**High Volume--High Value Usage of Flue Gas Desulfurization
(FGD) By-Products in Underground Mines
Phase 2: Field Investigations**

**Quarterly Report
July 1 - September 30, 1997**

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High Volume--High Value Usage of Flue Gas Desulfurization (FGD) By-Products in Underground Mines

Phase II: Field Demonstrations

Cooperative Agreement No.: DE-FC21-93MC30251

Quarterly Report for the Period July 1 to September, 1997

Summary of Activity for the Quarter

During this quarter, the majority of activity focused on grout emplacement at the Lodestar Energy Inc. (formerly Costain Coal Co.) surface mine auger holes described in the previous report. Specifically, two different types of grout pumps were investigated: a piston pump used in previous demonstrations, and a progressive cavity pump. The latter is currently utilized for grouting in underground coal mines, is relatively small and portable, and is capable of receiving dry material (e.g. fly ash) and water, mixing it to produce a grout, and pumping the grout at high pressure. It is therefore worthwhile to investigate it's potential use in auger mine filling.

Several field demonstrations were conducted using the different pumps. Numerous problems were encountered when using the progressive cavity pump, all of which were related to its inability to handle the highly reactive and heterogeneous FBC fly ash. Even relatively small ash agglomerates (< 1 in. in diameter), which were not a problem for the larger piston pump, caused blockages in the progressive cavity pump which not only proved extremely difficult to clear, but also resulted in significant mechanical failures. Furthermore, mixing of dry fly ash with water within the progressive cavity pump was inconsistent and difficult to control. Consequently, the pump was unable to completely fill even a single auger hole.

Using the truck-mounted concrete piston pump, three auger holes were selected for grouting using both fly ash and bed ash grouts. The reason for these additional tests was to determine if the methodology devised during previous experiments can be used with different types of ash; it is likely that, in practice, there will be different proportions of bed ash and fly ash in the grouts, thus producing a heterogenous material with respect to water required to achieve a desired slump, heat generated, and stiffening and setting times. In fact, it was found that a large proportion of bed ash in the grout generated a large amount of heat and caused early stiffening of the material.

During the experiments, cylinders of grout were prepared for compressive strength testing, and moisture contents were determined on-site. A thermocouple assembly was also constructed to record grout temperatures within an auger hole.

Task 1. Field Demonstration

Subtask 1.2 Auger Hole Emplacement Demonstration

Site Preparation

Information on the auger holes described in the April 1 to June 30, 1997 report is again provided herein for reference (Table 1). Additional site preparation consisted mainly of pumping water from the individual holes and from the area in front of the highwall. No additional auger holes were uncovered. Auger holes designated L1, L2, and R13 were selected for grout emplacement using the piston pump, and hole L8 was selected for the progressive cavity pump demonstration.

Table 1. Data for Lodestar Mine Auger Holes (31 in. diameter)

Hole No.	Depth (ft.)	Vol. (yds ³)	General Condition
L1	70	18	Standing water; not connected with L2; top 6" of hole uncovered
L2	70	18	Standing water; not connected with L1 or L3; good cond.
L3	78	20	Standing water; not connected with L2 or L4; good cond.
L4	85	22	Standing water; connected with L5; partially blocked at 33 feet
L5	85	22	Standing water; connected with L4; partially blocked at 33 feet
L6	96	25	Standing water; partially blocked
L7	>125	33	Standing water; good condition
L8	37	9	Blocked at 30 feet; connected with L9
L9	90	24	Partially blocked at 20 feet; connected with L8
L10	105	28	Standing water; good condition, no caving, small crack in part of wall
R1	n.d.	n.d.	Uncovered only top 6" of hole; no depth/condition data
R2	75	20	Standing water; connected with R3
R3	70	18	Cave-in at 70 feet; hole may actually be deeper
R4	100	26	Good condition
R5	20	5	Cave-in at 20 feet; hole may be deeper
R6	20	5	" " "
R7	20	5	" " "
R8	20	5	" " "
R9	20	5	" " "
R10	n.d.	n.d.	Hole is extensively caved-in and connected with R11; standing water
R11	n.d.	n.d.	Same condition as R10; standing water
R12	85	22	Standing water; connected with R11
R13	80	21	Standing water; connected with R12

* n.d. = no data

Grout Emplacement: Progressive Cavity Pump

In this demonstration, a progressive cavity pump was chosen for testing. It is produced by FOSROC Inc. and is designed to pump a foam-like grout into underground coal mines. The unit is permanently mounted on a skid, is relatively compact and portable (Figure 1), and is reportedly capable of pumping a stiff, low-slump (and thus, high-strength) grout. It is electric driven, thus requiring a 480V 3-phase generator on-site and produces between 10 and 15 h.p., depending on the specific model. The FOSROC design contains a screened hopper that conveys the dry fly ash to a screw feeder via gravity. The ash is fed into a small chamber where it is mixed with an adjustable amount of water, and is then conveyed to the pump. The grout mix is pumped through a 4 inch opening, a "t" connection that contains several valves and a pressure gauge, and finally through a 1 in. high-pressure flexible hose, from which it is delivered into the auger hole. For the field demonstration, a dump truck was employed to deliver moist (7-8% moisture) to the mine site (Figure 2), and a skid-steer and hand shovels were used to load the ash into the hopper (Figure 3).

Moisture content of the grout (Table 2) was obtained on-site using a microwave oven and electric balance. Samples of fresh grout were placed into an tared Pyrex dish, weighed, and placed into the microwave oven (powered by an electric generator) and dried for 15 minutes. The samples were then removed from the oven and re-weighed.

Table 2. Moisture content of progressive cavity pump grouts

Sample No.	Moisture (wt.%)
1	46.8
2	41.2

Although the progressive cavity pump was relatively straightforward to operate, numerous problems were encountered when using it for the field demonstration, all of which were related to its inability to process the highly reactive and heterogeneous FBC fly ash. Mixing the dry fly ash with water was not only difficult to control, but was inconsistent to the extent that partially wetted clumps of ash became tightly compacted within the exit hose, thus causing the pump to clog and shut down. This was particularly a problem within the steel "t" connection; the interior of the valves in this assembly were merely 3/4 inch in diameter. The grout flow was therefore highly constricted at this junction, and blockages resulted. Even relatively small fly ash agglomerates (< 1 inch diameter) caused blockages that not only proved extremely difficult to clear, but also resulted in catastrophic and, in some cases, spectacular mechanical failures. Although the grout was prepared at a high slump (>10 inches, 41-47% moisture; Table 2) to prevent clogging, the low throughput rate and repeated blockages resulted in the failure to significantly fill even a single auger hole (L8) with grout.

Figure 1. Backhoe moving the progressive cavity pump.

Figure 2. Close-up of progressive cavity pump unit. Outlet is to the right.

Figure 2. Dump truck delivering FBC fly ash to test site at surface mine.

Figure 3. Loading fly ash into progressive cavity pump hopper.

Some of the problems encountered with progressive cavity pump were specific to the design of the equipment used. The auger feed system and the barrel of the pump shared a common drive. This arrangement caused problems during failures. For example, at one point the clutch failed causing loss of power to both the feeder and pump. The grout stiffened during the period it required to replace the clutch. This caused the second clutch to fail. By the time the pump was returned to the lab, the grout was completely solidified, requiring complete disassembly. After several days of coaxing the auger with sledge hammers and concentrated acids the repair of the pump was deemed beyond the capacity of the University and was returned to the factory. After the project personnel had deactivated three pumps, the mining equipment vendor's enthusiasm appeared to wane and some resistance was encountered obtaining more equipment.

Although our experience was negative, the use of this style of equipment should not be ruled out. However, much more robust equipment with higher horsepower motors and at least 2-inch diameter delivery pumps would be required to succeed in this application.

Grout Emplacement: Piston Pump (August 1, 1997)

The equipment utilized for the grout emplacement is similar to that used in previous field tests, described in the October 1 through December 31, 1996 quarterly report. In summary, concrete mixing trucks were charged with FBC ash and water, to produce a grout, at the Lodestar Energy Inc. railway load-out facility, approximately five miles from the surface mine (test site). The material was then transported to the site and transferred to a truck-mounted concrete piston pump used to inject the material into the auger holes. Grout was pumped into the holes through 4 inch i.d. pvc pipe that was connected to the concrete pump via a flange assembly. Hardened chunks of fly ash, formed within the railcars during transit to the load-out facility, were removed from the grout using a large screen (1 inch openings) installed on the concrete pump hopper.

Several auger holes were selected for grouting in this field demonstration. The reason for these additional tests was to determine if the methodology devised during previous experiments can be used with different "types" of ash; it is likely that, in practice, there will be different proportions of bed ash and fly ash in the grouts, thus producing a heterogenous material with respect to the amount of water required to achieve a desired slump, heat generated, and stiffening time. Each of the auger holes selected for these tests were prepared for grouting by uncovering only the top 6-10 inches of the hole, thus leaving in-place a large amount of rock and soil to function as a bulkhead.

A total of six truckloads of grout, (10 yds³ each) were used for the tests. Water content was adjusted at the load-out facility by preparing the grout with a slump (measured with a concrete slump cone) of approximately 10 inches. General information on the contents of each truck are provided in Table 3.

Table 3.

Truck No.	Contents	Tare Wt. (lbs.)	Final Wt. (lbs.)	Water Added (gal.)	Water Added (lbs.)	Ash Weight (lbs.)
1	BA*	28520	51180	900	7497	15163
2	BA	28120	60820	950	7914	24787
3	BA/FA	29940	61980	913	7605	24435
4	FA	28836	59180	800	6664	23680
5	FA	29571	57840	800	6664	21605
6	FA	35911	58940	800	6664	16365

* BA=bed ash, FA=fly ash, BA/FA=bed ash/fly ash mix

Because of the significant amount of time required for the concrete trucks to drive to the mine site after loading with grout (ca. 30 minutes), additional water was required at the site. The grout exhibited some stiffening during transport, and over the course of the grouting operation. In addition, a considerable amount of steam was lost from the top of the mixing drum. This meant that water needed to be added to the mixing trucks before and during the discharge of grout into the concrete pump. As a result, simply recording the amount of water added would not provide an accurate record of the water content of the grout: on a percentage basis, this value probably changed during the operation. Therefore, moisture content was obtained at the site using the microwave method described above. Several samples were taken from each truck at various stages of discharge; the results are reported in Table 4.

Table 4. Moisture content of piston pump grout

Truck No.	Sample No.	Moisture (wt.%)
1	1-1	31.2
1	1-2	31.0
2	2-1	28.2
2	2-2	31.2
3	3-1	33.6
3	3-2	34.7
4	4-1	40.0
5	5-1	38.0
5	5-2	38.0
6	6-1	42.0

The moisture contents are in the range of the targeted upper limit of 35%, which was derived from laboratory tests on the effects of water content on compressive strength (described in earlier reports). However, the moisture values are also probably not entirely accurate because the microwave oven probably has not completely decomposed the calcium hydroxide that forms upon hydration of the calcium oxide ("quicklime") in the ash. Because the bed ash generally comprises a greater amount of calcium oxide, the error is potentially greater for this material. This would partially explain the low moisture values for Trucks #1 and #2, despite the copious amount of water added to the grout. Furthermore, a great deal of steam was produced (thus removing some of the water prior to analysis) upon hydration of the bed ash. Note that with a decreasing amount of bed ash in the mix, the moisture content generally increases (Tables 3&4).

Although the moisture content of the fly ash grout (~40%) is higher than the laboratory-specified maximum, it is anticipated that the compressive strength of the grout will be sufficient because of the high curing temperature within the auger hole. The rationale for this has been discussed in the April 1 to June 30, 1997 report. Temperature measurements of the grout were obtained during the field demonstration, both on cylinder samples (obtained for compressive strength testing) and within an auger hole. Cylinder temperatures were obtained using a thermocouple with a battery-powered digital readout, and ranged from 45° to 75°C (Table 5).

Table 5. Grout cylinder temperatures

Truck No.	Cylinder No.	Temperature (°C)
1	1-1	59
1	1-2	54
2	2-1	75
2	2-2	75
2	2-3	71
3	3-1	69
3	3-2	69
3	3-3	69
4	4-1	45
5	5-1	52
5	5-2	n.d.
6	6-1	n.d.

Because of their relatively small mass, the cooling rate of the grout cylinder samples is not representative of that within the filled auger holes. Consequently, an apparatus was constructed to measure the temperature within auger hole L2 (70 feet deep) before and after grouting. It

consisted of 75 feet of 1.5 inch pvc pipe with thermocouples mounted at the end and in the middle. The pvc pipe was configured such that the ends of the thermocouples were not lying on the bottom of the auger hole (Figure 4). Each thermocouple was connected to a wire that was threaded through the inside of the pvc pipe, leading out to the hole entrance (Figure 5). Temperature data was recorded from each thermocouple using a battery powered digital readout, and is discussed below in the descriptions of grouting procedures for each auger hole.

Auger Hole L1

Prior to grouting, hole L1 was not pumped of standing water in order to determine if the FBC grout could displace the water out the entrance of the hole, since this hole was not connected (via caving of the walls) to the adjacent holes. Almost two (2) truckloads (approximately 10 yds³ each) of primarily bed ash-based grout were successfully placed into the auger hole, which is consistent with a calculated capacity of 18 yds³. Forty feet of 4 inch Schedule 80 pvc pipe was utilized to place the grout. After approximately 1/2 of the second truckload was injected, a large amount of water began to flow from the hole entrance and continued to do so until grout was rejected from the hole. Based on the amount of grout pumped into the hole and the amount of

water expelled, it was concluded that the grout had sufficient slump to flow to the back of the hole and effectively displace the standing water. However, the large amount of bed ash in the grout generated a large amount of heat and caused early stiffening of the material which was difficult to control, even with nearly continuous water additions. Although hole L1 was filled with this material, it would be preferable to prepare grout with less bed ash.

Auger Hole L2

This hole was selected for temperature measurement using the thermocouple apparatus described above. The assembly was placed in the hole such that temperatures could be obtained from 40 foot (middle of hole) and 70 foot (end of hole) depths. To accomplish this, standing water within the hole was pumped out prior to insertion of the thermocouples and subsequent grouting. The temperature of this auger hole prior to grouting was 19°C in the middle, and 16°C at the end.

The grout used in this hole comprised a portion of Truck #2 (mainly bed ash) and the majority of Truck #3 (fly ash/bed ash mix), indicating that only about 10 yds³ was placed in the hole before rejection of the grout. This was confirmed by temperature data: whereas the middle of the hole reached a temperature of 70°C during the grouting procedure, the rear of the hole remained at 16°C, indicating that the hot grout did not flow the length of the hole. The problem was caused by the material being too stiff. In retrospect, more water should have been added to the grout to increase the slump. However, there was concern that too much water would result in low compressive strength. It is now felt that the high curing temperature within the hole would help counteract the negative effects of the high water content. Laboratory experiments have been devised to determine if this is indeed the case. Moreover, temperature measurements taken 5 days after grout emplacement revealed that the middle portion of the auger hole was still at 62°C.

Figure 4. End of thermocouple-PVC assembly. This section was placed at the back of the hole. Thermocouple protrudes through the black cap at top.

Figure 5. Top view of thermocouple-pvc middle section. Note wires threaded through pipe. Thermocouple protrudes through black rubber cap at top.

Auger Hole R13

Similar to hole L1, standing water was left in R13. During grouting, a very large quantity of water was observed flowing from the adjacent open hole (R12). It is estimated that hole R13 was filled to its capacity of 21 yds³, since approximately 2 ½ truckloads of grout were placed into this hole. In fact, more grout was injected than the hole should have been able to accommodate, suggesting that some of the grout flowed into an adjacent hole, which is consistent with the observation of water flowing from the adjacent hole R12.

General Comments

Tests were only conducted on three auger holes mainly because of the extensive amount of time that elapsed between truckloads of grout arriving at the mine site, often in excess of one hour. This not only severely limited the number of holes grouted, but also caused problems with grout slump; the grout stiffened within the mixing trucks, pump, and (partially filled) auger holes between deliveries.

Based on the three field demonstrations with the piston pump, it is concluded that the use of concrete mixing trucks be avoided in favor of mixing the grout at the mine site using a mill. The dry (or slightly moist for dust prevention) FBC ash could be delivered to the site by truck, and the ash loaded into the mill with a wheel loader or skid steer. Upon mixing with a specified amount of water, the grout product would then be directly conveyed to the concrete pump for emplacement into the auger holes. The truck-mounted concrete pump is well suited for this work mainly because of the high pumping rate and the extendable 90 foot boom. The boom was able to maneuver the heavy, Schedule 80 pvc pipe with ease and, more importantly, could hold the pipe in the auger holes during pumping. As each hole is filled, there is a tendency for the pipe to be ejected from the hole as the back pressure increases (some pressure is necessary to completely fill the horizontal holes). It is very difficult to manually keep the pipe in place, whereas the hydraulic-powered boom effectively restrains it. In addition, the boom was able to span the 50 feet of mud and water between the access road and the highwall face containing the auger holes. This allowed for the majority of work to be performed on a dry, graded surface instead of in the very wet, muddy area directly in front of the auger holes.

Subtask 1.4 Monitoring of Strength, Stress, and Permeability

Compressive strengths of grout cylinders (6 in. by 12 in.) taken during operation of the progressive cavity pump are shown in Table 6. Despite the high moisture content of the grout mix, the compressive strength is good. It is anticipated that the 28-day compressive strengths will meet the 500 PSI criterion.

Table 6. 14 Day compressive strength of progressive cavity pump grout

Sample No.	Compressive Strength (PSI)
1	330
2	440

Numerous cylinder samples (2-3 per mixing truck) for compressive strength were also obtained on the grout prepared for injection by the piston pump. After temperature measurement of the grout, each cylinder was placed in an empty auger hole for curing and covered with wet burlap bags. After 5 days curing, the cylinders were retrieved from the site and stored in a controlled temperature/humidity room at the University of Kentucky Department of Civil Engineering laboratory.

Unconfined compressive strengths were planned to be acquired after 14 and 28 days curing. However, just prior to the 14 day test it was discovered that the temperature of the curing room had been lowered to below 0°C for an unrelated experiment, thus freezing the grout cylinders before they had time to properly cure. As a result, the structural integrity of the cylinders was comprised, resulting in grout spalling from the surface during the preparation steps for strength testing. Thus, strength data are not available for the August 1 field demonstration. At this point, the foreman of the Lodestar strip mine is confident that *in-situ* samples of grout can be obtained from the augered coal at a later date, because the company plans to mine through the site. Close correspondence will be maintained with the company so that this opportunity to recover compressive strength data is not lost.

Task 2.0 Data Analysis

In the previous report (April 1 to June 30, 1997) the influence of water content, and curing temperature on strength and composition of the FBC ash grout was discussed. In response, a series of laboratory experiments has been devised in which cylindrical samples of grout will be prepared at four different water contents and cured at a minimum of two different temperatures in a humid environment. The higher temperature environment will attempt to reproduce the curing conditions within an auger hole, whereas the lower temperature curing will be similar to that for the grout cylinders prepared during the field demonstrations. Compressive strengths will be acquired at four or five different times, over the course of approximately 30 days. X-ray diffraction (XRD) analysis will be conducted on the tested grouts to determine the composition of the crystalline phases. Optical microscopy will also be used on thin-sections of the grout samples in order to examine the physical structure of the grouts and the distribution of the different components, with the goal of elucidating the properties that significantly influence and control compressive strength of the FBC ash grouts.