GEOPHYSICAL MAPPING AND SUBSURFACE INJECTION FOR TREATMENT OF POST-RECLAMATION ACID DRAINAGE[1]

by

Van G. Plocus and Vijay Rastogi[2]

Abstract. Post-reclamation acid discharge has haunted abandoned mine lands reclamation programs and the mining industry reclamation efforts. Many mine sites have been reclaimed, as mandated by regulations, but continue to generate acid. Such sites represent perpetual treatment problems for operators and, in the case of bond forfeitures or abandoned mine reclamation projects, they represent sources of perpetual surface and groundwater degradation. Post-reclamation discharge occurs when the *Thiobacillus ferrooxidans* bacteria, not destroyed prior to soil cover in the reclamation process, continue to thrive, even in a supposedly anaerobic environment. A post-reclamation remediation system utilizing subsurface injection of sodium hydroxide and an anionic surfactant offers a two phase integrated technologies approach. In Phase 1, the site is characterized by geophysical mapping with (1) electromagnetic terrain conductivity meters to determine locations of subsurface aquifers and (2) proton processing magnetometers to delineate zones of pyritic oxidation in the subsurface environment. Infiltrometers are also used to determine permeability which influences pressure requirements and distance between wells. Site conditions and water analyses help quantify requirements for injection of sodium hydroxide and bactericide. Phase 2 involves drilling two sets of injection wells; the first into the acidified water table for injection of 20% sodium hydroxide solution to neutralize existing acid water, and the second into the acid producing material for injection of a 20% sodium hydroxide solution to neutralize existing acid salts, followed by a 2% solution of bactericide. The sodium hydroxide is injected to neutralize existing acid which prevents future acid generation. Results from a site in Pennsylvania, USA, which was treated in this manner are reported.

Additional Key Words: acid mine drainage, bactericides, sodium hydroxide, neutralization, surfactant, *thiobaccillus ferrooxidans*, magnetometry, electromagnetic terrain conductivity.

Introduction

Currently reclaimed mine sites throughout the Appalachian and central United States coal fields continue to experience significant acid mine drainage (AMD) problems. The sites represent a perpetual treatment problem for the mine operator, contribute to environmental degradation of surface water and groundwater resources, and may prevent bond release. Conventional methods typically employed at a mining operation employed at mining operations treat the waste stream with alkaline compounds such as hydrated lime, sodium hydroxide, or soda ash. Neutralization techniques treat only the symptoms of AMD, not the source, and therefore, become perpetual expenditures for mine operators.

The iron-oxidizing bacteria, *Thiobacillus ferrooxidans*, have been proven to play a critical role in creating AMD and are responsible for up to 98 % of the acid produced (Kleinmann, et.al. 1981). Metals found in mine soils, including iron, manganese, aluminum, magnesium, lead, copper, zinc, cadmium, and selenium are solubilized, creating drainage that is toxic to the environment. Elimination of *Thiobacillus ferrooxidans* has proven to significantly reduce and in some cases eliminate the

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generation of AMD at mine sites (Rastogi 1996).

Anionic surfactants are effective inhibitors of *Thiobacillus ferrooxidans*, as they destroy the integrity of the cytoplasmic membrane of the iron-oxidizing bacteria thus allowing the acid that the bacteria create to enter the cells and destroy them. The ProMac Mine Acid Control system (Hugo 1967) utilizes anionic surfactants as a bactericide and has been registered with the U.S. Environmental Protection Agency (EPA) for use on mine sites for AMD prevention. While ProMac was used on the Fisher Site, it is not endorsed as part of this study. However, it is the only EPA registered bactericide for mine land applications.

Until recently, anionic surfactants have only been applied to surface sources of AMD. VAPCO Engineering and MVTechnologies, Inc. (MVTI) have shown through practical application that subsurface injection of anionic surfactants to the acid-generating zones significantly reduced AMD on the Fisher Site in Banks Township, Indiana County, Pennsylvania. Post reclamation mine water quality on the Fisher Site did not meet Pennsylvania Title 25 Chapter 87.102 effluent limits prior to initiation of subsurface injection treatment. Geophysical mapping with electromagnetic terrain conductivity meters and magnetometers were utilized to identify pyritic locations which were zones of high acid production on the Fisher Site. This was followed with subsurface injection of sodium hydroxide and anionic surfactants through injection wells to obtain significant reduction of AMD.

Subsurface injection of anionic surfactants is an innovative technology developed by VAPCO Engineering and MVTI to directly inject a 20% solution of sodium hydroxide followed by a 2% of the anionic surfactant solution to the source of AMD production.

The Fisher Site

As a first trial and to develop and test the feasibility of this well injection technology, the Fisher Site was selected because the water quality at the site did not consistently meet effluent standards set forth by Pennsylvania Title 25 Chapter 87.102 effluent limits. In order to ensure effluent quality, chemical treatment on the Fisher Site was necessary, a situation representative of many other reclaimed mine sites. Table 1 identifies water quality effluent standards for bituminous coal extraction sites permitted by the DEP for selected parameters:

Table 1
DEP Water Quality
Effluent Standards

Parameter	Measurement Range 30 day Ave.	Instan. Max.
Fe	3.0 -	7.0 mg/l
Mg	2.0 -	5.0 mg/l
pH	6.0 -	9.0 mg/l

Site Summary

A & T Coal, Inc.'s Fisher Site in Banks Township, Indiana County, Pennsylvania, represents a typical reclaimed mine site which continued to generate post-reclamation AMD. A diagram of the Fisher Site is found in Figure 1. With the exception of the post-mine discharge which exceeded effluent limits, the Fisher Site had met all requirements established by the Pennsylvania Department of Environmental Protection (DEP) for bituminous coal extraction and reclamation. Effluent on the Fisher Site continuously exceeded effluent limits established by the DEP: selected parameters are presented in Table 2.

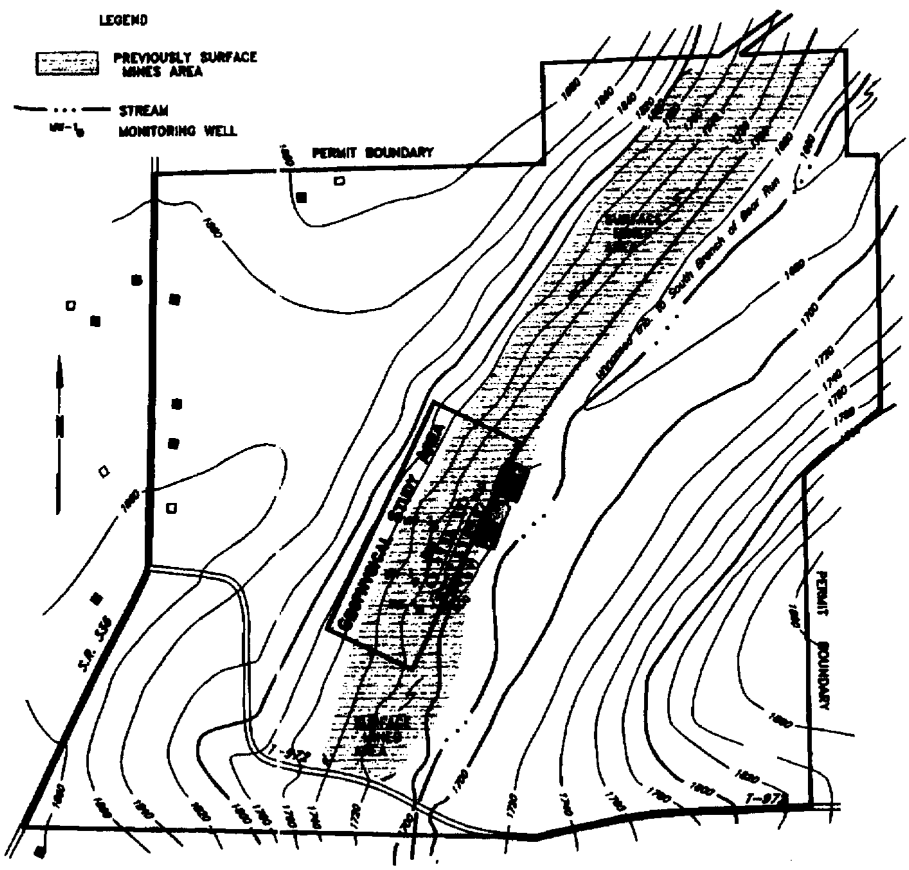
Table 2
Fisher Site Effluent Data
Before Treatment

Parameter	Measurement Ave. (mg/l)
Fe	17.71
Mn	12.35
pH	5.5

A small artificial wetland, constructed in 1985, followed by two treatment ponds utilizing sodium hydroxide, comprised the long-term treatment plan for this reclaimed and revegetated surface mine. Reclamation consisting of backfilling and revegetation was completed in 1984. Post-mining seeps developed after reclamation and the site failed to consistently meet effluent standards requiring continual chemical treatment before discharge into receiving waters. In 1993, VAPCO Engineering acquired the pollution liability of this site as a study area for the purpose of development of methods to minimize treatment of post mining discharges through the implementation of subsurface injection of sodium hydroxide and an anionic surfactant into pyritic overburden zones.

As at most reclaimed mine sites, the source of AMD on the Fisher Site was located in the buried mine spoil. Conventional surface application of anionic surfactants is ineffective on revegetated sites as it cannot penetrate through subsoil, topsoil and vegetation. Therefore, VAPCO Engineering and MVTI developed an approach to (1) identify the source of AMD on the Fisher Site using geophysical mapping, (2) install subsurface injection wells, and (3) inject sodium hydroxide and an anionic surfactant into the toxic zones within the subsurface strata of the Fisher Site.

Figure 1 - Fisher Site Diagram



Site Characterization and Geophysical Mapping

In order to accurately determine the location of acid-producing sources on the 8-acre study area, field survey and geophysical mapping was conducted by VAPCO Engineering and MVTI.

Shaley, high-ash coal containing pyritic acid-producing materials had been buried in the pit during the coal removal process. Infiltrating precipitation and contact with groundwater in these zones of concentrated pyritic material resulted in localized AMD production. A resultant AMD plume eventually surfaced as an AMD seep with levels of iron manganese and pH exceeding effluent limits. Table 3 provides water quality data on the raw AMD seep on the Fisher Site.

Table 3
Raw Seep Water Quality

Parameter	Measurement Range(mg/l)
Raw Fe	8-42
Raw Mn	6-12
Raw pH	5-6
Acidity > Alkalinity	

Geophysical mapping techniques proved useful in identifying areas of high pyritic concentrations and in evaluating groundwater movement within the reclaimed mine area.

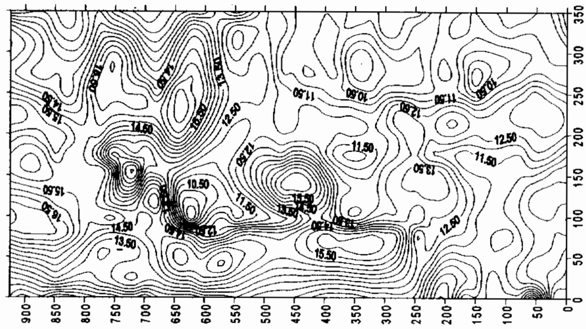


Figure 2
Terrain Conductivity Isopach Mapping
Vertical Dipole

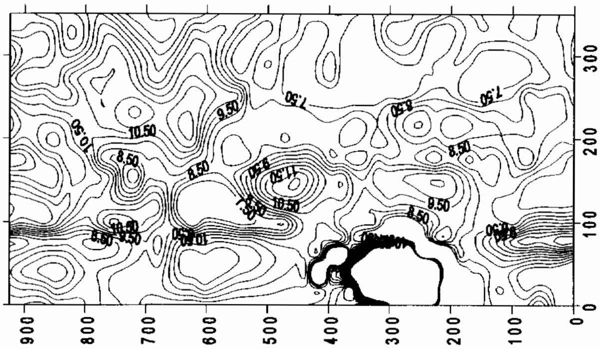


Figure 3
Terrain Conductivity Isopach Mapping
Horizontal Dipole

Electromagnetic terrain conductivity

One of the primary geophysical mapping techniques used for site characterization at the Fisher Site was Electromagnetic (EM) terrain conductivity which measures ground conductivity at various depths and can be used to determine the presence and direction of high conductivity and mine drainage. To evaluate the study area, the Fisher Site was divided into a 25'x25' grid over which conductivity readings were taken using a Geonics EM-31 electromagnetic conductivity meter. Figures 2 and 3 provide horizontal and vertical dipole modes resulting from terrain conductivity mapping. The horizontal and vertical modes are the result of rotating the instrument 90° so that the vertical dipole transmitter/receiver geometry becomes a horizontal dipole transmitter/receiver to exhibit different sensitivity at various depths. The readings of the horizontal and vertical dipole modes are useful in diagnosing and defining material at near surface and at depth based on the relative transmitter/receiver response to the secondary magnetic field.

Magnetometer Survey

A magnetometer survey was also conducted on the Fisher Site. The gradiometer readings predict regions of oxidized pyrite within the substrata of a reclaimed mine site. The magnetic field measuring process consists of polarization, deflection, and measurement of proton precession frequency that is converted to magnetic field units. While local ferromagnetic objects such as pocket knives or tools may interfere with or impair the quality of the measurement, in normal operations, the manufacturer's operating manual indicates that the magnetometer console does not produce appreciable effects or measurements. The 25'x 25' grid previously used for conductivity mapping was used for the magnetometer survey. A Gem systems GSM-19 portable, high sensitivity Overhauser magnetometer was used to collect field data. The GSM-19 gradiometer allowed for the detection of a magnetic field gradient between two sensors. Figure 4 shows the magnetometer isopach map.

Mapping

Based on the geophysical mapping and high conductivity readings, zones were targeted for overburden analysis at six (6) locations. The mapping techniques and overburden analysis was then used to delineate the depths and lateral extent of the oxidized pyritic materials.

Conductivity and magnetometer anomaly contours shown in Figures 2, 3 and 4 were plotted after several computer-

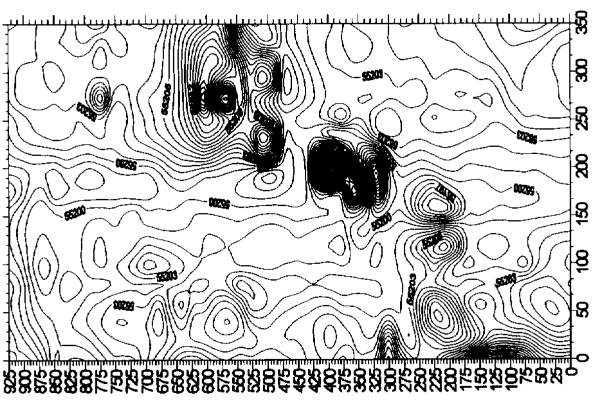


Figure 4

Magnetic Gradiometer Isopach Mapping

enhanced iterations to locate acid aquifers and zones of high pyrite oxidation activity. Contouring software by Surfer for Windows by Golden Software, Inc. was used in this study. Surfer is a grid-based contouring and three-dimensioned surface plotting graphics program which interprets data on a quad. The mapping techniques clearly predicted strong regions of acid production activity taking place within the Fisher Site. In comparing mapping data to overburden analysis, VAPCO Engineering found a strong correlation of sub-terrain target zones. Three of the most significant target zones were selected for subsurface injection of the anionic surfactant used in this study.

Application of Subsurface Injection Techniques

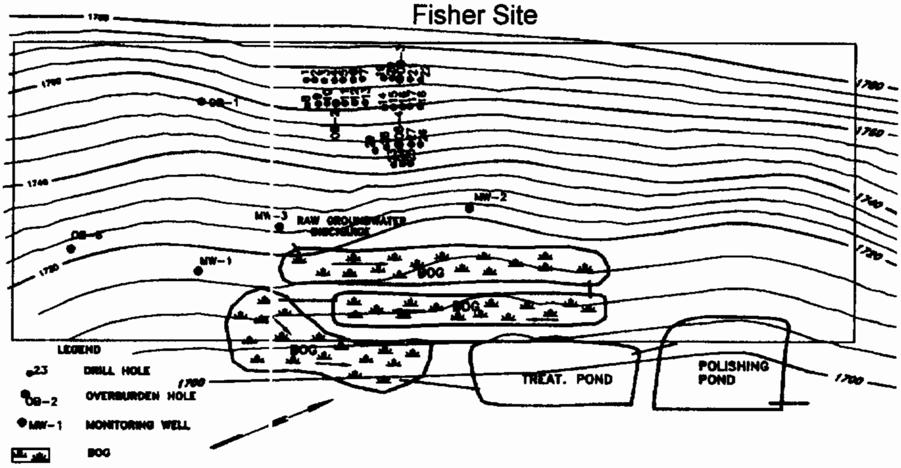
Identification of zones of high pyritic concentrations was critical in determining the targeted location for installation of injection wells. Based on the results of geophysical mapping, VAPCO Engineering drilled overburden holes into the center of the three primary acid producing zones. The location of injection wells, monitoring wells, artificial wetlands and treatment ponds are shown in the site map in Figure 5.

Deep Well Injection

After the acid-producing areas were located, four deep wells were drilled into the acid aquifers for sodium hydroxide injection to neutralize the existing acid waters, and 25 shallow wells were selected to be drilled into the pyritic zones for injection of an anionic surfactant bactericide to prevent future acid generation. Drilling activities were carried out in June 1995. During drilling activities, mine spoil at three-foot intervals was collected for overburden analysis.

A series of twelve 1 3/8" diameter drill holes were placed at the source of the acid producing area. Grout packers were installed to permit pressure injection.

Figure 5 - Location of Wells on Fisher Site



pipe with 5-foot screens and sealed with bentonite and concrete. The screen helped in pressurized distribution of the sodium hydroxide and the anionic surfactant. The depth of the shallow injection wells was approximately 10 feet and the depth of the deep injection wells and overburden wells averaged 53 feet.

Equipment capable of pumping at pressures of 3,000 psi was used to inject the 20 % sodium hydroxide solution in mid-June, 1995, to neutralize existing acid. This was followed by injection of 150 gallons of a 2% solution of the anionic surfactant bactericide manufactured by MVTI. A total of six overburden wells were also injected with the anionic surfactant.

The chemical treatment processes already in place at the Fisher Site were maintained in combination with sodium hydroxide/anionic surfactant injection for a one-month period after the initial injection. One month following subsurface injection, all post-AMD chemical treatment was discontinued.

Monitoring Wells

Prior to well injection, three monitoring wells were installed on the Fisher Site in early June, 1995 in the subsurface acid aquifer identified by the conductivity survey. The wells were sampled monthly by VAPCO Engineering to obtain before and after well injection data to determine effects of well injection treatment at intermediate locations prior to seep discharge. Water quality monitoring began prior to injection and is currently being monitored.

Results

Parameters evaluated by VAPCO Engineering as part of this project included the following: field pH, lab pH, specific conductivity, alkalinity, acidity, iron, manganese, sulfates, suspended solids, and sodium.

Raw Groundwater Discharge

The raw groundwater discharge point represents the acid seep discharge into the artificial wetland, or bog, at an average rate of 50 to 150 gpm. The raw groundwater discharge point is shown on the map found in Figure 5. Figures 6 through 8 summarize results for iron, manganese, alkalinity and acidity for this location; the data shows an overall improvement in water quality since subsurface injection activities commenced on June 19, 1995. While the raw groundwater levels at this pre-bog location continue, in some instances, to exceed DEP effluent standards, the overall favorable reduction continues to be measurable.

Manganese: Water quality data plotted from 1984 to the present shows that dissolved manganese had consistently exceeded DEP effluent limits prior to subsurface injection; pre-injection levels ranged from 4 to 12 mg/L, as shown in Figure 6. Immediately following subsurface injection of sodium hydroxide and the anionic surfactant, levels dropped to concentrations at or below the level necessary for bond release. Subsurface injection has been effective at reducing dissolved manganese at the point of raw groundwater discharge to a level acceptable for final discharge into receiving waters.

FIGURE - 8
Raw Seep Alkalinity & Acidity

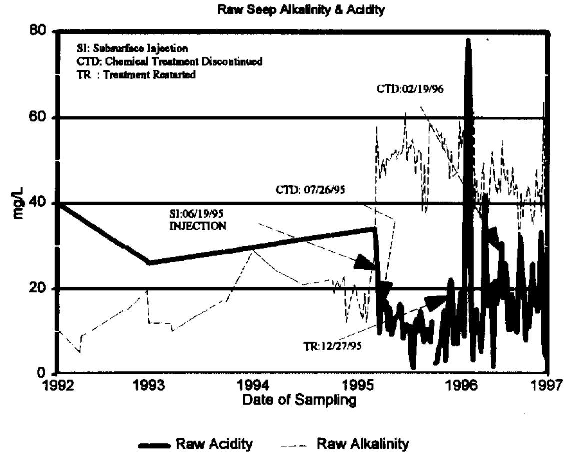
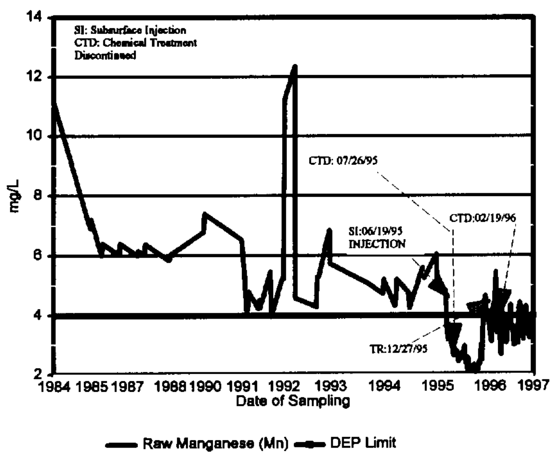
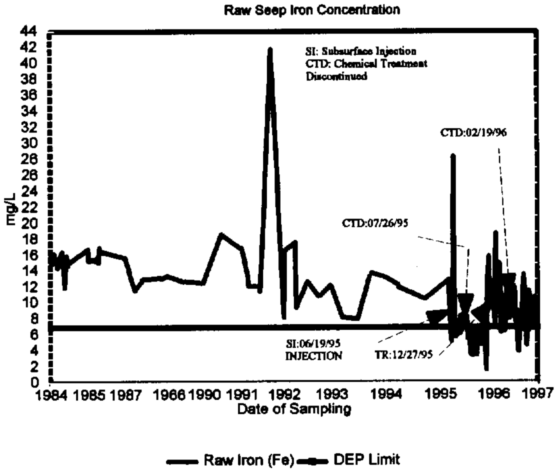


FIGURE - 6
Raw Seep Manganese Concentration



Iron: At the point of raw groundwater discharge prior to subsurface injection activities, iron concentrations ranged from 8 to 42 mg/L between 1984 and 1995. After subsurface injection in June 1995, there was an overall decreasing trend in dissolved iron. It is important to note that, while a certain percentage of measurements did exceed effluent limits, this was caused by unusual heavy snowfall, subsequent snowmelt and flooding caused significant groundwater recharge; a spike in iron concentrations exceeding pre-injection levels occurred as a result of this incident. Iron concentrations have stabilized at a level between 4 and 13 mg/L, well below pre-injection levels, and near the DEP effluent limit, as shown in Figure 7.

FIGURE - 7
Raw Seep Iron Concentration



Acidity and Alkalinity: Prior to subsurface injection, acidity exceeded alkalinity continually on the Fisher Site at the point of raw groundwater discharge, as shown in Figure 8. After subsurface injection of sodium hydroxide and the anionic surfactant, alkalinity has exceeded acidity, and is being maintained, a condition necessary for bond release. Figure 8 shows that alkalinity averaged between 40 and 50 mg/L after subsurface injection and acidity levels ranged between 10 and 20 mg/L. The increased alkalinity and reduced acidity levels at the point of groundwater discharge demonstrate that *Thiobacillus ferrooxidans* has been significantly reduced by the use of sodium hydroxide and an anionic surfactant, with lasting effects.

Monitoring Wells

Water quality data from the three downgradient monitoring wells on the Fisher Site show a measurable reduction in dissolved metals since the injection of sodium hydroxide and the anionic surfactant. Further, a gradual increase in alkalinity was realized in the monitoring wells eighteen months after subsurface injection. Overall, alkalinity has remained at a level greater than acidity, a condition required by DEP for bond release.

With regard to water quality results, VAPCO Engineering and MVTI have evaluated data from the Fisher Site for a total of eighteen months since the time of the initial subsurface injection. During the last twelve months, chemical treatment has not been necessary in order to meet the effluent limits. This is important as the DEP will consider a bond adjustment only when water quality standards are met for a twelve month period.

Conclusions

The Fisher Site subsurface injection project represents the first time that a combination of geophysical mapping and well injection of alkaline materials followed by efforts to inhibit bacterial production has been used to mitigate acid seeps from a reclaimed site. Much has been learned from this experience to improve mapping, determination of number of injection wells, their density and the quantity of fluids that should be injected. However, based on measurable improvements in groundwater quality, even this first attempt can be deemed successful.

Significant improvements in water quality at the point of raw groundwater discharge on the Fisher Site have been realized as a direct result of subsurface injection of sodium hydroxide and the anionic surfactant. A measurable reduction in acidity levels and dissolved metals suggests that injection of the anionic surfactant was effective in reducing the acid-reducing bacteria, *Thiobacillus ferrooxidans*, which in turn is successful in reducing and maintaining concentrations of dissolved metals over a prolonged period of time. No data was collected before and after treatment to prove bacterial inhibition. However, based on low sulfates for prolonged time periods in the effluent, it is our opinion that bacterial inhibition is preventing acid formation at the source. Alkalinity has consistently remained above acidity levels in the three groundwater monitoring wells on the Fisher Site.

VAPCO Engineering and MVTI believe that geophysical mapping techniques combined with targeted subsurface injection of sodium hydroxide and the anionic surfactant, is a cost-effective treatment that works at the source of the AMD problem. Key to the success of this technology is the identification of acid-producing areas using geophysical mapping techniques. The use of electromagnetic terrain conductivity and magnetometry, which show a correlation between high pyritic areas and resultant AMD plumes, were critical in determining the location and number of injection wells.

This technology may offer an opportunity for permanent solution to ameliorate existing discharge problems leading to protection of groundwater resources, elimination of permanent surface treatment facilities, and ultimately the release of mine reclamation bonds on revegetated mine sites currently experiencing AMD problems.

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