42-22	0.91	12.94	1.46	8.67	0.46	8.06	1.53			
42-23	0.90	11.97	1.52	8.63	0.46	8.60	1.59			
42-24	0.90	16.02	1.56	9.05	0.50	8.84	1.55			
42-25	0.91	13.09	1.52	8.33	0.46	8.67	1.60			
42-26	0.90	16.45	1.42	8.33	0.42	7.89	1.60			
42-1	0.77	11.22	1.28	7.16	0.39	7.14	1.65	7.87	0.15	0.27
42-b1	0.81	12.26	1.46	8.08	0.45	8.66	1.59			
42-2a	0.81	12.46	1.48	8.19	0.46	8.79	1.59			
42-2b	0.82	11.67	1.43	8.16	0.47	8.72	1.59			
42-2c	0.44	6.37	1.56	7.93	0.43	8.01	1.59			
42-4	0.89	12.48	1.26	7.80	0.42	7.05	1.59			
42-5	0.85	12.21	1.48	7.91	0.42	8.05	1.59			
43	0.88	12.35	1.40	7.99	0.43	6.74	1.67			
44	0.86	11.68	1.36	7.67	0.39	7.76	1.74	7.89	0.21	0.86
45	0.84	12.17	1.33	7.04	0.38	7.18	1.77			
46	0.78	11.10	1.48	6.58	0.45	7.19	1.67			
47	0.82	11.84	1.27	7.24	0.39	7.63	1.68			
48	0.85	11.51	1.31	7.82	0.42	7.86	1.72			
49	0.15	19.89	1.46	8.07	0.43	7.70	1.60	7.52	0.22	0.63
50	0.76	11.39	1.40	8.39	0.41	6.50	1.76			
52	0.83	11.19	1.41	8.06	0.40	7.14	1.80			
53	0.77	10.40	1.30	8.55	0.40	6.89	1.86			
54	0.86	11.17	1.32	8.58	0.39	6.82	1.95			
56	0.95	11.07	1.52	10.16	0.42	6.83	1.88			
58	0.93	10.88	1.50	10.14	0.41	7.10	2.08			
60	1.07	10.61	1.30	11.67	0.38	6.05	2.01			
62	1.26	12.23	1.34	11.46	0.36	5.71	2.28			
64	1.28	12.65	1.46	12.27	0.39	6.31	2.44	6.20	0.16	0.27
66	1.33	12.53	1.62	13.20	0.41	6.49	2.34			
68	1.28	12.02	1.46	12.68	0.40	6.40	2.05			
70	1.26	11.95	1.45	12.59	0.40	6.32	2.35			
72	1.30	11.86	1.31	12.37	0.38	6.31	2.40			
74	1.27	12.02	1.45	12.51	0.39	6.12	2.43			
76	1.22	11.45	1.35	11.78	0.38	6.17	2.34			
78	1.17	11.23	1.52	12.37	0.39	6.11	2.48			
80	1.32	14.21	1.48	11.93	0.42	6.30	2.35			
82	1.22	13.72	1.64	11.97	0.46	7.06	2.08			
84	1.23	13.28	1.66	11.45	0.43	6.74	1.96			
86	1.18	12.85	1.55	12.10	0.44	6.35	2.16			
88	1.15	12.48	1.59	11.19	0.41	6.38	1.87			
90	1.08	12.08	1.53	10.97	0.42	6.46	1.87			
92	1.17	12.31	1.48	10.93	0.42	6.20	1.85	6.90	0.23	1.22

Table I
Elemental Concentrations

Concentrations of Major and Minor Elements in Coolside Solid Waste Samples

Barrel #	Na,%	Al,%	K,%	Ca,%	Ti,%	Fe,%	S,%	C,%	H,%	N,%
94	1.15	12.96	1.66	11.82	0.45	6.71	1.98			
96	1.09	11.94	1.44	10.43	0.44	6.23	1.80			
98	1.08	12.44	1.44	10.24	0.44	6.17	1.96	6.12	0.18	0.28
100	1.09	12.36	1.49	10.87	0.45	6.37	1.88			
102	1.01	11.27	1.37	10.04	0.40	6.01	1.89			
104	1.06	11.18	1.38	10.83	0.42	6.23	1.95			
106	1.10	11.06	1.43	11.28	0.41	6.29	1.87			
108	1.07	10.44	1.46	11.83	0.42	6.37	1.84			
110	1.09	10.17	1.40	11.93	0.40	6.11	2.00			
112	1.13	11.00	1.35	11.18	0.38	6.05	2.02			
114	1.08	10.25	1.34	11.45	0.38	6.12	2.00			
116	0.64	1.93	0.76	7.38	0.28	4.1	1.98			
118	1.14	11.71	1.43	11.68	0.42	6.84	1.87			
120	1.09	10.76	1.33	11.30	0.38	6.15	1.92			
122	1.15	11.32	1.39	11.06	0.37	6.30	2.00			
124	1.12	11.07	1.41	11.08	0.38	6.17	1.95			
126	1.15	10.25	1.37	11.51	0.36	5.92	2.15			
127	1.28	10.53	1.35	10.90	0.40	5.71	2.60			
128	1.28	11.07	1.43	12.23	0.38	6.37	2.16			
130	1.19	10.47	1.41	12.07	0.38	6.13	2.15			
132	1.14	10.12	1.41	11.76	0.37	6.04	2.16			
134	1.29	10.95	1.60	12.69	0.39	6.36	2.18			
136	1.20	10.14	1.50	12.27	0.36	5.69	2.22			
138	1.12	10.00	1.34	12.11	0.35	5.71	2.14			
140	1.07	10.17	1.48	11.54	0.34	6.07	1.91			
142	1.18	10.36	1.47	13.80	0.40	6.58	2.05			
144	1.19	10.43	1.33	11.97	0.36	6.05	2.15			
146	1.09	10.53	1.24	12.17	0.37	6.09	2.04			
148	1.04	9.90	1.36	12.34	0.38	6.06	2.04	11.58	0.25	0.79
150	1.17	10.66	1.39	12.73	0.38	6.15	2.10	11.98	0.28	0.78
152	0.97	11.45	1.48	10.68	0.41	6.85	1.75			
154	0.94	11.50	1.54	10.50	0.44	7.11	1.68			
156	1.04	10.38	1.40	10.72	0.40	6.49	1.75			
158	0.91	11.74	1.46	10.06	0.43	7.14	1.70			
160	0.84	10.30	1.37	9.45	0.40	6.41	1.92			
162	1.13	11.93	1.56	11.04	0.43	7.10	1.92			
164	0.98	11.12	1.48	10.19	0.42	6.82	1.77			
166	1.06	10.23	1.51	11.33	0.40	6.40	2.01			
168	1.07	11.02	1.45	11.38	0.41	6.77	1.99			
176	0.82	12.60	1.46	8.10	0.41	7.04	1.13			
180	0.73	11.25	1.34	6.94	0.39	6.40	1.11			
186-1	0.79	12.38	1.50	8.20	0.44	6.85	1.10	8.10	0.17	0.54
186-2	0.75	11.70	1.45	8.49	0.45	6.67	1.10	9.03	0.17	0.70
188-1	1.15	9.83	1.36	11.95	0.36	5.69	2.21			
188-2	0.76	11.72	1.67	7.85	0.40	6.43	2.21			
190-1	1.11	10.06	1.30	10.88	0.33	5.41	2.24			
190-2	0.70	11.11	1.51	7.55	0.41	6.41	2.24	8.68	0.20	0.68
190-3	1.14	10.12	1.35	11.90	0.37	5.94	2.24			
190-4	1.20	10.84	1.76	13.73	0.40	6.59	2.24			
196	0.82	12.19	1.86	9.55	0.45	7.86	1.18	8.66	0.17	0.77
200	0.86	12.37	1.90	10.67	0.48	8.08	1.21	9.66	0.23	0.63
210	0.84	11.72	1.71	10.47	0.46	7.46	1.19			
212	0.85	11.50	1.69	10.99	0.46	7.44	1.21			
224	0.91	12.13	1.77	10.51	0.47	7.39	1.41			
228	0.91	11.58	1.80	10.55	0.47	7.60	1.41			
240	0.89	11.05	1.64	10.63	0.45	7.56	1.33			

Table I
Elemental Concentrations

Concentrations of Major and Minor Elements in Coolside Solid Waste Samples

Barrel #	Na,%	Al,%	K,%	Ca,%	Ti,%	Fe,%	S,%	C,%	H,%	N,%
246	0.89	11.05	1.87	11.47	0.49	7.97	1.33			
262	0.98	12.57	1.45	9.79	0.44	7.27	1.33			
274	0.84	12.52	1.47	8.71	0.46	7.33	1.24			
276	0.93	12.71	1.56	9.17	0.44	7.16	1.47			
280	0.96	12.07	1.51	10.08	0.45	7.02	1.62			
294	1.19	10.51	1.26	9.62	0.38	5.35	1.71			
295	1.23	10.89	1.26	9.81	0.40	5.57	1.73			
296	1.11	10.66	1.34	9.41	0.38	5.44	1.72	9.45	0.23	0.76
297	1.18	10.78	1.34	9.46	0.39	5.28	1.76	7.60	0.15	0.66
298	1.21	10.60	1.27	9.29	0.38	5.17	1.79			
299	1.14	10.80	1.30	9.15	0.37	5.29	1.77	8.52	0.25	0.41
300	1.12	9.78	1.23	8.75	0.36	5.06	1.68			
301	1.21	10.58	1.38	9.91	0.40	5.51	1.76			
302	1.14	9.60	1.25	8.67	0.36	5.15	1.72			
303	1.17	9.47	1.22	8.85	0.37	5.08	1.80	9.73	0.16	0.48
304	1.18	9.81	1.23	7.86	0.38	5.38	1.57			
305	1.22	9.30	1.40	9.10	0.39	6.22	1.74			
306	1.20	8.76	1.32	8.21	0.37	6.23	1.68			
307	1.28	10.22	1.44	8.42	0.40	6.39	1.63			
308	1.16	9.03	1.22	7.21	0.35	5.88	1.60			
309	1.26	9.23	1.26	7.48	0.36	6.09	1.48			
310	1.17	9.82	1.32	7.23	0.36	6.09	1.57			
311	1.30	10.09	1.28	7.35	0.39	6.42	1.61			
312	1.27	10.36	1.22	6.78	0.36	6.46	1.54			
313	1.27	9.76	1.36	7.00	0.37	6.42	1.55			
314	1.25	9.61	1.26	6.83	0.38	6.68	1.59			
315	1.14	9.41	1.32	6.93	0.36	6.38	1.58			
316	1.25	10.36	1.35	7.15	0.38	6.71	1.57			
317	1.23	10.08	1.26	6.44	0.37	6.75	1.51			
318	1.22	9.93	1.30	6.56	0.37	6.11	1.49			
319-1	1.32	10.11	1.21	6.15	0.35	6.23	1.49			
319-2	1.26	10.54	1.24	6.43	0.37	6.96	1.49			
320	1.27	10.38	1.30	7.45	0.37	6.53	1.54			
321	1.26	10.50	1.36	6.63	0.39	7.09	1.28			
322	1.17	9.73	1.25	5.81	0.35	6.62	1.47			
323	1.38	10.75	1.31	7.08	0.38	6.28	1.46			
324	1.30	11.02	1.29	6.26	0.36	7.18	1.50			
325	1.27	10.72	1.33	6.26	0.38	7.31	1.54			
326-1	1.21	9.91	1.28	6.08	0.37	6.72	1.42			
326-2	1.30	11.76	1.41	6.14	0.41	6.83	1.42			
327	1.34	10.70	1.34	6.50	0.38	6.96	1.46			
328	1.34	11.42	1.33	6.45	0.38	6.73	1.53	8.67	0.20	0.63
329	1.28	10.32	1.33	6.43	0.38	6.62	1.53			
330	1.36	10.08	1.31	6.50	0.38	6.73	1.46			
331	1.30	10.10	1.25	6.34	0.37	6.42	1.55			
332	1.28	9.88	1.30	6.70	0.36	6.53	1.46			
333	1.28	10.11	1.30	7.13	0.36	6.39	1.54			
334	1.26	10.04	1.31	7.85	0.36	5.98	1.57			
335	1.31	10.50	1.32	8.28	0.37	6.38	1.67			
336-1	1.40	11.61	1.38	8.44	0.41	5.74	1.63			
336-2	1.33	10.24	1.26	7.83	0.34	5.87	1.63			
337	1.27	9.45	1.29	8.30	0.34	5.86	1.72			
338	1.32	9.23	1.29	8.51	0.34	5.80	1.68			
339	1.36	9.47	1.19	8.40	0.33	5.64	1.70			
340	1.26	10.45	1.22	8.63	0.34	5.50	1.76			
341	1.37	9.93	1.34	9.11	0.35	5.64	1.76			

Table I

Elemental Concentrations

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Concentrations of Major and Minor Elements in Coolside Solid Waste Samples

Barrel #	Na,%	Al,%	K,%	Ca,%	Ti,%	Fe,%	S,%	C,%	H,%	N,%
342	1.42	10.08	1.31	9.27	0.35	5.81	1.84			
343	1.26	8.93	1.24	8.64	0.34	5.35	1.79			
344	1.19	8.81	1.18	8.53	0.33	5.40	1.80			
345-1	1.09	8.29	1.17	8.36	0.33	5.44	1.77			
345-2	1.19	8.64	1.11	7.92	0.31	5.12	1.80			
346-1a	1.04	9.22	1.20	8.57	0.34	5.93	1.73			
346-1b	1.04	8.60	1.17	8.20	0.36	5.24	1.73			
346-2	1.13	9.33	1.19	7.94	0.31	4.87	1.73			
347	1.15	8.92	1.17	8.20	0.32	5.59	1.75			
348	1.00	7.72	1.08	7.44	0.30	5.12	1.72			
349	1.09	8.35	1.10	8.01	0.32	5.66	1.70			
350-1	1.02	8.86	1.17	8.42	0.33	5.82	1.70			
350-2a	1.11	8.52	1.24	8.41	0.32	5.71	1.70			
350-2b	1.15	9.13	1.19	8.20	0.33	5.91	1.70			
350-2c	1.13	8.86	1.13	7.47	0.33	6.43	1.70			
351	1.12	7.83	1.23	8.46	0.33	5.62	1.69			
352	1.19	9.71	1.23	8.79	0.35	6.17	1.75			
353	1.18	9.89	1.21	8.65	0.34	6.23	1.72			
354	1.21	9.21	1.22	9.12	0.35	6.05	1.69			
355	1.17	9.32	1.25	8.81	0.33	5.97	1.74			
356	1.17	9.24	1.25	8.94	0.34	5.70	1.76			
357	1.23	9.24	1.19	9.12	0.34	5.61	1.82			
358	1.24	8.92	1.18	9.10	0.33	5.73	1.82			
359	1.20	10.02	1.17	9.18	0.34	5.61	1.85			
360	1.22	10.57	1.20	8.91	0.32	5.47	1.87			
361	1.16	9.43	1.19	9.14	0.33	5.26	1.85			
362	1.17	8.64	1.20	9.31	0.33	5.39	1.89			
363	1.17	8.27	1.20	9.15	0.33	5.22	1.90			
364	1.17	8.81	1.20	9.28	0.33	5.44	1.89			
365	1.17	9.45	1.22	9.23	0.33	5.30	1.94			
366	1.16	8.74	1.19	9.06	0.33	5.23	1.88			
367	1.16	8.63	1.20	8.95	0.32	5.02	1.94			
368	1.17	8.52	1.19	9.52	0.34	5.47	1.94			
369	1.11	8.11	1.09	8.74	0.31	5.01	1.84			
370	1.18	8.42	1.32	9.76	0.34	5.38	1.91			
371	1.22	8.34	1.27	9.77	0.34	5.34	1.95			
372	1.26	10.73	1.21	9.74	0.34	5.38	2.05			
373	1.20	9.48	1.22	10.70	0.32	5.53	2.11			
374	1.17	9.31	1.29	10.45	0.31	5.26	2.18			
375	1.21	8.67	1.30	10.87	0.33	5.57	2.08			
376	1.05	8.80	1.20	10.41	0.31	5.31	2.13			
377	1.18	8.79	1.32	10.67	0.31	5.28	2.13			
378	1.29	10.08	1.32	11.58	0.34	5.69	2.23			
379	1.30	9.42	1.46	11.73	0.34	5.64	2.18			
380	1.28	10.74	1.37	11.41	0.33	5.54	2.20			
381	1.20	9.14	1.35	10.57	0.32	5.44	2.14			
382	1.14	8.75	1.24	10.77	0.33	5.76	2.06			
383	1.22	9.91	1.34	10.91	0.33	6.01	2.11			
384	1.17	9.27	1.19	10.24	0.32	5.66	2.09			
385	1.25	9.08	1.36	10.37	0.33	5.79	2.64			
386	1.24	10.19	1.29	10.40	0.33	6.00	2.00			
387	1.20	9.57	1.22	9.92	0.32	6.08	2.05			
388	1.18	8.44	1.20	9.48	0.31	5.65	2.01			
389	1.15	9.39	1.26	9.54	0.33	6.23	1.93			
390	1.18	10.38	1.38	10.02	0.33	6.36	1.88			
391	1.17	9.89	1.27	9.30	0.33	6.48	1.85			

Table I
Elemental Concentrations

Concentrations of Major and Minor Elements in Coolside Solid Waste Samples

Barrel #	Na,%	Al,%	K,%	Ca,%	Ti,%	Fe,%	S,%	C,%	H,%	N,%
392	1.18	13.24	1.32	9.68	0.33	6.33	2.07			
393	1.18	9.16	1.20	9.21	0.31	6.24	1.81			
394	1.24	8.98					1.91			
395	1.20	8.99	1.34	10.09	0.34	6.44	1.81			
396	1.14	9.37	1.40	10.07	0.35	6.47	2.00			
397	1.12	9.31	1.18	9.17	0.31	5.97	2.01			
399	1.06	9.64	1.16	8.93	0.35	5.65	1.98			
400	1.12	9.60	1.31	9.94	0.38	6.07	1.96			
401	1.15	9.37	1.25	9.81	0.33	6.05	2.01			
402	1.06	9.39	1.32	10.25	0.39	5.96	2.06			
403	1.12	9.41	1.23	9.84	0.36	5.47	2.06			
404	1.13	9.93	1.29	10.08	0.37	5.65	2.06			
405	1.12	9.99	1.30	10.18	0.38	5.80	2.08			
406	1.17	10.38	1.29	9.68	0.36	5.55	2.11	10.32	0.21	0.69
407	1.06	8.55	1.21	9.26	0.34	5.51	2.13			
408	1.06	8.55	1.32	9.84	0.36	5.59	2.22			
410	1.11	9.49	1.20	9.45	0.33	5.53	2.09	7.43	0.22	0.62
411	1.11	9.61	1.24	9.15	0.34	5.55	2.10			
413	1.31	11.51	1.41	10.51	0.36	5.76	2.21			
414	1.22	10.76	1.24	9.91	0.34	5.46	2.31			
415	1.36	11.74	1.45	11.27	0.37	5.58	2.30			
418	1.16	8.85	1.11	9.88	0.30	5.31	2.51			
423-a	1.19	8.36	1.36	10.51	0.31	5.12	2.71	9.64	0.30	0.89
423-b	1.14	7.86	1.19	10.34	0.30	5.09	2.71			
423-c	1.15	8.69	1.15	10.31	0.31	5.10	2.71			
424	1.22	10.32	1.38	10.40	0.36	5.31	2.59			
428	1.24	10.21	1.29	9.59	0.35	5.26	2.57	9.17	0.16	0.37
429	1.22	9.96	1.31	9.73	0.36	5.17	2.66	8.12	0.13	0.36
430	1.22	10.30	1.39	9.90	0.37	5.37	2.77			
431	1.28	10.55	1.29	10.52	0.39	5.59	2.60			
432	1.52	12.35	1.47	10.14	0.42	6.00	2.68			
433	1.46	11.82	1.40	9.15	0.38	5.61	2.72			
434-1a	1.20	9.09	1.24	8.91	0.34	5.93	2.74			
434-1b	1.24	9.43	1.24	8.95	0.34	5.14	2.74			
434-1c	1.25	9.26	1.26	8.70	0.33	5.68	2.74			
434-2a	1.20	8.59	1.16	8.28	0.32	5.62	2.74			
434-2b	1.25	9.56	1.17	8.69	0.33	5.43	2.74			
434-2c	1.23	10.01	1.17	8.69	0.33	5.43	2.74			
434-3	1.43	11.47	1.44	9.10	0.38	5.47	2.74	8.13	0.13	0.39
434-4	1.39	11.20	1.25	8.60	0.36	5.43	2.74			

Table I

Elemental Concentrations

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Concentrations of Major and Minor Elements in Coolside Solid Waste Samples

Barrel #	Na,%	Al,%	K,%	Ca,%	Ti,%	Fe,%	S,%	C,%	H,%	N,%
Overall Average										
AVG	1.11	10.55	1.35	9.40	0.38	6.29	1.87	8.54	0.20	0.59
STD	0.18	1.65	0.15	1.69	0.05	0.91	0.35	1.43	0.04	0.25
RSD	16.45	15.64	11.06	18.01	12.09	14.45	18.89	16.72	22.65	42.89
N	262	262	261	261	261	261	262	25	25	25
MIN	0.15	1.93	0.76	5.81	0.28	3.14	1.10	6.12	0.13	0.18
MAX	1.52	19.89	1.90	13.80	0.50	8.94	2.77	11.98	0.30	1.22
MED	1.16	10.38	1.33	9.23	0.38	6.17	1.82	8.17	0.20	0.63
Run 1										
AVG	1.00	11.67	1.43	10.11	0.41	6.89	1.89	8.17	0.20	0.55
STD	0.20	1.84	0.11	1.86	0.03	0.91	0.28	2.02	0.05	0.36
RSD	20.00	15.73	8.00	18.37	8.34	13.16	14.61	24.74	23.74	65.90
N	96	96	96	96	96	96	96	10	10	10
MIN	0.15	1.93	0.76	7.04	0.28	4.18	1.13	6.12	0.13	0.18
MAX	1.33	19.89	1.66	13.80	0.50	8.94	2.60	11.98	0.28	1.22
MED	1.05	11.69	1.44	10.59	0.41	6.72	1.87	7.72	0.20	0.46
Run 2										
AVG	0.91	11.55	1.59	10.00	0.43	6.98	1.55	8.83	0.19	0.66
STD	0.14	0.85	0.19	1.66	0.04	0.74	0.46	0.57	0.03	0.09
RSD	15.83	7.32	11.99	16.57	9.78	10.61	29.41	6.49	14.27	12.89
N	21	21	21	21	21	21	21	5	5	5
MIN	0.70	9.83	1.30	6.94	0.33	5.41	1.10	8.10	0.17	0.54
MAX	1.20	12.71	1.90	13.73	0.49	8.08	2.24	9.66	0.23	0.77
MED	0.89	11.70	1.56	10.47	0.45	7.16	1.33	8.68	0.17	0.68
Run 3										
AVG	1.21	9.67	1.27	8.83	0.35	5.80	1.91	8.77	0.20	0.59
STD	0.09	0.93	0.08	1.35	0.03	0.57	0.36	0.98	0.05	0.18
RSD	7.12	9.59	6.25	15.25	7.55	9.82	18.96	11.13	25.95	30.16
N	145	145	144	144	144	144	145	10	10	10
MIN	1.00	7.72	1.08	5.81	0.30	3.14	1.28	7.43	0.13	0.36
MAX	1.52	13.24	1.47	11.73	0.42	7.31	2.77	10.32	0.30	0.89
MED	1.20	9.57	1.26	9.08	0.34	5.66	1.81	8.60	0.21	0.63

Table II
Typical Detection Limit of PIGE and PIXE Analysis of Coolside Waste Samples

Element (ppm)	Detection Limit
Li ^a	14
F ^a	6
Na, % ^a	0.003
Al, % ^a	0.076
K	864
Ca	202
Sc	29
Ti	52
V	65
Cr	12
Mn	16
Fe	105
Co	544
Ni	28
Cu	11
Zn	10
Ga	9
Ge	10
As	13
Se	7
Br	13
Rb	12
Sr	7
Y	13
Zr	24
Nb	18
Mo	12
Ba	310
Pb	63

^aObtained by PIGE analysis. $LOD = 3 * \sqrt{BkG} * F_o/N_o$, where BKG is the background over 1 FWHM about the peak's centroid, N_o is the area under the γ -ray peak, F_o is the concentration of element in the sample.

PIGE & PIXE ANALYSIS OF COOLSIDE SOLID WASTE MATERIALS

ID	F	Li	Na	Al	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Ga
All Runs															
AVG	450	86	1.11	10.56	1.35	9.39	0.38	186	138	116	6.29	73	79	281	36
STD	95	27	0.18	1.65	0.15	1.69	0.05	14	19	20	0.91	10	8	35	6
RSD	21	31	17	16	11	18	12	7	14	17	14	14	10	13	16
N	264	263	264	264	263	263	263	263	155	263	263	253	263	263	263
MIN	93	8	0.15	1.93	0.76	5.81	0.28	151	87	81	3.14	41	53	190	19
MAX	682	201	1.52	13.89	1.90	13.80	0.50	215	183	217	8.94	157	105	424	50
MED	451	83	1.16	10.38	1.33	9.21	0.38	188	133	113	6.15	73	79	283	36
Run 1															
AVG	433	90	1.00	11.67	1.43	10.11	0.41	185	142	119	6.89	70	78	268	34
STD	100	34	0.20	1.84	0.11	1.86	0.03	16	17	13	0.91	3	6	41	6
RSD	24.46	37.68	20.00	15.73	8.00	18.37	8.34	8.49	12.05	10.73	13.16	11.36	7.76	15.48	16.52
N	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96
MIN	93	16	0.15	1.93	0.76	7.04	0.28	151	87	81	4.18	41	53	190	19
MAX	651	201	1.33	13.89	1.96	13.80	0.50	215	179	204	8.94	85	92	360	46
MED	474	91	1.05	11.69	1.44	10.59	0.41	188	139	117	6.72	70	79	270	34
Run 2															
AVG	471	74	0.91	11.55	1.59	10.00	0.43	190	152	158	6.98	75	86	317	36
STD	66	36	0.14	0.85	0.19	1.66	0.04	15	21	29	0.74	13	9	28	4
RSD	14.00	49.02	15.83	7.32	11.39	16.57	9.78	7.92	14.08	18.28	10.91	17.65	10.73	8.78	11.74
N	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
MIN	246	8	0.70	9.83	1.30	6.94	0.33	158	112	103	5.41	57	67	268	30
MAX	558	142	1.20	12.71	1.90	13.73	0.49	208	183	217	8.08	98	105	403	45
MED	476	79	0.89	11.70	1.56	10.47	0.45	193	148	163	7.16	69	86	311	36
Run 3															
AVG	456	86	1.21	9.69	1.27	8.83	0.35	186	120	108	5.79	76	79	284	38
STD	90	19	0.09	0.94	0.08	1.34	0.03	12	10	12	0.57	11	8	27	5
RSD	19.69	22.35	7.33	9.71	6.30	15.14	7.53	6.54	7.95	11.20	9.78	14.04	10.41	9.41	14.31
N	147	146	147	147	146	146	146	146	38	146	146	146	146	146	146
MIN	286	41	1.00	7.72	1.08	5.81	0.30	155	107	83	3.14	57	61	220	27
MAX	682	134	1.52	13.24	1.47	11.73	0.42	214	150	160	7.31	157	98	424	50
MED	436	83	1.20	9.60	1.26	9.08	0.34	186	119	106	5.68	76	79	283	38

Table III Element Concentrations

ID	Ge	As	Se	Br	Rb	Sr	Y	Zr	Mo	Ba	Pb	S	C	H	N
All Runs															
AVG	47	219	12	113	97	318	62	175	29	428	112	1.880	8.54	0.20	0.59
STD	8	31	4	51	10	32	8	29	6	190	32	0.360	1.43	0.04	0.25
RSD	16	14	31	45	10	10	13	17	21	44	28	19.173	16.72	22.65	42.96
N	263	263	263	263	263	263	263	263	154	222	263	264	25	25	25
MIN	24	135	2	48	59	121	37	110	14	86	53	1.097	6.12	0.13	0.18
MAX	69	317	22	812	125	400	87	321	49	949	196	2.774	11.99	0.30	1.22
MED	48	222	12	115	97	318	61	176	29	392	106	1.830	8.17	0.20	0.63
Run 1															
AVG	45	211	11	95	100	306	63	195	29	578	129	1.885	8.17	0.20	0.55
STD	11	41	4	78	10	26	7	24	6	172	28	0.275	2.02	0.05	0.36
RSD	23.93	19.50	33.92	82.19	9.77	8.57	11.65	12.16	20.95	29.81	21.74	14.61	24.74	23.74	65.90
N	96	96	96	96	96	96	96	96	96	76	96	96	10	10	10
MIN	24	135	2	48	59	203	37	113	14	246	66	1.125	6.12	0.13	0.18
MAX	69	317	19	812	125	362	86	321	49	949	196	2.604	11.99	0.28	1.22
MED	46	193	11	96	100	306	63	193	29	588	132	1.872	7.72	0.20	0.46
Run 2															
AVG	49	247	12	106	107	319	68	200	31	561	153	1.553	8.83	0.19	0.66
STD	6	19	4	22	11	23	11	24	7	205	18	0.457	0.57	0.03	0.09
RSD	11.82	7.54	30.33	20.38	10.34	7.15	16.65	11.97	21.75	36.57	11.92	29.41	6.49	14.27	12.89
N	21	21	21	21	21	21	21	21	21	13	21	21	5	5	5
MIN	39	208	5	72	84	275	47	163	14	251	118	1.097	8.10	0.17	0.54
MAX	62	282	20	161	121	352	87	243	41	861	187	2.240	9.66	0.23	0.77
MED	50	250	12	108	108	322	69	204	33	500	154	1.332	8.68	0.17	0.68
Run 3															
AVG	49	221	13	126	95	326	60	158	28	330	95	1.924	8.77	0.20	0.59
STD	5	19	3	15	9	34	7	22	5	124	23	0.373	0.98	0.05	0.18
RSD	9.84	8.78	26.81	11.97	9.58	10.33	12.04	13.81	19.47	37.70	23.65	19.37	11.13	25.35	30.16
N	146	146	146	146	146	146	146	146	37	183	146	147	10	10	10
MIN	36	162	4	96	72	121	42	110	19	86	53	1.278	7.43	0.13	0.36
MAX	61	277	22	174	121	400	76	239	42	680	156	2.774	10.32	0.30	0.89
MED	48	223	13	123	94	327	60	153	28	312	90	1.818	8.60	0.21	0.63

Table IV. Elemental Concentrations of Barrel # 434 Coolside Waste Samples

Element (ppm)	Homogeneity of Mixing (n=3)			Homogeneity of Mixing (n=3)			Average of #434 (n=6)			Coolside Wastes (n=263)		
	434a-avg	SD	RSD	434-b-avg	SD	RSD	AVG	SD	RSD	AVG	SD	RSD
F	477	45	9.5	476	18	3.7	476	26	5.5	450	95	21
Li	76	3	4.5	72	6	8.3	85	22	25.8	86	27	31
Na, %	1.23	0.03	2.3	1.23	0.02	1.9	1.27	0.09	7.0	1.11	0.18	17
Al, %	9.26	0.17	1.8	9.39	0.73	7.8	9.83	1.02	10.4	10.56	1.65	16
K, %	1.25	0.01	1.2	1.17	0.00	0.3	1.24	0.09	7.1	1.35	0.15	11
Ca, %	8.85	0.13	1.5	8.55	0.23	2.7	8.74	0.25	2.9	9.39	1.69	18
Ti, %	0.34	0.00	1.2	0.32	0.00	1.1	0.34	0.02	5.6	0.38	0.05	12
V	190	8	4.4	198	16	8.1	190	14	7.5	186	14	7
Mn	99	4	3.7	105	5	4.8	101	5	5.0	116	20	17
Fe, %	4.92	1.54	31.3	5.49	0.11	2.0	5.26	0.87	16.6	6.29	0.91	14
Ni	83	6	7.7	78	3	3.4	79	6	7.2	73	10	14
Cu	79	6	7.2	76	3	4.0	77	6	7.4	79	8	10
Zn	309	16	5.3	294	1	0.4	294	17	5.9	281	35	13
Ga	41	4	9.3	43	1	2.7	40	4	10.2	36	6	16
Ge	58	3	5.0	56	5	9.5	56	4	7.5	47	8	16
As	229	6	2.5	228	10	4.3	226	8	3.5	219	31	14
Se	13	2	12.8	14	1	3.8	12	2	18.3	12	4	31
Br	161	13	8.0	148	2	1.2	158	11	6.9	113	51	45
Rb	91	7	7.5	95	9	9.0	94	6	6.8	97	10	10
Sr	391	8	2.0	371	2	0.7	375	14	3.9	318	32	10
Y	64	6	9.2	58	2	3.0	59	8	12.8	62	8	13
Zr	142	4	2.9	148	5	3.5	154	18	11.4	175	29	17
Nb	33	3	10.0	23	4	18.1	24	10	42.0	22	8	39
Ba	288	89	30.8	320	25	7.8	334	96	28.9	428	190	44
Pb	84	14	16.1	78	10	12.7	90	22	24.3	112	32	28
Th	7	1	15.7	8	2	24.7	9	4	44.2	12	7	59

Table Va. Elemental Concentrations of Barrel # 42 Coolside Waste Samples

Element (ppm)	Repeat Irradiations, #42b (n=3)			Multi-Samples, Vial #42-b (n=5)			Barrel #42-Layer #1 42-1x, (n=6)			Barrel #42-Layer #2 42-2x, (n=6)		
	Avg	SD	RSD	Avg	SD	RSD	Avg	SD	RSD	AVG	SD	RSD
F	314	11	3	279	78	28	316	12	3.82	351	18	5.05
Li	72	23	31	55	42	75	88	9	10.48	93	28	30.53
Na, %	0.82	0.00	0.1	0.73	0.20	28	0.81	0.04	5.47	0.94	0.08	8.19
Al, %	12.13	0.41	3	10.57	2.85	27	12.34	0.59	4.75	13.94	1.84	13.17
K, %	1.46	0.03	2	1.39	0.15	11	1.41	0.04	2.96	1.50	0.05	3.42
Ca, %	8.15	0.06	0.7	7.70	0.37	5	7.89	0.22	2.76	8.80	0.55	6.30
Ti, %	0.46	0.01	1	0.41	0.01	3	0.44	0.01	3.32	0.46	0.02	5.12
V	172	9	5	171	9	5	172	12	7.15	189	4	2.36
Cr	169	1	0.5	156	10	6	169	7	4.23	167	7	4.19
Mn	135	2	2	122	8	7	124	6	4.46	126	8	6.18
Fe, %	8.72	0.06	0.7	7.56	0.54	7	8.25	0.41	4.91	8.38	0.38	4.53
Ni	60	6	11	74	12	16	66	7	10.64	64	4	6.67
Cu	81	2	3	81	4	5	79	4	5.37	82	5	6.21
Zn	209	2	1	225	2	1	222	9	4.07	234	10	4.29
Ga	29	1	3	28	3	12	32	2	7.61	32	5	14.99
Ge	31	3	9	35	4	11	33	2	7.31	37	3	8.05
As	179	4	2	183	9	5	185	5	2.65	192	8	4.04
Se	9	4	48	9	2	27	10	1	13.44	9	5	57.27
Br	55	6	11	58	5	9	57	5	8.08	64	5	8.00
Rb	103	6	6	104	7	6	106	8	7.66	109	9	7.82
Sr	289	9	3	272	4	2	295	15	5.03	305	12	4.09
Y	62	10	17	62	6	10	64	1	1.57	63	5	8.45
Zr	221	7	3	193	12	6	206	20	9.48	211	17	8.31
Mo	26	2	6	29	4	15	29	4	14.88	30	5	18.14
Ba	702	59	8	622	171	27	487	77	15.75	502	111	22.11
Pb	110	13	12	105	23	22	109	17	15.37	115	11	9.73

Table Vb
Elemental Concentrations of Barrel # 42 Coolside Waste Samples

Element (ppm)	Barrel #42 Samples (n=17)			Average Coolside Wastes (n=263)		
	AVG	SD	RSD	AVG	SD	RSD
F	319	43	14	450	95	21
Li	80	29	36	86	27	31
Na, %	0.83	0.12	15	1.11	0.18	17
Al, %	12.44	1.99	16	10.56	1.65	16
K, %	1.44	0.09	6	1.35	0.15	11
Ca, %	8.18	0.57	7	9.39	1.69	18
Ti, %	0.45	0.02	5	0.38	0.05	12
V	177	12	7	186	14	7
Cr	166	8	5	138	19	14
Mn	126	7	6	116	20	17
Fe, %	8.22	0.53	6	6.29	0.91	14
Ni	66	8	13	73	10	14
Cu	81	4	5	79	8	10
Zn	224	11	5	281	35	13
Ga	31	4	12	36	6	16
Ge	34	3	10	47	8	16
As	186	8	4	219	31	14
Se	9	3	36	12	4	31
Br	59	6	10	113	51	45
Rb	106	7	7	97	10	10
Sr	293	16	6	318	32	10
Y	63	5	8	62	8	13
Zr	207	17	8	175	29	17
Mo	29	4	15	29	6	21
Ba	558	131	24	428	190	44
Pb	110	15	14	112	32	28

Table VI
Concentrations of Major and Minor Elements (in weight %) in Feed Coal, Hydrated Lime, ESP Hopper Ash, Recycled Solids and Deposit Samples During Edgewater Coolside Process Demonstration Runs¹

Operation Date	Ohio Compliance Coal Feed Stock (n=8)		Turning Vane Deposit (n=1)	Hydrated Lime (n=1)	ESP Hopper Ash (n=12)		Recycled Solids (n=14)	
Feb. 8-16, 90	AVG	SD	AVG	AVG	AVG	SD	AVG	SD
Moisture	4.16	0.19	0.40	0.70	0.61	0.17	0.38	0.11
Ash	10.38	0.002	96.53	77.50	90.21	1.28	89.39	1.73
C	74.35	0.37	1.44	-	5.85	1.27	6.87	2.52
H	4.92	0.02	0.88	-	0.51	0.10	0.48	0.12
N	1.39	0.03	0.08	-	0.06	0.03	0.08	0.03
S	1.47	0.12	16.52	-	2.60	0.39	2.23	0.46
Si	2.29	0.07	4.84	1.87	16.84	0.81	16.61	1.08
Al	1.20	0.03	2.76	0.62	9.07	0.45	8.78	0.53
Ti	0.06	0.001	0.16	0.04	0.46	0.01	0.45	0.02
Fe	1.11	0.14	2.39	0.25	6.89	0.50	9.02	1.39
Ca	0.10	0.01	20.16	70.89	10.52	1.30	9.80	2.04
Mg	0.05	0.002	0.60	2.23	0.61	0.02	0.60	0.03
Na	0.03	0.01	4.54	0.03	1.36	0.37	1.10	0.35
K	0.19	0.01	0.53	0.10	1.45	0.08	1.40	0.08

¹Based on the daily operation logs of the Coolside process demonstration runs. These logs provide a detailed description of the equipment operations and operating problems encountered. McCoy, D. C., Scandrol, R. O., Statnick, R. M., Stouffer, M. R., Winschel, R. A., Withum, J. A., Wu, M. M. and Yoon, H., "The Edgewater Coolside Process Demonstration", a topical report, (CONSOL, Inc., Pittsburgh, PA 15129), February 1992, Appendix C.

Table VII
Elemental Concentrations of Hydrated Limes used in
Edgewater Coolside Demonstration Runs and Pilot Test Runs (n=2)

Element	Black River Hydrated Lime		Mississippi Hydrated Lime	
	AVG	SD	AVG	SD
F	100	1	90	1
Si, % ¹	0.61	0.05	0.37	0.05
Mg, % ¹	1.27	0.01	0.36	0.01
Na, %	0.01	0.00	0.01	0.00
Al, %	0.24	0.01	0.18	0.00
K, %	<DL	-	<DL	-
Ca, %	57.10	1.65	59.01	2.15
Mn	27	4	24	4
Fe, %	0.08	0.01	0.06	0.00
Cu	3	2	3	2
Zn	14	6	31	7
Ga	2	1	2	1
Sr	519	19	381	24

¹ Based on XRF data from CONSOL

Table VIII
Correlation Coefficients (r) for Pairs of Elements
Whose Concentrations in Coolside Wastes Varied with Time

Element Pair	Correlation Coefficient	p-Value	n
Na-S	0.392	<.0005	263
Na-Br	0.365	<.0005	263
Na-F	0.515	<.0005	263
Ca-S	0.516	<.0005	263
Ca-F	0.477	<.0005	263
Ca-Sr	0.347	<.0005	263
Ca-Fe	-0.191	0.0018	263
Fe-S	-0.537	<.0005	263
Fe-Sr	-0.207	0.0007	263
Al-Fe	0.650	<.0005	263
As-Zn	0.822	<.0005	263
As-Se	0.326	<.0005	263
As-Pb	0.273	<.0005	263
Se-Zn	0.374	<.0005	263

Table IX
Elemental Concentrations (ppm) of KY, OH, and W.Va. Fly Ash Samples¹

Element	KY	OH	W.Va	AVG	STD
Al*	13.15	13.12	8.88	11.72	2.01
As	79	62	27	56.00	21.65
Ba	769	772	618	719.67	71.90
Br	4	2.4	6.6	4.33	1.73
Ca*	5.47	0.6012	1.753	2.61	2.08
Cr	162	177	105	148.00	31.02
Cu	107	153	113	124.33	20.42
F	0.8	3.1	1.7	1.87	0.95
Fe*	3.81	4.86	7.99	5.55	1.78
Ga	110	40	15	55.00	40.21
K*	2.23	2.25	1.26	1.91	0.46
Mn	117	103	90	103.33	11.03
Mo	12	18	14	14.67	2.49
Na*	0.1326	0.1822	0.3154	0.21	0.08
Ni	21	15	24	20.00	3.74
Pb	19	15	8	14.00	4.55
Rb	279	256	127	220.67	66.89
Se	16	16.3	5.4	12.57	5.07
Sr	220	650	1484	784.67	524.74
Th	50	60	27	45.67	13.82
Ti*	0.763	0.7857	0.4379	0.66	0.16
V	257	238	152	215.67	45.68
Zn	41	21	16	26.00	10.80

*Concentration in weight %

¹Based on Furr, A. K., et al, Environ. Sci. Technol., 11, 1977, 1194-1201.

Table X
Concentrations of Major, Minor and Trace Elements (ppm) in Crustal Abundance, Appalachian Coal and U.S. Bituminous Coal Samples

Element (ppm)	Crustal Abundance ¹	Appalachian Coal Average ²	Range of U.S. Bituminous Coal ³
S, %	0.026	2.3	
F	625	80	< 13 - 1900
Li	20	28	1.1 - 370
Na, %	2.36	0.032	0.04 ²
Al, %	8.23	1.600	2.0 ²
K, %	2.09	0.230	0.24 ²
Ca, %	4.15	0.120	0.07 ²
Sc	22	5	0.6 - 27
Ti, %	0.57	0.090	0.15 ²
V	135	20	2 - 120
Cr	100	20	2 - 84
Mn	950	600	1 - 1400
Fe, %	5.63	1.900	0.44 ²
Ni	75	15	1.4 - 130
Cu	55	24	3 - 160
Zn	70	20	1 - 1600
Ga	15	7	0.7 - 35
Ge	1.5	6	<0.07 - 36
As	1.8	27	<1 - 170
Se	0.05	4.7	<0.6 - 20
Br	2.5	12	<0.6 - 160
Rb	90	22	-
Sr	375	100	4 - 920
Y	33	10	<1 - 41
Zr	165	50	1 - 170
Nb	20	5	-
Mo	1.5	3	<0.1 - 16
Ba	425	100	4 - 570
Pb	12.5	15	<1 - 62
Th	9.6	5	<3 - 26

¹Taylor, S. R, *Geochimica et Cosmochimica Acta*, 28, 1064. 1273-1285.

²U.S. National Geochemistry Committee, "Trace-Element Geochemistry of Coal Resource Development Related to Environmental Quality and Health", National Academy Press, Washington, DC, 1980, p.21.

³Swaine, D. J., "Modern Methods in Bituminous Coal Analysis: Trace Elements" in *Crit. Rev. Anal. Chem.*, 15(4), 315-346.

Table XI
Enrichment Factors of Elements in Average KY, OH, W.Va Fly Ash Samples
and Coolside Waste Samples with Respect to the Crustal Abundance¹

Element	<u>Avg. Fly Ash^a</u> EF $\pm \sigma$	<u>Coolside Avg.^b</u> EF $\pm \sigma$
As	22 $\pm$ 11	95 $\pm$ 13
Ba	1.19 $\pm$ 0.15	0.79 $\pm$ 0.35
Br	1.22 $\pm$ 0.60	35 $\pm$ 16
Ca	0.44 $\pm$ 0.43	1.76 $\pm$ 0.32
Cr	1.04 $\pm$ 0.27	1.08 $\pm$ 0.15
Cu	1.59 $\pm$ 0.32	1.12 $\pm$ 0.11
F	-	0.56 $\pm$ 0.12
Fe	0.69 $\pm$ 0.27	0.87 $\pm$ 0.13
Ga	2.58 $\pm$ 2.31	1.89 $\pm$ 0.29
Ge	-	25 $\pm$ 4
K	0.64 $\pm$ 0.19	0.50 $\pm$ 0.06
Li	-	3.37 $\pm$ 1.06
Mn	0.08 $\pm$ 0.01	0.10 $\pm$ 0.02
Mo	6.87 $\pm$ 1.43	15 $\pm$ 3
Na	0.06 $\pm$ 0.03	0.37 $\pm$ 0.06
Nb	-	0.85 $\pm$ 0.33
Ni	0.19 $\pm$ 0.04	0.76 $\pm$ 0.11
Pb	0.79 $\pm$ 0.31	7.00 $\pm$ 1.97
Rb	1.72 $\pm$ 0.64	0.84 $\pm$ 0.09
Se	177 $\pm$ 87	188 $\pm$ 58
Sr	1.47 $\pm$ 1.20	0.66 $\pm$ 0.07
Th	3.34 $\pm$ 1.24	1.00 $\pm$ 0.59
Ti	0.81 $\pm$ 0.23	0.52 $\pm$ 0.06
V	1.12 $\pm$ 0.29	1.08 $\pm$ 0.08
Y	-	1.46 $\pm$ 0.19
Zn	0.26 $\pm$ 0.13	3.13 $\pm$ 0.39
Zr	-	0.83 $\pm$ 0.14

¹Taylor, S. R, *Geochimica et Cosmochimica Acta*, 28, 1064. 1273-1285.

^aAvg. conc. of KY, OH, W. Va fly ash, based on Furr, A. K., et al, *Environ. Sci. Technol.*, 11, 1977, 1194-1201.

^bAvg. conc. of Coolside waste samples from all three runs (n=263).

Table XII
Elemental Concentrations (ppm) of Pilot Test Runs¹ Samples by PIGE/PIXE Analysis

Element	Test 1 (n=5) AVG $\pm$ 1 σ	Test 2 (n=5) AVG $\pm$ 1 σ	Test 3 (n=5) AVG $\pm$ 1 σ	Test 4 (n=5) AVG $\pm$ 1 σ
C, % ²	1.66	1.51	1.36	1.32
H, % ²	1.21	0.92	0.95	1.36
S, % ²	7.72	8.21	9.52	5.90
N, % ²	0.40	0.53	0.48	0.55
F	102 $\pm$ 10	120 $\pm$ 12	59 $\pm$ 4	116 $\pm$ 8
Li	50 $\pm$ 9	57 $\pm$ 7	44 $\pm$ 5	27 $\pm$ 3
Na, %	2.08 $\pm$ 0.03	2.03 $\pm$ 0.04	0.18 $\pm$ 0.01	0.18 $\pm$ 0.01
Al, %	5.50 $\pm$ 0.30	6.30 $\pm$ 1.40	5.40 $\pm$ 0.40	4.70 $\pm$ 0.40
K, %	0.78 $\pm$ 0.08	0.72 $\pm$ 0.02	0.80 $\pm$ 0.03	0.78 $\pm$ 0.02
Ca, %	24.1 $\pm$ 0.7	17.2 $\pm$ 0.5	21.1 $\pm$ 0.1 *	27.00 $\pm$ 0.10
Sc	868 $\pm$ 85	635 $\pm$ 23	685 $\pm$ 157	728 $\pm$ 57
Ti, %	0.12 $\pm$ 0.09	0.16 $\pm$ 0.03	0.15 $\pm$ 0.03	0.11 $\pm$ 0.03
V	150 $\pm$ 2	157 $\pm$ 1	13 $\pm$ 2	149 $\pm$ 2
Mn	78 $\pm$ 2	88 $\pm$ 9	80 $\pm$ 1	69 $\pm$ 5
Fe, %	3.72 $\pm$ 0.05	4.48 $\pm$ 0.02	4.22 $\pm$ 0.02	3.34 $\pm$ 0.01
Ni	39 $\pm$ 3	25 $\pm$ 3	24 $\pm$ 3	31 $\pm$ 4
Cu	31 $\pm$ 8	35 $\pm$ 7	27 $\pm$ 4	21 $\pm$ 3
Zn	60 $\pm$ 1	73 $\pm$ 1	76 $\pm$ 2	54 $\pm$ 3
Ga	18 $\pm$ 1	22 $\pm$ 5	21 $\pm$ 1	12 $\pm$ 2
Ge	13 $\pm$ 1	20 $\pm$ 2	14 $\pm$ 1	10 $\pm$ 1
As	43 $\pm$ 9	54 $\pm$ 4	50 $\pm$ 5	36 $\pm$ 4
Se	<DL	<DL	<DL	<DL
Br	10 $\pm$ 2	12 $\pm$ 1	<DL	1 $\pm$ 2
Rb	39 $\pm$ 3	51 $\pm$ 4	41 $\pm$ 7	39 $\pm$ 2
Sr	389 $\pm$ 3	461 $\pm$ 4	417 $\pm$ 25	399 $\pm$ 4
Y	11 $\pm$ 4	14 $\pm$ 4	18 $\pm$ 1	15 $\pm$ 8
Zr	91 $\pm$ 9	99 $\pm$ 12	95 $\pm$ 5	63 $\pm$ 5
Mo	14 $\pm$ 1	<DL	14 $\pm$ 1	11 $\pm$ 4
Ba	<DL	<DL	<DL	<DL
Pb	11 $\pm$ 1	8 $\pm$ 2	14 $\pm$ 2	18 $\pm$ 1

¹Test 1 = once-through mode with Na

Test 2 = recycle mode with Na

Test 3 = adv. Coolside mode without Na

Test 4 = once-through without Na

²Concentrations of C, H, N and S are based on 1 determination.

Table XIII Elemental Concentrations (ppm) of Avon Lake Fly Ash, Trans Ash and Ottawa Sand

ID	Trans Ash (n=2)		Avon Lake Ash (n=2)		Sand
	AVG	SD	AVG	SD	(n=1)
C, %	1.90	0.06	0.72	0.04	-
H, %	0.07	0.04	0.10	0.02	-
S, %	0.13	0.01	0.36	0.02	-
N, %	0.40	0.12	0.42	0.06	-
F	68	3	155	8	-
Li	188	14	151	15	-
Na, %	0.225	0.002	0.46	0.01	0.00
Al, %	17.40	0.05	12.86	0.03	0.05
K, %	2.17	0.03	1.95	0.08	0.00
Ca, %	0.85	0.006	2.81	0.09	0.01
Ti, %	0.88	0.01	0.65	0.04	0.00
V	241	4	218	49	1
Cr	176	4	247	6	14
Mn	136	6	211	20	7
Fe, %	7.99	0.28	12.46	0.91	0.05
Ni	76	2	160	139	8
Cu	172	1	95	3	1
Zn	149	1	150	6	6
Ga	58	2	47	3	1
Ge	39	3	52	2	1
As	108	4	141	11	1
Se	3	1	14	3	
Rb	142	2	121	15	
Sr	632	8	814	54	
Y	98	10	56	4	
Zr	376	4	344	4	29
Nb	38	7	22	11	
Mo	25	3	23	8	
Ba	1805	86	1401	152	
Pb	93	11	46	1	
Th	29	6	17	5	

¹Avon Lake Fly Ash is the parent materials used in the pilot test runs.
Trans Ash is the control ash used in the field lysimeter experiments.

Table XIV
Elemental Concentrations of LIMB Wastes by PIGE/PIXE Analysis

Element	AFBC Waste		FBC-Hydrated		FBC-Non Hydrated	
	AVG	SD	AVG	SD	AVG	SD
C, % ¹	2.91	-	5.15	-	5.07	-
H, % ¹	0.63	-	1.25	-	0.34	-
N, % ¹	0.71	-	0.32	-	0.66	-
S, % ¹	0.02	-	5.06	-	4.08	-
F	1046	42	281	2	315	2
Li	<DL	-	32	4	39	7
Na, %	0.05	0.001	0.16	0.02	0.18	0.02
Al, %	1.22	0.12	2.88	0.10	3.48	0.29
K, %	0.54	0.05	0.59	0.04	0.88	0.03
Ca, %	26.00	2.13	29.41	0.83	23.62	7.18
Ti, %	<DL	-	0.05	0.02	0.08	0.04
V	105	57	135	24	133	20
Cr	12	3	41	16	55	20
Mn	91	7	126	27	130	22
Fe, %	0.28	0.05	2.53	0.58	2.99	0.85
Ni	14	3	4	2	10	4
Cu	12	3	32	6	24	5
Zn	174	46	26	12	59	4
Ga	3	2	9	7	8	3
Ge	4	1	9	1	20	5
As	10	2	21	4	16	9
Se	3	1	9	2	7	2
Br	11	3	30	3	32	2
Rb	6	2	28	10	45	14
Sr	348	26	713	101	738	31
Y	3	1	20	2	18	2
Zr	20	6	101	19	91	12
Ba	<DL	-	3486	343	3838	378
Pb	6	3	15	3	37	23

¹ Concentrations of C, H, N, and S are based on 1 analysis.

Figure

Elemental Concentrations of Coolside Solid Materials

Figure 2

COOLSIDE

Figure 3

COOLSIDE

Figure 4

COOLSIDE

NaOH Pump
Hydrated Lime
Recycled Solid

Figure 5

COOLSIDE

Figure 6

Figure 7

Figure 8

FBC Pellets

Figure 9 1.Swell Versus Time, FBC Pellets.

Figure 10 . Swell Versus Time, Coolside Run #2 CBR Samples.

Figure 11 . Swell Versus Time, FBC Ash CBR Samples.

Figure 12 . Swell Versus Time, FBC Ash (Non-Hydrated) CBR Samples.

Figure 13 . Unconfined Compressive Strength Versus Time, FBC Ash (Hydrated), 95% Standard Density.

COOLSIDE WASTE MANAGEMENT RESEARCH

Technical Progress Report

Contract No: DE-AC21-91-MC8162

Report Period: June 1, 1993 to June 30, 1993

Statement of Project Objectives

Produce sufficient information on the physical and chemical nature of Coolside waste to design and construct physically stable and environmentally safe landfills.

Summary of Progress for Period

Monitoring of swell has continued on Coolside pilot plant #2 and FBC hydrated ash which have been remolded under a variety of conditions.

Subtask 2.3 Geotechnical Characterization of the Waste

Swell Tests

Monitoring of swell continued on the following samples: Coolside pilot plant run #2 and FBC ash. Swell specimens for both materials were remolded near 95% of standard maximum dry density and optimum moisture content. The samples were remolded in CBR molds (6 inch diameter, 4.584 " height) and swell was monitored under the following conditions:

- approximately 12.5 lb. surcharge, no age time
- approximately 2.5 lb. surcharge, no age time
- approximately 12.5 lb. surcharge, 7 days age time
- approximately 2.5 lb. surcharge, 7 days age time

Time of aging represents the amount of time before the samples were placed in water. Aged specimens were sealed at room temperature to prevent moisture loss before placement into the water tank.

Swell tests were continued on non-hydrated FBC specimens remolded near 95% of standard density and optimum water content in CBR molds. Swell is being monitored with aging and surcharge conditions similar to those of hydrated FBC ash and Coolside #2. Results, to date, of swell tests are presented in Figures 1 - 4.

Swell measurements also continued on FBC pellets. The pellets were loosely placed in CBR molds. Two samples are being monitored with surcharges of approximately 2.5 and 12.5 pounds.

Reports

Four papers authored or co-authored by Tommy Hopkins and Tony Beckham were prepared for publication at the Tenth Annual Pittsburgh Coal Conference. The publications are results of some the research, performed to date, in the Coolside Waste Management Study. The titles and respective authors are:

Title	Authors
"Mineralogical Transformations of Ettringite in Concrete Derived from Dry FGD By-Products"	U.M. Graham M. M. Wu T. L. Robol T.C. Hopkins
"A Proposed Procedure for Compacting Samples for Physical Properties Testing"	T.C. Hopkins T.L. Beckham
"Swelling Characteristics of Coolside and FBC By-Products"	T.C. Hopkins T.L. Beckham M.M. Wu
"Techniques used in Placement of Coolside By-Product in Field Lysimeters"	T.L. Beckham T.C. Hopkins

Work Planned For Next Month

Monitoring of swell will continue on FBC ash, FBC pellets, and Coolside run #2 samples.

Figure 1. Swell Versus Time, Coolside Run #2 CBR Samples.

Figure 2. Swell Versus Time, FBC Ash CBR Samples.

Figure 3. Swell Versus Time, FBC Ash (Non-Hydrated) CBR Samples.

FBC Pellets

Figure 4. Swell Versus Time, FBC Pellets

END

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