FLUID PLACEMENT OF FIXATED SCRUBBER SLUDGE IN ABANDONED UNDERGROUND COAL MINES TO REDUCE SURFACE SUBSIDENCE AND TO ABATE ACID MINE DRAINAGE

R. James Meiers
Indianapolis Power & Light Company
Indianapolis, Indiana

Abstract

The goal of this project was to demonstrate the technical feasibility of placing fixated scrubber sludge (FSS) into abandoned underground coal mines to control subsidence and to reduce acid mine drainage. The effectiveness of the technology was determined by the total reduction of the mine void and the strength of the injected FSS. The overall effect on the hydrogeologic environment by using this technology was determined through a ground water monitoring program. Laboratory and bench scale testing determined the composition for optimum flow, minimization of free water, and the optimum settling / physical characteristics. 'The full scale demonstration involved the injection of approximately 16,400 cubic yards of FSS. Borehole photography and core sampling of the placed FSS provided the data necessary to determine the effectiveness of subsidence reduction. The investigative techniques documented good overall roof contact of the injected FSS, unconfined compressive strengths greater than 100, and low permeability coefficients. The groundwater monitoring detected changes in the concentration of chemical parameters in the mine pool water, but no significant changes in ground water chemistry surrounding the mine.

Introduction

Indianapolis Power and Light Company (IPL) began this research to develop a technology to reduce surface subsidence using fluid placement techniques of the FSS because abandoned underground coal mines surrounded property adjacent to existing coal combustion by-product (CCBP) landfill area. Landfill expansion into the area is in question because of the high potential for sinkhole subsidence. Sinkholes manifested at the surface put the integrity of a liner or runoff pond containment structure for CCBP disposal facility at risk. The Indiana Solid Waste Regulations prohibit the construction of a land disposal facility over abandoned underground mines without some demonstrated method of subsidence control. The fluid placement techniques of FSS as a subsidence abatement technology was demonstrated during an eight week period in September, October, and November, 1994 at the Petersburg Generating Station located in Pike County, Indiana. The EPA (Region V) required IPL to register the injection boreholes used during the demonstration in the Underground Injection Control Program.

Site Selection

The abandoned underground coal mines evaluated for this project are found in the Illinois Basin No. V coal seam. The abandoned mines at.or around the Petersburg Station were ranked on the basis of the following criteria:

- probable open voids
- ability to isolate the area to receive the injected material
- ability to locate the mine by the use of mine maps and land surveying
- probable surface conditions.

The Arnold Willis "City" Mine was selected primarily because of its small size, available mine maps, easy surface access, and proximity to the power plant. The initial borings documented the accuracy of the City mine map and determined the condition of the mine workings. Depth to the mine voids varied from 32 to 64 feet. Mine void varied from 2.0 to 7.0 feet in height. The borings encountered both dry mine and flooded conditions. Due to the mine floor slope, sections of the mine workings were completely flooded. The mine pool elevation was at 436 and remained constant throughout the monitoring period. A map of the Arnold Willis "City" Mine *Figure 1. Mine Map* depicts the existing surface topography, and coal seam elevations. The coal was removed from this mine in the late 1940's and early 1950's at different extraction rates varying from 50% to 70%.

Environmental Monitoring

The objectives of the water quality monitoring plan were to define baseline conditions existing prior to the FSS injection and to monitor changes during and after the demonstration. The monitoring program assisted in identifying environmental changes related to the mine stabilization and defined the migration patterns of FSS constituents and the fluids that were displaced from the mine by the injected grout. The monitoring wells were placed in close proximity to the mine workings so that any water quality impacts would be readily detected and evaluated. There were two monitoring wells located upgradient to determine background water quality (SC-1 and FW-1). The monitoring points located in voids and pillars were used to monitor the water quality of the mine pool (B-4, B-7, B-12, B-14, B-16, B-22, B-23). Other monitoring points were located in the coal seam downgradient of the mined area (B-17, B-18, B-19, SC-3, and SC-4). The location of these monitoring points with respect to the mine can be found in *Figure 2. Borehole Location.*

A total of nine sampling events were completed. The monitoring points were sampled during each event and tested for twenty two different water quality parameters. In examining the post injection ground water monitoring data as compared to the leachate data for the FSS, the constituents that emerged as the most useful or as primary indicators of water quality changes related to the FSS injection were, in order of decreasing significance, sodium, potassium, calcium, boron, chloride, and magnesium. Sulfate, TDS, and specific conductance were secondary indicators of FSS injection effects, i.e., changes in these parameters were observable at some monitoring sites but were generally of lesser magnitude and frequency. Arsenic, cadmium, chromium, 'lead, selenium, aluminum, barium, nitrate, and sulfide were relatively unaffected by the injection of FSS into the mine. The pH (6.0 to 7.5) and acidity of the mine pool were not significantly affected by the injection of FSS into the mine, suggesting that the mine water's buffering capacity effectively resisted changes in these parameters.

Ground water in rock and tmmined coal exhibited no increases or only subtle, attenuated increases in constituent concentrations and in the number of affected chemical constituents compared to water in mine voids. Comparisons of leaching test and field monitoring data suggest the laboratory data can be employed as broad indicators of probable chemical changes within the mine pool.

'Fixated Scrubber Sludge - FSS

FSS is a flue gas desulfurization by-product blended with dry flyash and quicklime. The Petersburg Generating Station burns bituminous coal mined in Indiana. The resultant fly ash (Type F) is a good quality pozzolan meeting ASTM C-593. The flue gas desulfurization systems are wet limestone scrubbers. The scrubbers are inhibited oxidation systems which produce a by-product that is primarily a calcium sulfite hemihydrate, containing minor quantities of calcium sulfate dihydrate (gypsum) and silicon dioxide (as quartz). The pozzolanic activation additive is calcitic quicklime (calcium oxide) with minor quantities of magnesium oxide and silicon dioxide (as quartz). All of the CCBP components of FSS and the quicklime were characterized to develop a baseline of the constituents of the FSS grout. A surface water source (an abandoned strip pit) and the actual mine pool water were also characterized. The abandoned strip pit was used as dilution water source for the FSS blend during the demonstration.

Microstructure/Cementation/Stability Evaluation

EPRI has found in related studies of cementation in coal combustion residues, developing this type of chemical information is critical to optimizing performance and stability. FSS materials are chemically active in the sense that the main constituents (i.e., fly ash, scrubber sludge, lime and water) react over time with each other to form other distinct chemical and mineralogical phases. These phases are responsible for the “self-cementing” action which produces the physical strengths in the FSS by-products after they have “cured”. Understanding the chemical processes responsible for cementation of the FSS grout would determine the chemical stability of FSS by-product when exposed to the mine water environment.

The principal hydration product in FSS is calcium sulfoaluminate or ettringite $Ca_6Al_2(SO_4)_3(OH)_{12}\bullet 26(H_2O)$. The cementation in the FSS grouts occurs largely through the formation of the ettringite by sulfo-pozzolanic reactions involving the gypsum and aluminate derived from flyash in an alkaline media. The mineralogy data confirmed the reactive phase in the scrubber sludge is the gypsum $(CaSO_4)$, representing 5-10% by mass of total solids. The reactive component in a Class F flyash is principally the aluminosilicate glass representing 45-50% by mass. Other reactive components in flyash include soluble alkali sulfates (typically deposited on the surface of ash particles) and free lime.

The growth of ettringite strongly parallels the strength development in FSS. Also a notable feature is the steady increase in bound water with time which correlates with the compressive strength gains. The microstructure shows good densification by six months with cementing by the ettrignite and C-S-H. Some expansion ($\approx$5 vol%) during curing appears to be a characteristic feature of the FSS grout system which proved to be a beneficial effect underground improving contact with the walls and roof of the mine.

Bench Scale Test Program

Although a considerable amount of information has been generated by the utility industry and others on the chemical and physical properties of FSS by-product materials (e.g., strength, permeability, leachability), very little is known about the fluid and/or FSS grout materials used for injection. In meeting the goals of the project, the placement of FSS eliminated the mine void space with a minimal number of injections points. To accomplish this, the FSS mix design had to be optimized for flowability and strength development in a bench scale test program. The objective of the bench scale study was to provide information focused toward determining the best compositions for mine injection. Dispersion in underground voids is necessary if the voids are to be filled. In addition, quantities of supernatant fluid after settling, and resistance to acidic mine water were critical criteria.

The bench scale test program studied a wide range of compositions consisting of 36 test different compositions. Four levels of solids content (45%, 50%, 55%, 60%, wet weight basis), three levels of fly ash to FGD by-product ratios (0.7:1, 0.9:1, and 1.1:1 dry weight basis) and three levels of quicklime content (2%, 3%, and 4%, dry weight basis) were explored. The various compositions were evaluated for viscosity, density as blended, density after settling, flowability in a one-dimensional “tunnel flow” protocol, and angle of repose. The various compositions were then cured under accelerated conditions to project strength development. The underground void temperatures have been found to be in the range of 50” F to 55” F. Ambient conditions as defined by ASTM, focus on 73” F. Time temperature relationships for pozzolanic or sulfopozzolanic reactions are approximately as follows: 50” F for eight weeks is approximately equal to 73” F for four weeks. The accelerated cure test promoted the desired hardening chemistry in half the time.

Optimization of Strength of the FSS Mix Design

Laboratory testing determined the range of strengths available from different FSS mix designs conforming to the flow characteristics developed during the bench scale testing. The solids content of the FSS grout mixtures is the dominant factor in determining strength property. Quicklime content is also a critical component of the FSS grout. It was determined that a minimum of 4% lime content is required to meet a design specification of 100 psi or greater. It is possible to tailor the strength potential of the FSS to different areas of the mine by increasing flyash to sludge ratios or increasing quicklime content without changing the moisture content. The higher strength mix could be designed into the “batch mix” when additional ground or lateral support is required; and a lower strength used when bulk filling a large underground void.

Optimization of Flow/Rheolonical Prouerties of FSS Mixes

The relationships between the rheological properties and mix proportions of the range of FSS mix designs over a wide range of solids contents were determined. Fluid characteristics were determined to be cohesive and stable under shearing conditions. The flyash to sludge ratio of the grouts was a less important design variable. However a higher flyash content has been shown to improve fluidity of the grout. Higher flyash contents are also expected to improve stability of the grout underground.

An examination of the effect of selected chemical flow additives (such as water reducers or plasticizers) on the rheological properties of the FSS mixtures was conducted. Chemical agents of this type are widely used in the concrete construction industry as a means of reducing the amount of water needed in a cementitious mixtures for a given flow/workability. The feasibility of using these flow enhancing additives determined the solids content of the FSS mixtures can be increased while at the same time maintaining adequate flow. Selection of the proper plasticizers is critical because some effect the pozzalonic chemistry that can result in a decrease in strength

Equipment Testing: One critical equipment component extensively tested was the fluid placement pump. Both centrifugal and positive displacement pumps were considered. The centrifugal pumps have characteristics of high capacity but low to medium discharge head delivery and extreme sensitivity to viscosity. The general experience shows that the centrifugal pumps can be used to pump slurried grout 45% to 50% solid. The positive displacement pumps have been widely used in the concrete and the mining industry for a variety of applications. In the mining industry, these pumps are used to pump mine tailing and backfill material, which can be as much as 80% in solids content. These pumps are known to exhibit high discharge head delivery. Generally, positive displacement pumps are more expensive to purchase and maintain than centrifugal pumps. A series of pipeline tests were performed to determine the flow characteristics of the slurries on the centrifugal pump performance. The experimental work was conducted in a 3 inch diameter pipeline loop powered by a centrifugal pump. The FSS tested in **this** pipe loop test would be classified as pseudo-plastic material. FSS, with high solids content, clearly indicates its non-Newtonian behavior.

Project Demonstration

The field work was designed to demonstrate the concept of the fluid placement of FSS at full scale. The demonstration was a continuous operation requiring large inventories of the FSS. During the demonstration approximately 250 to 600 cubic yards of FSS was placed each eight hour working day for a total of 16,351 cubic yards over the eight week period. The demonstration plant was operated one shift a day, five days per week.

Process Equipment

Freshly produced FSS was trucked to the demonstration site and stored on a small temporary storage pad adjacent to the dilution plant. The dilution plant used for this full scale demonstration was a tractor trailer mounted unit manufactured by Excel Machinery Co., see *Figure 3. Dilution Plant. The* portability of this unit allows it to be moved to multiple locations for injection on projects covering large areas. For this demonstration the unit was centrally located over the City mine and was not moved during the eight week demonstration period. The discharge piping was flexible and easily moved to the various injection points, some were located as far as 300 feet from the unit. The mixing of FSS materials for small projects can also be accomplished utilizing cement mixing trucks or other portable batch plants.

A front end loader was used to transfer the material from the temporary storage pad to the feed hopper of the dilution plant. The FSS was weighed on a belt scale as it discharged from the feed hopper which discharged into a 4' x 8' heavy duty twin shaft pugmill mixer. A programmable controller operated the lime and water feed equipment to achieve the desired ratios of the grout mix. This dilution plant was able to consistently mix the FSS grout to the optimum percent solids content required for fluid placement. The FSS grout discharged from the pugmill onto an inclined belt conveying it to the .surge hopper located over top of the injection pump. The FSS was then pumped into the mine voids using a Schwing trailer mounted concrete pump (max. capacity - 127 $yrds^3$ / hr). The positive displacement injection pump delivered the FSS through an overland slurry line to the various injection points. A 90' elbow directed the FSS down the injection hole.

At the beginning of the demonstration, the FSS was allowed to fall unrestricted down the hole and into the mine workings. After a few premature refusals, the free-fall method was changed to a "tremie" method. A tremie system is simply a pipe that is long enough so that the lower end of the pipe is always kept below the mine roof, see *Figure 4. Injection Borehole with Tremie Pipe. The* length of the tremie pipe varied from borehole to borehole depending on the depth of individual mine void from the surface, generally, from 30 to 60 ft.

As with any equipment startup, adjustments to the equipment were required initially. After making the startup revisions, injection proceeded at a satisfying pace. The first injection hole was B-10, borehole television examination showed good void height and interconnected mine workings. Injection into the mine workings was monitored at the injection site utilizing a pressure gauge mounted on the 90" elbow at the top of the hole. Pressure would build as injection proceeded and then suddenly fall off to zero as the grout's path opened into another room or void. The pressure would begin to increase again and the process would repeat itself. Injection into a particular borehole continued until the hole refused by blowing FSS out the top of the hole between the casing and the injection pipe or when the sustained injection pressure became high enough to cause concern. At the completion of injection each day, water was pumped through the pugmill, concrete pump and injection piping to both clean all the equipment and to open the flow path through the FSS in the mine workings for startup the next day.

Injected FSS Monitoring: During the field demonstration, monitoring of the FSS placement consisted of two different methods. The first method consisted of observations of depth to bottom of the mine in the boreholes located in the mine workings. The changes to the water level in the mine pool and to the water quality, specifically the pH and specific conductance, also indicated the path that the FSS traveled. The other method was conducted only briefly but was the most informative, that being the borehole photography. Daily monitoring during the FSS injection was concentrated in the boreholes directly around the injection point, although all open boreholes into the mine workings were monitored every few days. The results of the monitoring gave good indications of FSS movement. Once the FSS arrived at a monitoring hole, the grout level in the hole rose to the mine roof within one or two days of injection. Water levels in the mine varied little during injection but on occasion, a rise in the mine pool of about one tenth of a foot was noted at the end of a day. The mine pool would be at its normal level the next morning. No evident changes were noted in the pH or specific conductance of the mine pool until FSS was actually measured in a particular hole.

Injection Rates: The injection rates varied from about 280 to 650 cubic yards of FSS per day, with the lower rates occurring primarily during the first two weeks of injection and the rates generally increasing thereafter as the system operation was refined. Overall, 16,351 cubic yards of FSS was injected during the eight week field demonstration with 6,782 cubic yards in B-10 (covering approximately 1.3 acres), 4.318 cubic yards in B-20 (covering approximately 1.2 acres), 4,874 cubic yards in B-35 (covering approximately 1.1 acres). All of the injection holes were filled to refusal. In general, the FSS fluid placement material contained about 55% to 60% solids, fly ash to filter cake ratio per plant production (to be 0.7 to 1 or higher as circumstance allowed), and more than 4% total lime content. *Figure 5. FSS Injection Calculated Volumes* detail the quantities injected and test results of core samples retrieved after the demonstration can be found below.

Borehole Television: Three rounds of borehole photography was conducted by a crew from the Eastern Technical Center of the Office of Surface Mining, Reclamation, and Enforcement (OSMRE), U.S. Department of the Interior, Pittsburgh, Pennsylvania. The camera work was requested from OSMRE through the Abandoned Mine Lands Program of the Indiana Department of Natural Resources. The initial camera work was used to determine which borings had encountered open voids and which were into obstructed (broken rock) mine workings. The camera work completed during demonstration concentrated on observing FSS as it was placed in the mine void. While injecting into B-20, and photographing in B-21, movement of FSS was recorded almost from the time it entered the mine room where B-21 was located, until the room was completely filled. The camera showed that the FSS did move as a mass in a lava type flow. The third and final round of camera work was used to verify roof contact into the random boreholes drilled to retrieve core samples and also in the existing boreholes.

Conclusions

- The demonstration clearly showed that the FSS flow from the injection borehole exceeded 100 feet, and based upon volume estimates, approached 135 feet. A mine void area in excess of one acre can be filled with one injection point.
- The lava-like flow of FSS does not appear to mix with mine water but rather displace it, only the outer surface of the FSS grout is exposed to the mine water. Air and water in the voids can be completely displaced by FSS grout injection, the potential for acid generation from pyrites and organic sulfides is then greatly diminished.
- The FSS grout does not shrink or settle away from the mine roof and generally achieves unconfined strength of 100 psi or higher.
- FSS grout injection can be accomplished with “off the shelf’ equipment with only minor modifications required.
- Short term results indicate no discernible chemical effects from FSS on mine water and no chemical effects on the surrounding ground water.

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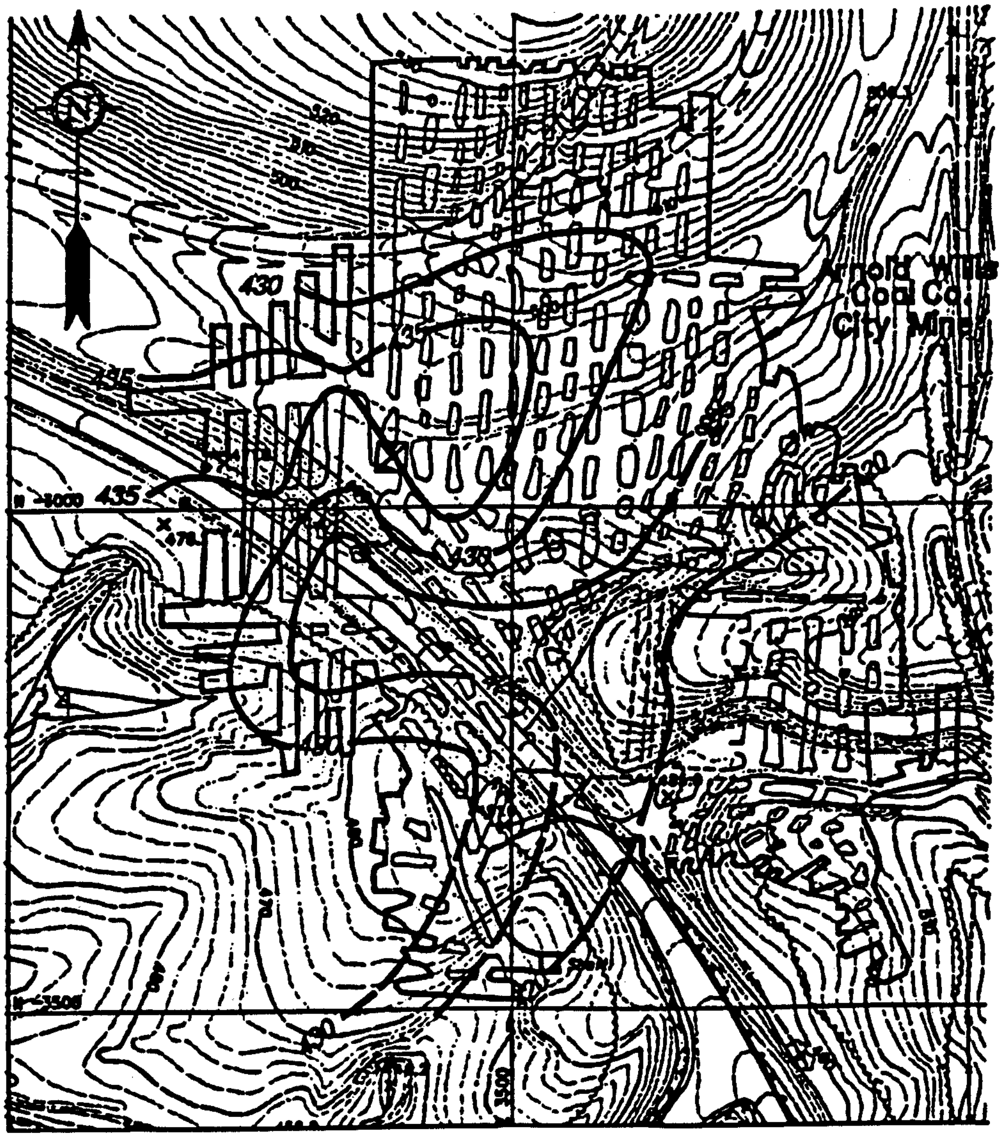


FIGURE 1.

MINE MAP

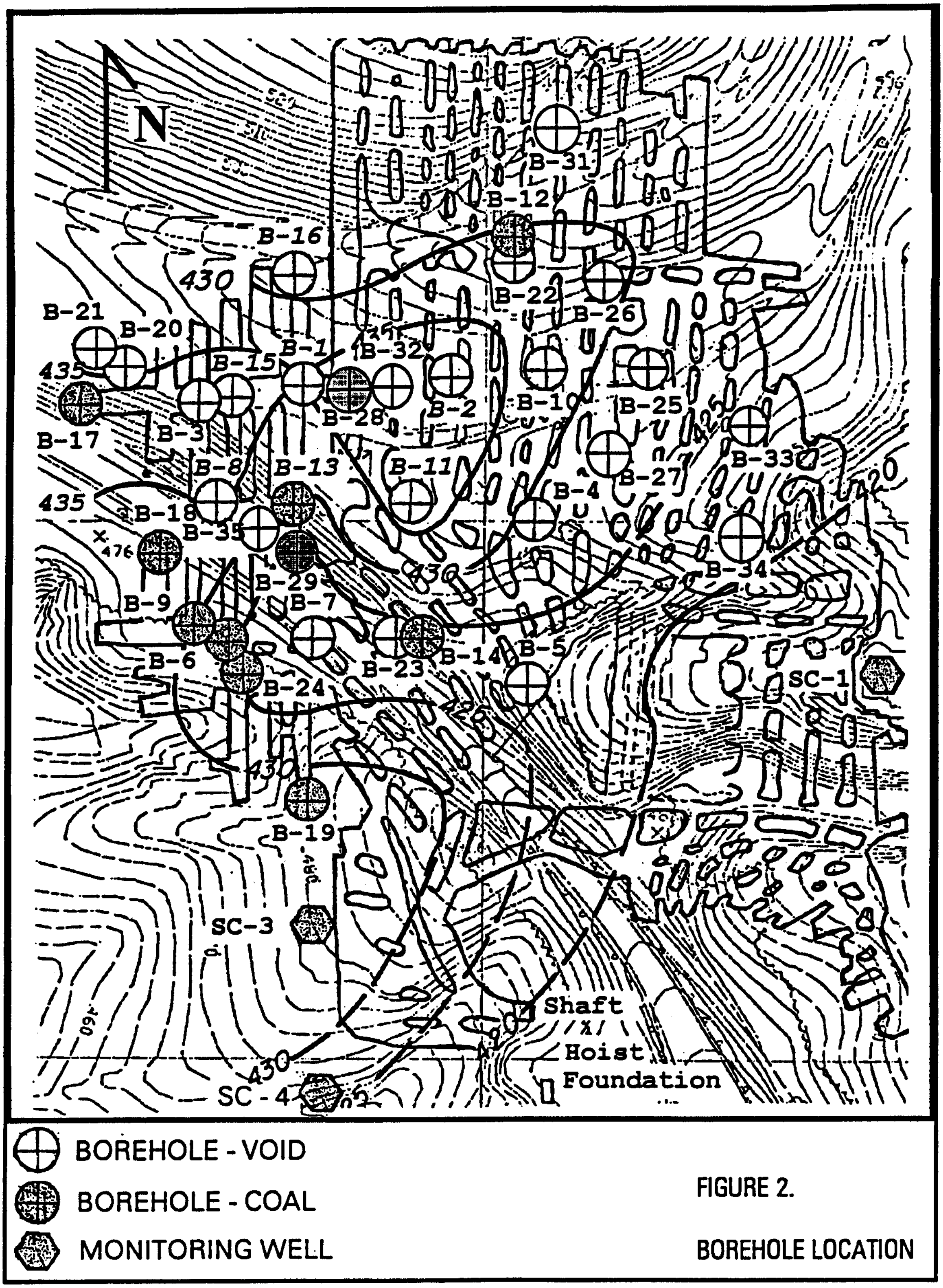
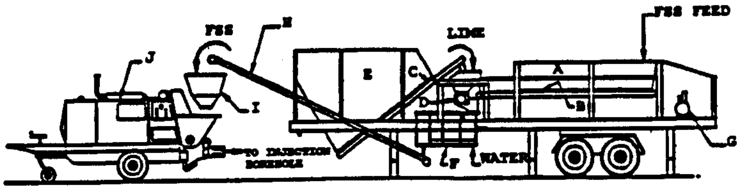


FIGURE 2.

BOREHOLE LOCATION



A - Feed Hopper
B - FSS Belt Feed
C - Lime Screw Feed
D - Lime Weigh Scale
E - Lime Silo
F - Pug Mill Mixer
G - Air Compressor
H - Mixer Discharge Belt
I - Pump Feed Hopper
J - Injection Pump

FIGURE 3.
DILUTION PLANT

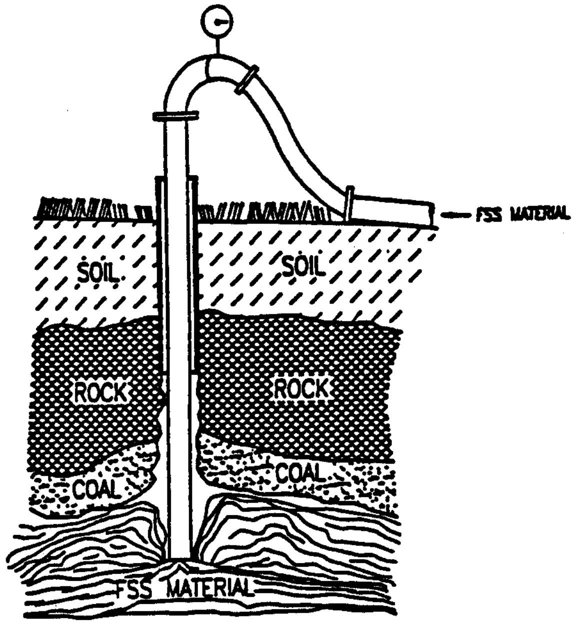


FIGURE 4.
INJECTION BOREHOLE
WITH TREMIE PIPE

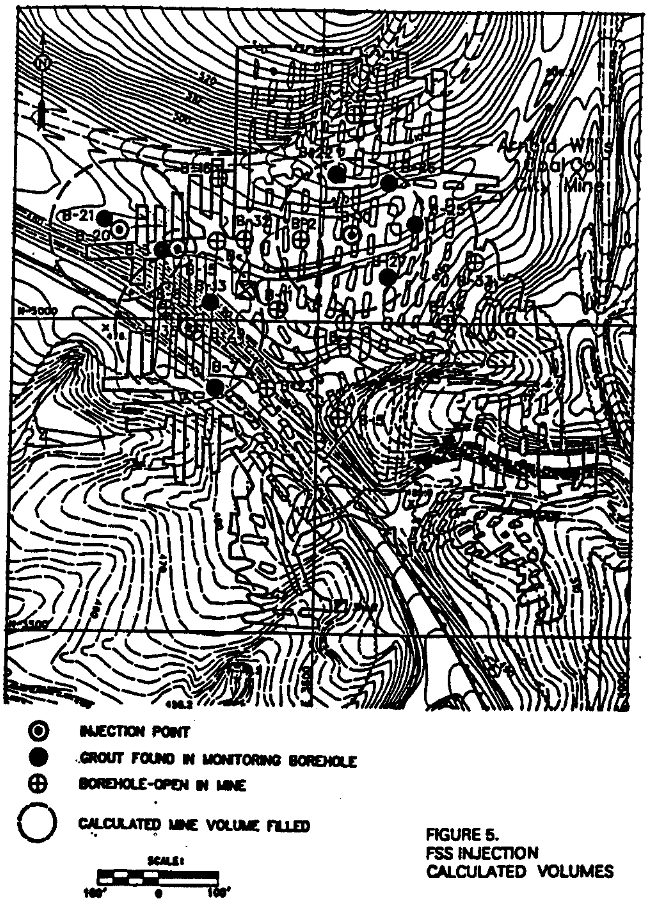


FIGURE 5.
FSS INJECTION
CALCULATED VOLUMES

Borehole B-10 Flooded Mine Void

FSS 6,315 tons Ave. 371.5 tons/day
Dilution Water 522,040 gals. Ave . 30,708 gals./day
Quicklime 229 tons Ave. 13.4 tons/day
FSS Grout Injected 9,374 tons or 6,782 cubic yards
QA/QC tests → 17 Samples = 1 test / 398 yrds^3 injected
Ave.: Solids - 56.10 % Lime - 4.36% FA/FC Ratio - 0.80:1.00

Cores - Test Results

9 cores collected, 9 months after injection
Ave. Strength (U.C.S.) 190.1 psi Range → 99 - 479 psi
Ave. Density (Wet) 96.9 lbs/ft^3 Range → 93 - 102 lbs/ft^3
Ave. Permeability (2 cores) 3.58 x 10^{-5} cm/sec

Borehole B-20 Dry Mine Void

FSS 3,938 tons Ave 393.8 tons/day
Dilution Water 351,100 gals. Ave. 35,110 gals./day
Quicklime 144 tons Ave. 14.4 tons/day
FSS Grout Injected 5,538.1 tons or 4,318 cubic yards
QA/QC tests → 10 Samples = 1 test / 432 yrds^3 injected
Ave.: Solids - 58.70% Lime - 4.43% FA/FC Ratio - 0.73:1.0

Cores - Test Results

2 cores collected , 12 months after injection
Ave. Strength (U.C.S.) 316.5 psi Range → 276 - 357 psi
Ave. Density (Wet) 95.8 lbs/ft^3 Range → 90 - 101.2 lbs/ft^3
Ave. Permeability (3 cores) 3.14 x 10^{-6} cm/sec

Borehole B-35 Partially Flooded Mine Void

FSS 3,814 tons Ave. 381.4 tons/day
Dilution Water 46,200 gals. Ave. 34,620 gals./day
Quicklime 149 tons Ave. 13.5 tons/day
FSS Grout Injected 5,993.7 tons or 4,874 cubic yards
QA/QC tests → 11 samples = 1 test / 443 yrds^3 injected
Ave.: Solids - 56.50 Lime - 4.39% FA/FC Ratio - 1.03:1.00

Core - Test results 1 Core collected 12 months after injection
Strength (U.C.S.) 348 psi
Density (Wet) 97.37 lbs/ft^3
Ave. Permeability (2 cores) 1.60 x 10^{-7} cm/sec