ACID MINE DRAINAGE ABATEMENT USING FLUIDIZED BED COMBUSTION ASH GROUT AFTER GEOPHYSICAL SITE CHARACTERIZATION[1]

Joseph Schueck,[2] Terry Ackman,[3] and Barry Scheetz[4]

Abstract: Pyritic coal refuse and pit cleanings buried in a 15-ha (37-acre) surface mine produce severe acid mine drainage (AMD). The pyritic material had been buried in discrete piles or pods in the backfill. The pods and the resulting contaminant plumes were initially defined using geophysical techniques and were confirmed by drilling. Fluidized bed combustion (FBC) ash, mixed with water to form a grout, was used in different ways to isolate the pyritic material from water and oxygen. In the first approach, grout was pressure injected directly into the buried pods to fill the void spaces within the pods and to coat the pyritic materials with a cementitious layer. A second approach used the grout to divert water from specific areas. Pods which did not accept grout because of a clay matrix were isolated from percolating water with a cap and trench seal of the grout. The grout was also used in certain areas to blanket the clay pit floor since clays are believed to be a primary source of aluminum at this site. In certain areas, the AMD migrates downward through fractures in the pit floor to the groundwater table. Grout was injected along the fractures in some of these areas to seal them. This would inhibit further AMD migration toward one of the receiving streams. The initial postgrouting water quality data have been encouraging.

Additional Key Words: AMD, magnetometry, electromagnetic terrain conductivity, VLF, grouting.

Introduction

Effective AMD abatement first requires locating the acid production source(s). For example, pyritic material, such as coal refuse or pit cleanings, was often placed in discrete piles and buried at surface mine sites. Improper isolation of the piles from infiltrating precipitation or groundwater often results in severe localized AMD production. These pods and the resultant AMD plume can be detected using geophysical mapping techniques (Schueck 1988, 1990). Geophysical detection of the sources would be less successful at sites where the pyritic material was disseminated throughout the backfill.

Once the acid-producing materials buried within the backfill are delineated, abatement technology can be applied. Permanent isolation of pyrite from water or oxygen will stop AMD production. This paper describes the use of FBC ash as a grout to potentially isolate pyrite from oxygen and water. Geophysical applications are discussed as well.

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[2] Joseph Schueck, P.E., Hydrogeologist, Pennsylvania Department of Environmental Resources, Bureau of Mining and Reclamation, Harrisburg, PA, USA.

[3] Terry Ackman, Mining Engineer, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, USA.

[4] Barry Scheetz, Ph.D., Professor of Materials, Penn State University Materials Research Lab, University Park, PA, USA.

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Site Description

The project site is located in north-central Pennsylvania in the Sproul State Forest, Clinton County. This site was mined by mountaintop removal between 1974 and 1977. The Lower Kittanning coal seam was present in two splits separated by 3 to 6-m (10 to 20-ft) of clay. Only the upper split was mined, leaving the thick underclay as pavement. The coal was overlain by black shale capped by a sandstone unit. The black shale is suspected of being pyritic and potentially acid producing. The only source of groundwater i: infiltrating precipitation. Acidic discharges developed soon after reclamation and were first noted when they resulted in a fish kill in 1978. One discharge is a toe-of-spoil seep which flows to Camp Run. Three other discharges flow into Rock Run as groundwater base flow. Total flows from the site are estimated to average 2.2 lps (35 gpm). The discharges completely destroyed 8 km (5 miles) of native trout streams. Water treatment was initiated by the operator, who subsequently went bankrupt; $9,400 in bonds were forfeited.

Technical Approach

The primary objective of this AMD abatement approach was to isolate pyritic material from water and oxygen. Geophysical investigations were used to locate the pods of acid-producing materials, evaluate local hydrology, and monitor grout propagation. Monitoring wells were used to evaluate water quality within and adjacent to the site. Water quality was also monitored at the toe-of-spoil seep and in the receiving streams.

FBC ash was the material selected to be used in this isolation approach. FBC ash was chosen because it was available at a low cost, is alkaline, and is pozzolanic (or cementitious). A low-viscosity FBC ash grout was pressure injected into the geophysically targeted zones (pods) as a means of encapsulating the pyritic materials with a cementitious coating. In addition, diversion grouting was used to create zones of low permeability and redirect groundwater flow, so as to further reduce contact of the pyrite with water.

Pregrouting Investigations

Geophysical Investigation

Several geophysical mapping techniques were used for site characterization. Electromagnetic terrain conductivity (EM) measures ground conductivity at various depths and can be used to determine the presence and flow path of AMD within the spoil. Mine spoil is a poor electrical conductor, whereas AMD, because of its high ionic content, is an excellent conductor. The contrast readily provides for the detection of AMD within the spoil. Static water elevations across the site confirmed the flow path and direction. The depth of measurement depends on equipment and the configuration used. An EM-31 was used at this site to measure conductivity at depths of approximately 3 and 6 m (10 and 20 ft). Measurements were taken on a 7.6-m (25-ft) grid spacing across the 15-ha (37-acre) site. The values were contoured and an isoconductivity contour map was prepared (fig. 1). Only values greater than 8 mmho/m are shown in figure 1, depicting the flow path of the AMD. The groundwater drains from the northern (updip) portion of this mountaintop site to the southeast then splits into the east and south lobes (downdip portions of the mine site). The high conductivity values on both lobes indicate where pit water has pooled within the spoil. The EM mapping also indicated discharge plumes from the site at three locations where toe-of-spoil seeps are not present. Correlation of mining events, VLF mapping, drilling, and monitoring data provide evidence that the nonsurfacing plumes represent AMD draining

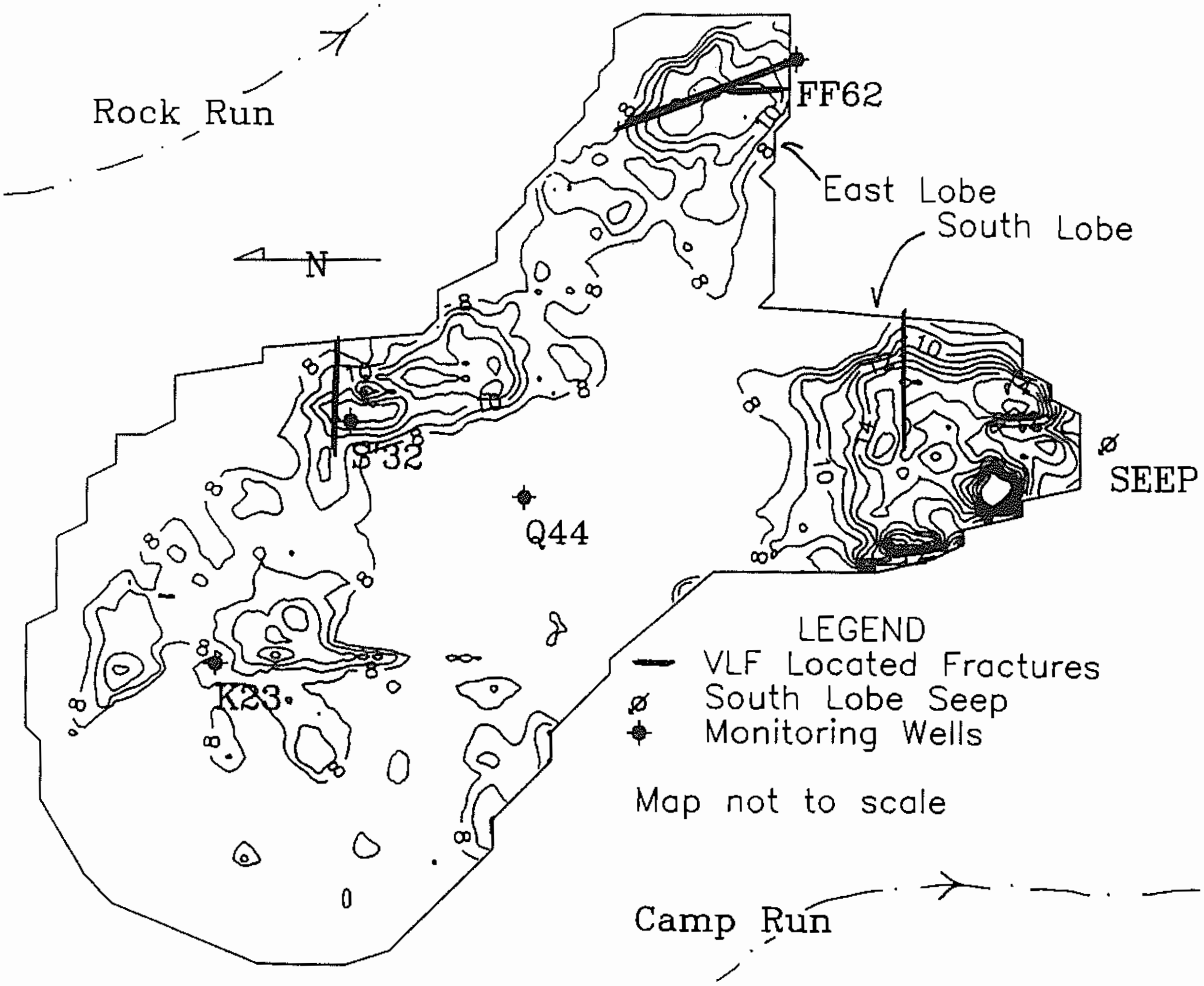

Figure 1. Isoconductivity contour map of site. Contour interval = 1 mmho/m.

through the pit floor via fractures and discharging as base flow into Rock Run.

A very low frequency (VLF) electromagnetic technique was used for fracture delineation. VLF utilizes the magnetic components of the electromagnetic field generated by military radio transmitters on the VLF frequency band (15 to 30 kHz). When the electromagnetic field from a VLF transmitter passes through a conductive body within the earth, secondary currents are induced. These secondary currents in turn generate a magnetic field, which is sensed by the instrument. However, only steeply dipping conductive bodies (e.g., water-filled fractures) are sensed. VLF surveys were performed on and off site as a means of locating water-filled fractures in the pit floor and in bedrock adjacent to the site. The onsite VLF mapping was completed on 3-m (10-ft) centers in the areas of the suspected discharge plumes. The mapping indicated fractures in the pit floor at locations that corresponded to the discharge plumes indicated by EM (fig. 1). Based on the available evidence, these fractures channel the AMD from the mine spoil to a major joint system beneath the site. The joint system then conveys the AMD as base flow to Rock Run, some 76-m (250-ft) lower in elevation. The evidence includes timing of mining events, monitoring and grout well drilling and sample analyses, and discharge locations and water quality in Rock Run.

A "total field" proton precession magnetometer was also used in this study. The premise for the magnetic investigations is that the oxidation of pyrite (which is paramagnetic) produces a mineral phase change with magnetic properties that locally affects the earth's total field. A magnetometer or gradiometer detects total field and local changes, respectively, hence locating zones of pyrite oxidation. Magnetometer mapping was also done on the same 7.6-m (25-ft) grid spacing to determine the locations and configurations of concentrated pods or piles of pyritic materials such as coal refuse. Similar to the EM, the readings were plotted as a contour map (fig. 2). Only the high polarity portions of the anomalies are shown. In this case, the magnetic anomalies (closed contours) represent the locations of the pods of pyritic material buried beneath the surface. Each of these anomalies was later mapped on 3-m (10-ft) centers in the gradiometer mode to provide for better definition of the pile configuration. During drilling of the grout wells, samples were visually identified and magnetic susceptibilities were measured. This information, along with the gradiometer mapping, was used to

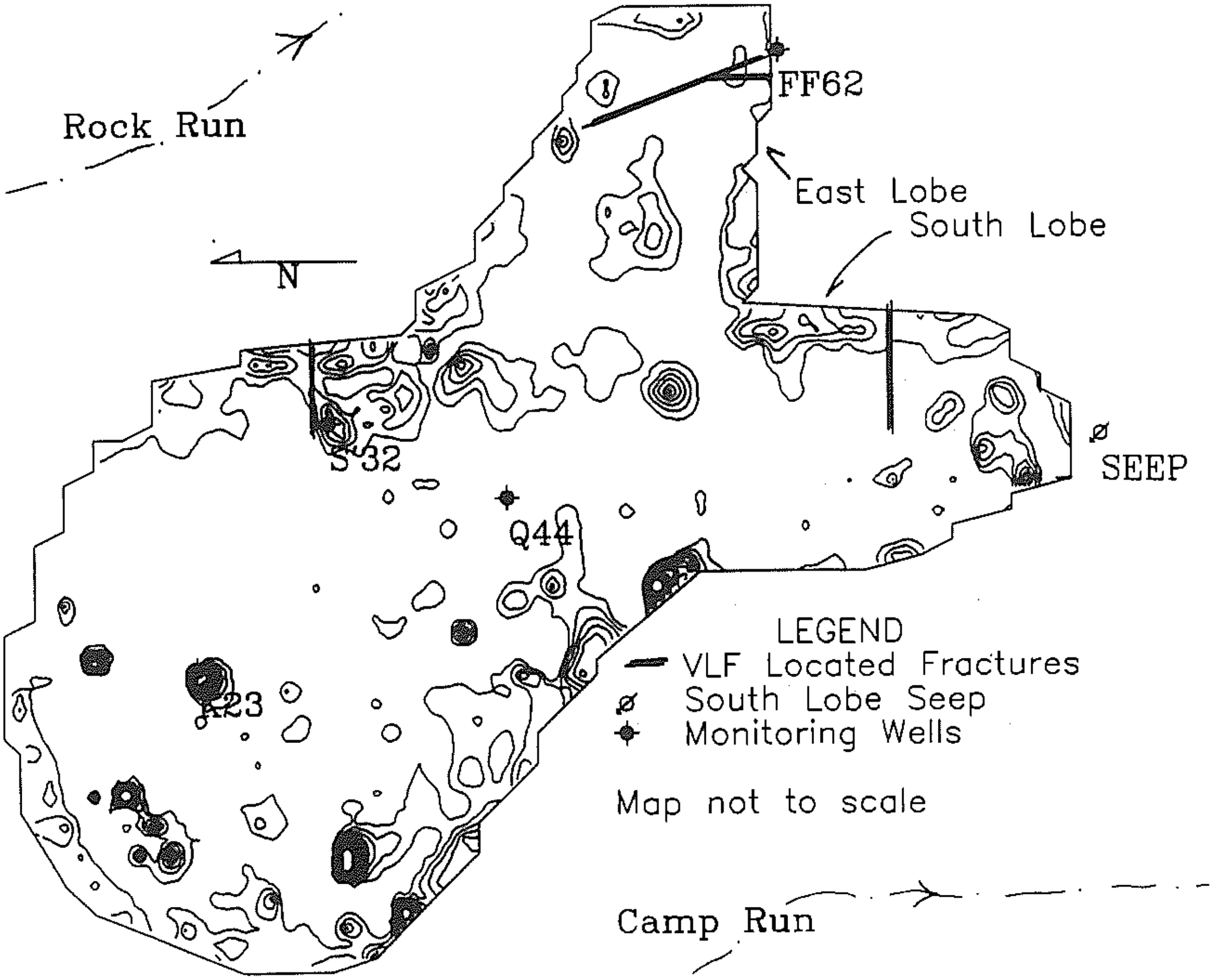

Figure 2. Magnetic anomaly map of site. Contour interval = 1 gamma.

delineate the depths and lateral extent of the oxidized pyritic materials.

When the magnetic anomaly map was overlain with the terrain conductivity map and compared to water quality data, it became apparent that the pods of refuse and pit cleanings were the sources of severe AMD production. The observed conductivity values were highest at or adjacent to the magnetic anomalies. The conductivity values gradually decreased in the direction of flow. This observation is consistent with severe AMD production within the buried pod of pyritic material followed by dilution as the AMD migrates further away from the pod. Water quality data confirmed that the most severe AMD was located within the pods and less severe AMD was found at distances downgradient from the pods.

Water Sampling

Thirty-six monitoring wells were drilled in April 1990. These wells are located on and adjacent to the site. Monitoring wells located adjacent to the site were drilled to the bottom of the lower split of the Kittanning coal seam. The wells located onsite were drilled through spoil to the pit floor, with depths ranging from approximately 3 to 12 m (10 to 40 ft). Several additional monitoring wells were installed during and after the grouting operation. Monitoring well sampling was done on approximately a monthly schedule after their installation (weather permitting). Sampling included purging and bailing of the wells. Temperature, static water level, pH and conductivity measurements were completed in the field. The samples were then analyzed in the laboratory for 20 parameters.

Water sampling was also performed at the only surface discharge, which is a toe-of-spoil discharge located 60 m (200 ft) beyond the south lobe. The discharge rate varied from 0.13 to 1.3 lps (2 to 20 gpm). This discharge flows into Camp Run. The receiving streams, Camp Run, Rock Run, and Cooks Run, were also sampled on a monthly basis.

Water Quality

Table 1 presents the average, high, and low pH values and selected metal concentrations for the toe-of-spoil seep and selected monitoring wells considered to be representative of the site. These data are based on 8 to 15 sampling events. Results from the monitoring wells show that pods of refuse or pit cleanings were indeed sources of severe AMD production. Concentrations

Table 1. Pregrouting water quality

Range	pH	Acidity,mg/L	SO_4,mg/L	Fe_{tot},mg/L	Al,mg/L	Cu,ug/L	Cr,ug/L	Cd,ug/L
Seep:								
High	4.00	3,520	4,368	466	304	958	269	74
Low	2.40	576	1,245	93	242	741	191	18
Avg.	2.60	2,830	2,642	271	290	855	232	59
Monitoring Well FF62:								
High	2.60	6,740	5,773	1,500	562	989	301	167
Low	2.20	1,940	1,272	386	114	611	142	29
Avg.	2.32	4,088	3,458	877	255	730	221	98
Monitoring Well K23:								
High	2.50	23,900	25,110	5,000	2,240	6,950	1,060	1,190
Low	2.00	9,420	3,560	1,120	758	6,710	443	270
Ave.	2.32	14,657	12,705	2,955	1,247	6,830	904	841
Monitoring Well Q44:								
High	5.30	134	175	16	5	28	6	2
Low	3.20	10	62	1	1	22	4	1
Avg.	4.06	42	101	7	3	25	4	2

of the mine drainage parameters in the water in or adjacent to these piles are often several times greater than the concentration of the same parameters in the discharge or elsewhere on the site.

The toe-of-spoil seep and well FF62 (table 1) represent site discharge quality. Well FF62 is located within the discharge plume (as identified by EM survey) and is located offsite and adjacent to the east lobe. In addition, well FF62 is located in the lower split of coal, thus demonstrating fracture communication between the pit floor and lower coal seam.

The water quality of monitoring wells K23 and Q44 (table 1, fig. 1) illustrate the effect that pods of concentrated pyritic material can have on AMD production. Well K23 penetrates a pod of coal refuse that was located using magnetometry. Well Q44 is located near the center of the 15-ha (37-acre) site, but is located some distance from any of the mapped piles of pyritic material. The water quality differences of these two wells vary by orders of magnitude. This implies that the final discharge quality should improve considerably if the AMD production from the pyritic material at K23 and similar locations can be reduced.

The concentrations of ferric iron generated from these pods of pyritic material must also be considered. Garrels and Thompson (1960) have shown that pyrite is rapidly oxidized by ferric iron in the absence of oxygen and at low pH values:

$$FeS_{2(s)} + 14Fe^{3+} + 8H_2O \ -> 15Fe^{2+} + 2SO_4{}^{2-} + 16H^+. \qquad (1)$$

In addition to total dissolved iron, concentrations of ferrous and ferric iron were determined in the lab. According to the monitoring well data, ferric iron concentrations from these pods commonly exceed 1,000 mg/L, with pH values close to 2.0. Once the water exits from the pod, such as the one at the K23 location, it must migrate through 450 m (1,500 ft) of spoil before discharging from the site. This ferric iron is available to rapidly oxidize any pyrite located in its flow path. A reduction in ferric iron formation should thus result in reduced pyrite oxidation.

Suspected sources of Al at this site include clay within the coal refuse and spoil as well as the 3 to 6-m (10 to 20-ft) thick clay unit that splits the coal seam and constitutes the pit floor. Clays are the most common of the sedimentary aluminum-enriched minerals, and the Al^{+3} cation predominates in many solutions in which pH is less than 4.0 (Hem 1992). Concentrations of Al greater than 0.1 mg/L can be deleterious to aquatic life (EPA 1973). Table 1 shows that the concentrations of Al leaving the site in groundwater are three orders of magnitude greater than the 0.1-mg/L limit for aquatic life. The concentration of Al almost 3.2 km (2 miles) from the site in both receiving streams ranged from 4 to 8 mg/L.

Literature shows that Al solubility becomes limited at a pH above 4.5 and will precipitate out of solution (Snoeyink and Jenkins 1980, Stumm and Morgan 1981, Hem 1992). Consequently, this suggests that if the pH of the ground water within the spoil can be raised to a pH 4.5 or greater, the instream hazard from dissolved aluminum can be reduced.

FBC Ash Characterization

In order to use high-sulfur fuels in power plants, atmospheric FBC systems have been developed. Coal and/or coal refuse is burned at 815 to 870 C in a limestone fluidized bed combustion system, limestone is calcined, and most of the sulfur oxides produced are adsorbed by the calcium oxide. The ash from this system is different from traditional fly ashes generated from pulverized coal combustion. The formation of glassy phases in ash particles is retarded because of the lower combustion temperatures. The ash also exhibits high reactivity with water and has cementitious properties due to a high content of calcium and sulfate. The ash used for this project contained 12.51% Al_2O_3, 38.03% CaO, 23.91% SiO_3, and 16.02% SO_2 (Zhao 1993). Mixed with only water, FBC ash forms a low-strength cement. After 20 days at a water-to-solids ratio of 0.5, the ash develops a strength of 135 kg/cm^2 (1,920 psi). The compressive strength continues to develop slowly, up to slightly over 140 kg/cm^2 (2,000 psi) in about 90 days (Zhao 1993).

Grout Injection

Only those pods of pyritic material identified by magnetometry were targeted for grouting. Each of the pods was mapped on 3-m (10-ft) centers using the magnetometer in the gradiometer mode for better pile definition. Grout well locations were based on the gradiometer maps. The wells were installed in August 1992 on 3-m (10-ft) centers using an air track drill rig with a 10.2-cm (4-in) diameter rock bit.

A total of 650 holes were drilled, with depths ranging from 3 to 9 m (10 to 30 ft). Almost 3,940 m (13,000 ft) of 6.3-cm (2-1/2 in) perforated schedule 40 PVC casing was used for this project.

Grouting operations began September 1, 1992, and continued through the end of October 1992. During that time period, 215 of the 650 grout wells were injected with grout. The rest of the wells were grouted when operations resumed in June 1993. The project was completed in August 1993.

The FBC ash was transported to the site in bulk from Fort Drum, NY. A mix ratio of 4.8 m^3 (6.25 yd^3) of FBC ash for every 3,780 L (1,000 gal) water was used. A conventional cement truck was used for mixing and transporting the grout to the injection wells. A portable grout pump, capable of producing pressures up to 42 kg/cm^2 (600 psi), was used for well injection. Each well was pumped until refusal. The amount of grout accepted by the wells ranged from less than 0.2 to 63.5 m^3 (0.3 to 83 yd^3).

Originally, only pressure injection directly into the pods was planned for the isolation of the pyritic materials. However, soon after the grouting operations began, it became evident that this method would not work for all the pods within the site. Several of the piles that refused to accept grout were identified as coal refuse with a clay matrix. It was decided to form a grout cap over these piles to ward off the infiltrating precipitation. The ground above the piles was excavated and the perimeter was trenched. The excavation was then pooled with fly ash grout. After hardening of the grout, these areas were backfilled and regraded.

Paving areas of the pit floor with a grout slurry along the AMD flow path was another diversion technique applied at this site. Chemical analysis of the water within the spoil showed Al concentrations in excess of 1,000 mg/L at various locations. The pit floor is clay and is considered to be a primary source of Al. Success in this approach depends upon the permeability of the spoil materials covering the pit floor.

A third method of diversion involved the use of the grout in the east lobe to seal targeted fractures in the pit floor. These were located geophysically using the VLF technique. Sealing these fractures would cause water within the spoil to flow to the south and eventually discharge into Camp Run instead of Rock Run.

Postgrouting Investigations

Postgrouting Water Quality

Since grouting continued until August 1993, a complete evaluation of the impacts the FBC ash grout had on AMD production from the entire site will not be possible until at least 1994. However, it is possible to comment on some local water quality changes associated with pods grouted in 1992.

Water quality improved in several monitoring wells located downgradient of the pods grouted in 1992. Abundant snowfall and heavy spring precipitation provided an opportunity for the site to be well flushed following the fall grouting effort. Concentration decreases of 50 to 90% in mine drainage parameters were noted in several of these downgradient wells. For example, Table 2 compares 11 pregrouting and 6 postgrouting samples of well S'32 (fig. 1) located within a pod grouted during September 1992. This well is also in the primary flow path of mine drainage produced further to the north and the postgrouting water quality is influenced by that drainage. The water quality improvements observed in this and other wells are encouraging. The reduction in sulfate levels suggests that at least part of the improvement is due to decreased AMD production rather than just neutralization. Other parameters commonly associated with AMD also show reduced concentrations. Water quality in wells not located downgradient of the 1992 grouting remained within observed pregrouting ranges. The postgrouting monitoring period includes all of 1993.

Table 2. Monitoring well S'32 water quality data

Range	pH	Acidity,mg/L	SO_4,mg/L	Fe_{tot},mg/L	Al,mg/L	Cu,ug/L	Cr,ug/L	Cd,ug/L
Pregrouting:								
High	3.60	6,300	6,380	1,860	455	1,410	415	323
Low	2.40	1,220	1,125	184	121	1,030	257	161
Avg.	2.91	3,701	3,195	934	307	1,220	348	223
Postgrouting:								
High	3.60	2,900	3,761	934	166	435	109	38
Low	2.60	1,040	760	116	57	16	20	2
Avg.	2.96	1,486	1,610	452	112	281	78	11

Another encouraging sign is well FF62 (fig. 1) which is representative of the quality of water leaving the site from the east lobe and eventually discharging to Rock Run. Sample analyses show a 25 to 30% decrease in concentrations of mine drainage parameters in 1993 when compared to pregrouting data. Grouting upgradient of the toe-of-spoil seep from the south lobe was not completed until August 1993.

Geophysical Monitoring of Grout Propagation

The feasibility of monitoring grout propagation with EM is being evaluated. EM surveys of a 75- by 50-m (250- by 150-ft) section of the east lobe were completed in June 1993 immediately before and after grouting. Grouting activities took a week to complete, and no rainfall occurred between the two mapping periods. Figure 3 was compiled by comparing the pregrouting and postgrouting data; it shows only the observed changes in ground conductivity. Only wells that accepted more than 0.7 m^3 (1 yd^3) of grout are shown in the figure. It is believed that conductivity changes show the extent of grout propagation within the spoil. Future ground-proofing activities (core drilling and excavated pits) are planned to confirm this observation. The observed conductivity increase is believed to be due to spoil saturation resulting from grouting (excess water associated with the thin grout mixture). This area was resurveyed in August 1993, 2 months after grouting was

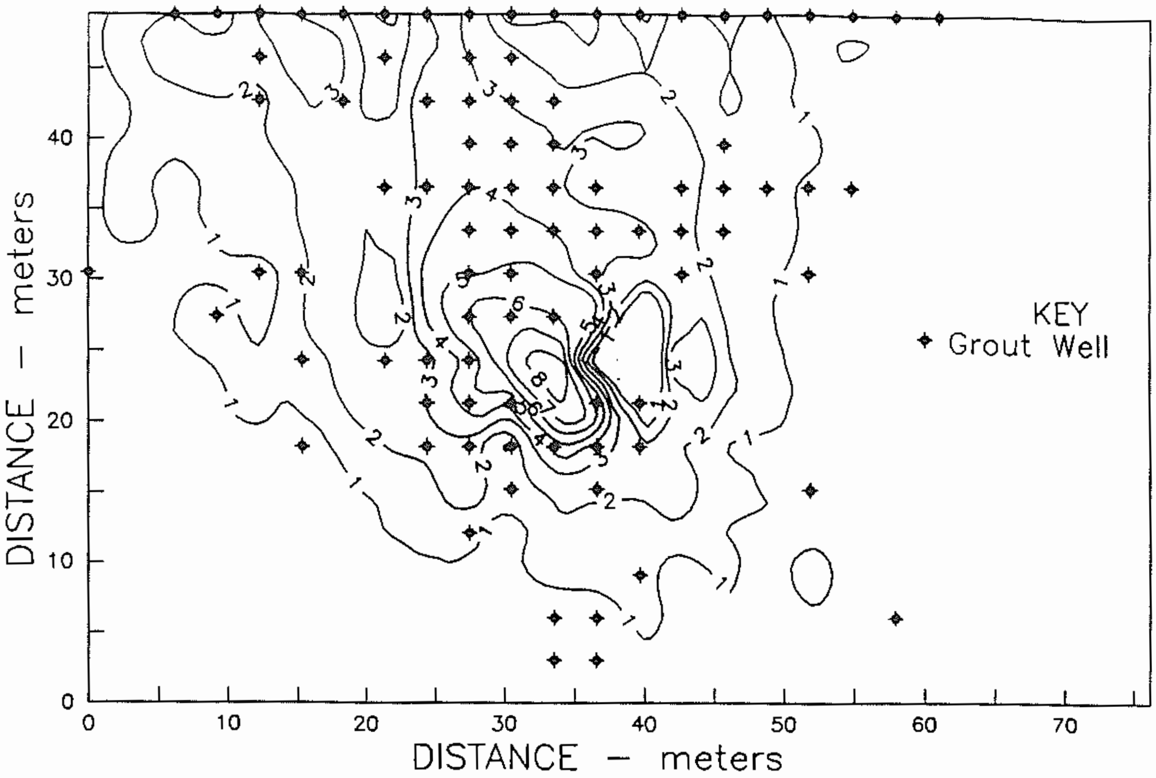

Figure 3. Grout propagation determination using EM. Contour Interval=1 mmho/m.

completed. When compared to the initial postgrouting survey, a general decrease in ground conductivity was observed in this area. It is believed that these observed changes result from the excess water draining away as well as hardening of the grout.

Conclusions

Geophysical site characterization was critical to the development of the abatement plan. In the pregrouting evaluation, confirmation by drilling demonstrated the value of magnetometry for locating buried acid-producing materials. Magnetometry and EM data also showed a correlation between the pyritic pods and resultant AMD plumes, which was confirmed by drilling and water quality monitoring. EM and VLF data were also used to identify fractures beneath the pit floor. Data suggest that there is a potential for geophysical monitoring of grout propagation as well.

The diversion technique of excavating and placing a grout cap and trench seal is a positive, direct approach with the operator having total control over the application. However, in the pressure injection approaches, spoil permeabilities may influence grout placement. Low permeability targets are likely to accept only limited grout quantities.

In addition to continued groundwater and stream monitoring, remapping the site with EM is planned. This mapping will be compared with pregrouting mapping to determine if any large-scale changes in conductivity patterns have occurred. Such changes will then be correlated with abatement of AMD from the pyritic materials and changes in the flow patterns through the spoil. Although complete evaluation of the project will not be possible until at least 1994, the current trend in the monitoring data in the postgrouting evaluation phase is encouraging.

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