

Prevention of Acid Mine Drainage Generation from Open-pit Highwalls—Final Report

Mine Waste Technology Program Activity III, Project 26

by:

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Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

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Sally Gutierrez, Ph.D., Acting Director
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Acronyms and Abbreviations

AGP	acid generating potential
Al	aluminum
AMD	acid mine drainage
ANP	acid neutralizing potential
As	arsenic
ASTM	American Society for Testing and Materials
bgs	below ground surface
Cd	cadmium
cm/s	centimeter per second
cp	centipoise
Cu	copper
DOE	U.S. Department of Energy
EcoBond	EcoBond™ ARD
EC	electric conductivity
EH	oxidation-reduction potential
EPA	U.S. Environmental Protection Agency
FARS	furfuryl alcohol resin sealant
Fe	iron
Fe+2	ferrous iron
Fe+3	ferric iron
ft	foot
gal	gallon
gpm	gallons per minute
GSM	Golden Sunlight Mines, Inc.
HC	humidity cell
IAG	Interagency Agreement
ICP	inductively coupled plasma spectrometer
ID	inner diameter
K	hydraulic conductivity
kg	kilogram
KP	potassium permanganate
m	meter
MCL	maximum contaminant level
MEND	Mine Environment Neutral Drainage (Canadian)
mg/L	milligram per liter
MgO	magnesium oxide
mL	milliliter
MLI	McClelland Laboratories, Inc.
Mn	manganese
MSE	MSE Technology Applications, Inc.
MT2	Metals Treatment Technologies, LLC
mV	millivolt
MWTP	Mine Waste Technology Program
Ni	nickel

Acronyms and Abbreviations (Cont'd)

NNP	net neutralization potential
P	phosphorus
Pb	lead
ppm	parts per million
QA	quality assurance
QAPP	quality assurance project plan
QC	quality control
RPD	relative percent difference
SO ₄	sulfate
SU	standard unit
TSA	technical systems audit
UNR	University of Nevada-Reno
UNR/KP	potassium permanganate technology developed and patented by DuPont Technology, field applications developed and applied by UNR, the current patent holder
UNR/MgO	magnesium oxide passivation technology developed by UNR
Zn	zinc

Abstract

This document summarizes the results of Mine Waste Technology Program Activity III, Project 26, Prevention of Acid Mine Drainage Generation from Open-Pit Highwalls. The intent of this project was to obtain performance data on the ability of four technologies to prevent the generation of acid mine drainage (AMD) from an open-pit highwall. The four technologies applied included Ecobond™ ARD developed by Metals Treatment Technologies, LLC of Denver, Colorado; a magnesium oxide passivation technology developed by the University of Nevada-Reno (UNR); a potassium permanganate technology developed and patented by DuPont Technology and applied by UNR (the current patent holder); and a furfuryl alcohol resin sealant developed by Intermountain Polymers of Idaho Falls, Idaho.

The demonstration was conducted at the Golden Sunlight Mine, an active open-pit gold mine. The four technology providers spray applied their technologies to a designated 50-foot-high by 50-foot-wide area on the highwall. The primary objective of this demonstration was to determine the impact of the treatments on the designated plot areas compared to an untreated area of the highwall. Also, during application of the technologies, each technology provider was required to apply the technology to a specially prepared sample that underwent humidity cell (HC) testing.

Each technology inhibited AMD differently, dependent on chemistry of the treatment formulation, sulfide content, morphology, pH of the waste material, weather conditions, and the amount of water draining from the highwall. Overall, each of the technologies applied to the highwall decreased the generation of acid and the mobility of metals from the highwall. However, the results from the highwall residual wash sampling indicate that in the field the technologies perform differently in comparison to samples analyzed in a controlled laboratory environment such as the HC.

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This document was prepared by MSE Technology Applications, Inc. (MSE) for the U.S. Environmental Protection Agency's (EPA) Mine Waste Technology Program (MWTP) and the U.S. Department of Energy's (DOE) National Energy Technology Laboratory. Ms. Diana Bless is EPA's MWTP Project Officer, while Mr. Gene Ashby is DOE's Technical Program Officer. Ms. Helen Joyce is MSE's MWTP Program Manager.

Executive Summary

The primary objective of the Mine Waste Technology Program (MWTP) is to advance the understanding of engineering solutions to national environmental issues resulting from the past practices in mining and smelting of metallic ores. The MWTP is funded by the U.S. Environmental Protection Agency (EPA) and is jointly administered by EPA and the U.S. Department of Energy. This final report is for MWTP, Activity III, Project 26, Prevention of Acid Mine Drainage Generation from Open-Pit Highwalls.

This demonstration focused on the identification and development of open-pit highwall technologies that provide engineering solutions for future applications. The intent of the demonstration project was to obtain performance data on the ability of four technologies to prevent the generation of acid mine drainage (AMD) from an open-pit highwall. The four technologies applied included:

- EcoBond™ ARD (EcoBond) developed by Metals Treatment Technologies, LLC (MT²) of Denver, Colorado;
- a magnesium passivation technology (UNR/MgO) developed by the University of Nevada-Reno;
- a potassium permanganate technology (UNR/KP) developed and patented by DuPont Technology with field applications developed and applied by UNR (the current patent holder); and
- a furfuryl alcohol resin sealant (FARS) developed by Intermountain Polymers of Idaho Falls, Idaho.

The demonstration was conducted at Golden Sunlight Mines, Inc. (GSM) an active open-pit gold mine located near Whitehall, Montana. The four technology providers spray applied their technologies, which were in a liquid form, to a designated 50-foot-high by 50-foot-wide area on the highwall. Each of the technologies created an inert layer or coating on the sulfide material, preventing contact with the atmospheric oxygen/water during the weathering of the sulfide highwall rock and thus preventing sulfuric acid generation and metals mobilization. A background/control plot of the same size was designated and used to evaluate and compare to the four treatment technologies.

The primary objective of this demonstration was to determine the impact of the treatments on the designated plot areas compared to the untreated area of the highwall. To achieve this objective, the highwall at the project site was geologically, hydraulically, and geochemically characterized prior to technology application.

To evaluate and determine if the objectives had been achieved, two test procedures were used: one test method was humidity cell (HC) testing in the laboratory, and the other procedure was a field mine wall sampling method. NOTE: These two procedures should not be compared because the data were gathered under distinctively different conditions.

Data from the untreated GSM highwall, for both field monitoring and HC laboratory testing, showed that untreated material would produce acid in a natural weathering and oxidizing environment. The same background data from the untreated GSM plot were used for comparison of all the treatment technologies to determine if the technologies were effective in reducing the potential for AMD.

Humidity Cell Tests

Humidity cell testing is routinely used by the mining industry to predict if rock material has the potential to produce acid and mobilize metals when exposed to natural weathering. For this demonstration, HC testing was used to provide similar information. During application of the technologies, each technology provider was required to apply the technology to a specially prepared sample that was sent to McClelland Laboratories, Inc., (MLI) in Sparks, Nevada, where American Society of Testing Materials (ASTM) D5744-96 for Accelerated Weathering of Solid Materials using a Modified Humidity Cell (HC) testing method was con-

ducted. For the HC testing, the technology was allowed to contact the full surface area of the sample being treated for an extended period of time, allowing for the most ideal application conditions. The HC testing results, as with mining applications, allow and were used to predict whether the untreated and treated samples would produce acid and mobilize metals.

Results from 41 weeks of HC testing indicated and predicted that all technologies were effective in preventing acid production and the mobility of metals. Each technology was compared with the background sample results. After 21 weeks of testing, testing was halted, and the samples were allowed to rest for approximately 3 weeks.

When compared to the background plot for EcoBond technology, the pH was neutral; the electric conductivity (EC) was typical for systems exposed to air and indicated minimal metal mobility; iron (Fe), sulfate (SO₄), and acidity production was higher; and calculated ratios were substantially greater than regulatory guidelines. For the two UNR technologies, the pH was slightly greater than 6; the EC was typical for systems exposed to air and indicated minimal metal mobility; Fe, SO₄, and acidity production was higher; and calculated ratios were substantially greater than regulatory guidelines. Essentially, no metals were mobilized from EcoBond, UNR/MgO, and UNR/KP cells. The lack of metals mobility indicates that three treatment technologies prevented acid production.

For the FARS technology, the pH ranged between 4 and 5, the EC was typical of systems exposed to air and indicated some metals mobility for Fe and SO₄. The FARS treated sample did prevent AMD but not as well as the other three technologies. Because the FARS technology has binding/stabilizing capabilities, the FARS HC sample had to be broken apart to allow it to fit into the HC test cells, which exposed rock surfaces that otherwise would have been covered.

Residual Wash Sampling Tests

After the technologies were applied to the GSM highwall, a mine wall/residual wash water sampling test method that was developed for the Canadian Mine Environment Neutral Drainage Program was implemented where the total metals loading per unit area and the pH of the highwall in the field were calculated and measured, respectively. This method allowed the technologies to be evaluated under field conditions and field designed application rates, which can be less than ideal. An example of nonideal conditions would include the loss of several mine wall sampling ports when mine wall movement caused the highwall to become unstable. The loss of the sampling ports has the potential to affect the overall results, leaving for the final sampling event only one UNR/MgO and three Ecobond sampling ports. Due to the instability of most highwalls and for future research on open-pit highwalls, it is recommended that a surplus of sample ports be applied in the event some ports are damaged.

Field results for the mine wall sampling show that for the EcoBond, UNR/MgO, and UNR/KP plots, the pH was as low as the pH of the background plot. This means that the pH was less than 4 and the range of average percent metals reduction was between -211% and 82% (see Table ES-1). The FARS recorded pH was steady at pH 4 to 4.5, extending for the full demonstration, and the percent metals reduction ranged between 75% to 91%, compared to the background results. A large negative number for the percent metals reduction indicates high metals mobility, and a high positive number indicates a low mobility.

Table ES-1. Percent reduction of total metals from the treated technology plots compared to the untreated plot (Plot A)

Treated Plot vs. Background	FARS	EcoBond	UNR/MgO	UNR/KP
% Reduction of Al	75	20	38	62
%Reduction of Cu	85	-211	26	76
% Reduction of Fe	85	24	-16	30
% Reduction of Mn	84	49	82	51
% Reduction of Ni	90	48	50	72
% Reductio of Zn	91	-40	75	76

In the field, physical stabilization of the highwall was only observed on the FARS technology plot. The other three technologies provided chemical passivation of the wall but not physical stabilization.

Test results, from both the field and the HC tests, indicate that all of the treatment technologies (to some degree) controlled the acid generation potential of a mine highwall. The results from the highwall residual wash sampling indicate that in the field the technologies did not perform as well as the samples analyzed in the laboratory (HC testing) in a controlled environment. If these technologies were to be applied at another site, a small-scale field application should be performed to evaluate the full effectiveness of the technology before investing in a full-scale technology application.

Upon completion of the demonstration, several question remain unanswered.

-
- What is the effect of the airborne particulate and runoff on the field results?
 - What was the effect of allowing all HC samples that were saturated during the application to sit until testing was initiated and what was the effect on the samples that were allowed to sit during the time that HC testing was suspended?
 - Was the FARS technology performance altered when the sample for HC testing had to be broken into smaller particles to fit into the HC, thus exposing untreated surfaces to the induced weathering processes?

These questions still exist. However, overall, the technologies reduced the potential for acid production on the GSM highwall material, whether in the field or in the laboratory.

Each technology inhibits AMD differently, dependent upon chemistry of the treatment formulation, sulfide content, morphology, pH of waste material, weather conditions, and the amount of water draining from the highwall. By reducing the potential for AMD generation from a mine highwall, reclamation costs for mining companies and regulatory agencies could be minimized.

Overall, each of the four technologies applied to the highwall decreased the generation of acid and the mobility of metals from the highwall. After evaluating the HC testing results using GSM highwall material, it was predicted that materials treated with the technologies were not acid forming; however, additional testing would need to be performed for the FARS technology to determine if breaking the sample and exposing fresh rock surfaces caused metals values to be greater than the other technology results. Upon evaluation of the mine wall sampling results from the GSM highwall test plots, it was predicted that the average percent reduction of metal from the highwall was reduced. However, Ecobond would require additional testing if the highwall contained increased amounts of copper and zinc, as would the UNR/MgO technology for rock bearing a high iron content. Since these are fairly new technologies, a small-scale field application should be considered on future mine highwalls to observe the performance of the technologies on different highwall material. This would assist with designing a full-scale application of the selected technology.

1. Introduction

Acid mine drainage (AMD) is a significant and costly environmental concern in the mining industry. This is the final report for the Mine Waste Technology Program (MWTP), Activity III, Project 26, *Prevention of Acid Mine Drainage Generation from Open-Pit Mine Highwalls*. The project was funded by the U.S. Environmental Protection Agency (EPA) and jointly administered by EPA and the U.S. Department of Energy (DOE) through an Interagency Agreement (IAG). EPA, through the DOE, contracted MSE Technology Applications, Inc. (MSE) to implement the MWTP. The purpose of this project was to evaluate the ability of four technologies to reduce acid formation and the mobility of metals from an open-pit highwall. Golden Sunlight Mines, Inc. (GSM), a wholly owned subsidiary of Placer Dome America, was selected as the technology demonstration site.

1.1 Purpose and Project Description

Waste rock dumps have been categorized as a main source of AMD, although open-pit highwalls, underground workings, ore stockpiles, and concentrate storage and loadout areas can contribute significantly, generating volumes of AMD. Extensive research has been conducted to understand and reduce the AMD produced as a result of mining activity. This research has focused predominately on using physical, chemical, and passive treatment options to reduce AMD from surface waste piles, mine discharging adits, and tailings piles. However, only a minimal amount of information was available on chemically or physically passivating an open-pit highwall to reduce the production of AMD. This is partially due to the difficulty and danger involved when working on or near the face of a highwall. The overall objective of this project was to research current and innovative technologies capable of reducing and/or eliminating the generation of AMD (i.e., acid generation and mobility of metals) from an open-pit highwall and then apply and test the potential technologies under actual field conditions.

Four passivation technologies were selected and spray applied on the highwall. The technologies either physically or chemically treated the coated highwall depending on the treatment formulation used.

The major activities of the project were:

- site characterization;

- technology identification;
- technology implementation;
- quality assurance (QA);
- materials testing; and
- long-term monitoring and evaluation.

This final report will address the activities listed above. All pertinent information pertaining to the project will be addressed in this document to evaluate the critical measurement and effectiveness of each technology. Each technology was compared to an untreated plot on the open-pit highwall.

This report addresses the project activities as indicated below.

- The description and background information, scope of work, description of the demonstration site, project organization, project schedule, and determined criteria for success are presented in Section 1.
- The preapplication site characterization, including all of the geology, hydrogeology, GSM historic information, physical rock properties, water quality, and geochemistry, is presented in Section 2.
- The general description of the identified technologies and a list of the reasons the technology was selected are presented in Section 3, along with the descriptions of the project site and plot preparation and a brief description of the field sampling and laboratory methods used to evaluate the technologies.
- The general application of the technology, including the application materials and methods, equipment, procedures, and design of the application system, as well as the verification and monitoring events performed during technology application is presented in Section 4.
- Review and interpretation of the results from the sampling activities, including evaluation of all results from the field and laboratory monitoring (i.e., residual wash

and humidity cell (HC) analysis, respectively) is presented in Section 5.

- A summary of the QA activities used to determine the usability of the data generated is provided in Section 6.
- The conclusions derived from the field program, previous work performed, and recommendations for future projects are presented in Section 7.
- A list of references is presented in Section 8.

1.2 Project Schedule

This project was highly ranked among several potential projects presented to the EPA regional offices and to the MWTP Technical Integration Committee in April 2000. Once the project was selected, the project work plan (Ref. 1) was completed in November 2000, and characterization of the project site was performed in June 2001. Site characterization, which was performed in June 2001, included core drilling into the highwall and water injection testing.

The technologies were implemented independently at scheduled intervals on the highwall between October and December 2001. Residual wash sampling was performed on the highwall from April 2001 to November 2002 (Ref. 2). Humidity cell testing was performed for 41 weeks and was finished in July 2003 with project site closeout in December 2002. In September 2003, the test panels were mined by GSM during expansion of the open pit.

Regarding the technology application schedule, the furfuryl alcohol resin sealant (FARS) technology and the Metals Treatment Technologies, LLC (MT²) technology (EcoBond) were applied in October 2001, the University of Nevada-Reno (UNR) magnesium oxide (MgO) technology was applied in November 2001, and the UNR potassium permanganate (KP) technology was applied in December 2001.

1.3 Criteria for Success

The primary objective of the field demonstration was to evaluate the technologies applied to the highwall at GSM for

their ability to decrease or eliminate acid generation and mobility of metals from the treated areas. More specifically, Project 26 objectives included:

- determining any impact on the pH of the treated highwall areas compared to the pH of the samples from the untreated areas; and
- determining the impact of the treatments on the total metal loading per unit area in the rinsates compared to the total metals loading in the rinsates from the untreated area for aluminum (Al), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), and zinc (Zn).

Achievement of the objective was to be determined by comparing the data from treated areas with data collected from the untreated control/background area. Data from the residual wash highwall testing and the HC testing were also analyzed to compare measurements collected from the same location at different times. The analysis was performed to provide further indication of the spatial and temporal variability of parameters within the treated areas.

Each mine wall station was evaluated to determine the percent reduction in the cumulative metal loading per unit area in the rinsates over the monitoring period relative to the untreated control/background area. The concentration of each metal in the rinsates was converted to a mass loading per unit area based on the volume of the rinsate and the surface area of the mine wall station. A cumulative mass of each metal for each mine wall station was calculated over the duration of the test period. Percent reduction was based on the difference between the average mass per unit area of each metal generated from treated areas relative to the mass per unit area of metal from the untreated control station (Ref. 2). The equations used for this evaluation are provided in detail in the project quality assurance project plan (QAPP).

Similarly, the mean pH for each treatment area was compared to the mean pH for the control area to determine if the treated areas had positively impacted the acid generation of the highwall (i.e., the pH was higher in the treated areas when compared to the control).

2. Site Characterization and Pretreatment Activities

Characterization of the highwall was required for the demonstration to determine whether the treatment technologies impacted/passivated the acid generation occurring on the highwall. Tasks performed to characterize the highwall included securing all historical data pertaining to the project site, drilling core holes, and performing water injection tests. Oriented, horizontal, and vertical cores were collected prior to implementation of the technologies. The purpose of the cores was to characterize the site with respect to the geological description (i.e., fracture orientation, patterns, spacing, and mineralogical aperture), geochemical description (i.e., visible depth of oxidation, pH in fractures), and hydrogeological description (i.e., water injection at select intervals to determine wall permeability and characteristics).

2.1 Demonstration Site Description

The project site for the field application of the four selected innovative highwall technologies was GSM, an operating gold mine located in Jefferson County, 8 miles northeast of Whitehall, Montana (Figure 2-1). The northwest side of the open-pit highwall at the GSM was selected as the demonstration area (Figure 2-2).

As well as providing the project site, GSM also provided the following in-kind support:

- removal of fallen rock below the selected highwall area;

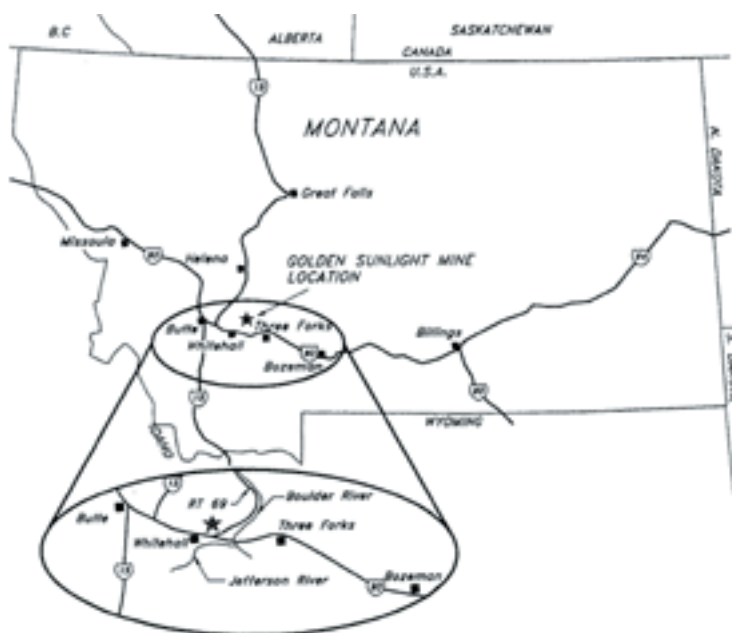


Figure 2-1. GSM location map.



Figure 2-2. GSM open-pit and Activity III, Project 26 site.

- cleanup of the highwall to reduce loose rock for safety purposes;
- a manlift with an operator for field sampling events;
- safety oversight;
- laboratory facilities for sample preparation and analysis; and
- technical assistance with subcontractor oversight.

The open-pit benches at the project site were 50 feet (ft) high and had near vertical slopes. Each technology was spray applied to a 50-ft-high by 50-ft-wide area of the highwall by the technology provider with oversight by MSE (Figure 2-3). A total of five test plots were located on the highwall, which included one plot for each of the four technologies (Plots B – E) and an additional plot designated for background and control (Plot A).

2.2 GSM Historical Data

Historical data were obtained from GSM prior to initiation of the field testing. The historical data were water quality data obtained from a monitoring well in the highwall at GSM to determine the average concentrations for constituents of interest. The data are summarized in Table 2-1. The acquired data were compared to the National Primary and Secondary Drinking Water regulations for pH, Cu, Fe, Mn, Ni, and Zn. The concen-

trations for most metals and sulfate (SO_4) were high; however, there is no a standard for SO_4 .

2.2.1 Geology

GSM is located on the southern flank of Bull Mountain. A general map of the surficial geology is shown in Figure 2-4. Bull Mountain is composed of ancient sedimentary rock that was deposited in a shallow sea during late Precambrian time. The Precambrian rock types in the vicinity of the mine include sandstone, siltstone, and shale. These rock units are known as the Belt Supergroup and have been referred to as the LaHood, Greyson, and Newland Formations and the Bull Mountain Shale.

2.2.2 Tectonic Activity

Approximately 70 to 85 million years ago, a period of tectonic activity known as the Laramide Orogeny occurred during Cretaceous time. During this time near GSM, regional compression of the earth's crust resulted in folded blocks of rock bounded by high-angle faults. Precambrian rocks were penetrated by igneous intrusions and overlain by volcanic materials. Cretaceous-age intrusive rocks in the vicinity of the mine include latite porphyry intrusions and numerous smaller lamprophyre dikes (Ref. 3).

After the Laramide Orogeny, the landscape was relatively stable with residual weathering of the rock surface that became

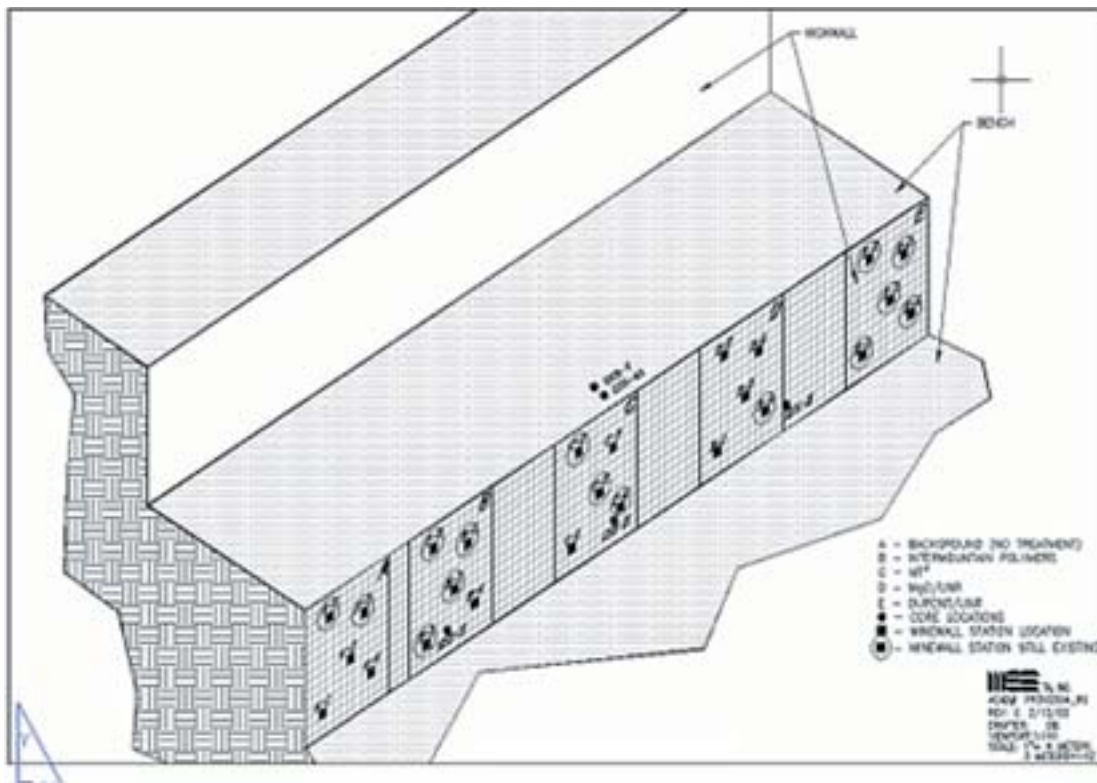


Figure 2-3. Landscape.

Table 2-1. GSM Highwall Monitoring Well Data Analytical Parameter Analytical Result (mg/L Unless Otherwise Indicated)

Analytical Parameter	Analytical Result (mg/L Unless Otherwise Indicated)	Primary and Secondary National Drinking Water Standards
pH	4.35 s.u.	6.5 to 9
SO ₄	4,773	250
Al	Data not available	0.05 - 2.0
Fe	1,042	0.3
Mn	18.9	0.05
Ni	3.15	0.1
Zn	29.3	2.1
Cu	Data not available	1.3

Note: The analytical results listed above are for the dissolved metal concentrations, and the units for metals concentrations are in parts per million (ppm)
mg/L = milligrams per liter

the dominant geologic process. During the later Tertiary period, tectonic activity resumed with a period of relaxation of compression or extension of the earth's crust. This formed the shallow marine basin east of Bull Mountain, which was later filled with Tertiary- and Quaternary-age sediments. This sediment-filled valley is presently the site of the GSM mine, mill buildings, tailings impoundments, and North and East Waste Rock Dumps.

The Precambrian sedimentary rock near the mine site is highly mineralized or impregnated with sulfide minerals, mostly pyrite. When these sulfide minerals become exposed to water and air, they can produce AMD. However, low levels of gold are present in the Precambrian sedimentary rocks, and the primary concentration of gold is a 700-ft-diameter breccia pipe of late Cretaceous age. The breccia contains a zone of broken, angular rock fragments cemented together by silica, sulfides, barite, and carbonate. The breccia pipe cuts through both the Precambrian sedimentary and Cretaceous intrusive rock at an angle plunging west-southwest.

Gold occurs primarily as micron-sized particles of ore that are disseminated within the breccia pipe and immediately adjacent rocks. Free gold occurs interstitially as microscopic particles between pyrite grains. Gold-bearing tellurides are present in minor amounts. Total reserves at GSM, including those mined since 1983, include approximately 55 million short tons grading 0.059 ounce of gold per ton with an average waste ore stripping ratio of 7.4:1 (Ref. 3).

The average range of pyrite in GSM ore is between 3% and 5%; concentrations of up to 20% can occur but are not typical. The relatively fine texture of pyrite enhances the surface area available for AMD generation. Other metallic minerals occur in minor amounts within waste rock and vary in accordance to position in the ore body. Metals of potential concern for water treatment of effluent include Al, cadmium (Cd), Cu, Zn, and arsenic (As). However, for this demonstration, the metals of



Figure 2-4. Surficial geology in the area of GSM.

concern were Al, Cu, Zn, Fe, Mn, and Ni. With the exception of Al, the other metals are predominately associated with sulfide complexes and minor oxides.

2.3 Pretreatment Core Drilling and Water Injection Testing

To geologically characterize the highwall, pretreatment core drilling and water injection testing were performed using a Hagby 1000 core drill. Five exploration core holes were drilled to investigate the parameters of the highwall. The cores were analyzed for fracture frequency; infilling and staining; dip or orientation of any discontinuity, which was quantified by rock quality designation; geology; and pH of the exposed fractured surfaces and the nonfractured rock surface. Approximately every 5 ft, pH measurements were taken on the surface of the core to determine the depth of oxidation and acid formation. Detailed core logs and water injection testing results are provided in Appendix A. The core holes drilled included:

- GS2-H, TD = 50 ft, inclination = -5 degrees;
- GS3-45, TD = 73 ft, inclination = -45 degrees;
- GS3-H, TD = 20 ft, inclination = -5 degrees;

- GS3-V, TD = 20 ft, inclination = -90 degrees; and
- GS4-H, TD = 20 ft, inclination = -5 degrees.

2.3.1 Water Injection Testing

Water injection testing was performed to determine the hydraulic characteristics (i.e., permeability) of the highwall (consolidated rock) at predetermined intervals below ground surface (bgs) and into the highwall. The water injection testing was performed after the core holes were drilled to a final depth, cleaned, and blown out. Inflatable, pneumatic packers were spaced on the drill stem and inflated to isolate the test interval. Testing started at the bottom of the drill hole, and an upstage testing method was used as tests were repeated until the entire hole was hydraulically characterized.

Multiple injection (pressure) tests were performed on GS3-45 and GS3-H, and (if possible) multiple tests were performed at each interval. This method involved testing each interval while increasing the pressure at stepped intervals. Each pressure step was maintained from between 10 to 25 minutes and water intake readings every 5 minutes on a continuous basis (see Appendix B).

3. Technology Identification Activities

Several activities were undertaken by MSE before the demonstration could be conducted. These activities included selecting technology providers, selecting a demonstration site and analytical laboratory, preparing regulatory documents and site access agreements, and selecting the methods used to evaluate each technology. The selection of the technologies involved researching detailed literature in reference to technologies applicable to the demonstration.

3.1 Technology Descriptions

The ore body at GSM is primarily composed of sulfide minerals, which when exposed to air and water can cause AMD generation. The metals concentrations and parameters of concern that were analyzed for this demonstration included pH, Al, Cu, Fe, Mn, Ni, Zn, and SO_4 . The four innovative technologies applied to the highwall were:

- FARS technology developed by Intermountain Polymers of Idaho Falls, Idaho;
- EcoBond developed by MT² of Denver, Colorado;
- UNR/MgO technology developed by the UNR; and
- UNR/KP Passivation technology developed by Dupont and presently owned by UNR.

3.1.1 FARS

The primary constituent of Intermountain Polymer's FARS technology is a byproduct of the agricultural and wood industry. The FARS material is a two-component, acid-catalyzed binder that produces a resistant, stable polymer when mixed that is environmentally innocuous. Polymerization of furfuryl alcohol occurs through a condensation reaction that occurs when mixed with a strong acid catalyst. Care should be taken to avoid free-standing catalyzed resin in order to prevent localized excessive exothermic reactions.

For this demonstration, the technology used acid-cured polymers to seal and encapsulate the highwall material, elimi-

nating the need for repeated future applications due to depleted effectiveness. Other studies have determined that this product is very resistant to dissipation or erosion over time (Ref. 4). The technology has been used for years in the oil industry to consolidate underground wand formations and is supported by numerous patents.

Additional work was performed by the Environmental and Waste Technology Center, Department of Advanced Technology, Brookhaven National Laboratory for the DOE under the In Situ Remediation Integrated Program. Under this program, a laboratory evaluation was performed to determine durability of polymer grouts for application as subsurface hydraulic and diffusion barriers. The acid-cured polymer (i.e., modified furfuryl alcohol) testing included hydraulic conductivity, compressive strength, flexural strength, splitting tensile strength, water immersion, acid resistance, base resistance, solvent resistance, wet-dry cycling, chloride diffusivity, thermal cycling, and irradiation stability testing (Ref. 4).

By adding the information obtained from patents used in the oil industry, further testing was performed by Intermountain Polymers on several variations of mining waste (i.e., fine grain mine tailings and waste rock having both acidic and basic characteristics).

For highwall application, the advantages that assisted with the selection of the technology were:

- the material provided a permanent layer over the waste material that was acid, base, and solvent resistant;
- the material was stable and polymerized further during wet-dry and thermal cycling;
- the material binds to the waste rock and, as a result, increases the physical stability of the highwall;
- ultraviolet light does not degrade the material;
- the material is inexpensive because it uses a byproduct from a wastestream;
- the material can be spray applied and has a viscosity of approximately 8 centipoise (cp), which is close to that of water (i.e., 1 cp); and

- hydraulic conductivities reached with a composite polymer material ranged between 4.5 to 4.8 by 10^{-9} centimeters per second (cm/s).

3.1.2 EcoBond

EcoBond is a proprietary process able to chemically bind with metals in contaminated soils and other wastes. The phosphate-based AMD treatment process was developed to prevent the oxidation of pyrite on mine dumps, highwalls, and in underground mine workings. The general technology formulation consists of a mixture of additives containing oxygen, sulfur, nitrogen, and phosphorous; each additive has an affinity for a specific class of metals (Ref. 5). By combining ferrous iron (Fe^{+2}) from the rock with EcoBond, a stable, insoluble compound is formed that renders the Fe^{+2} in the pyrite unavailable for oxidation by permanently coating all surfaces. A second, equally stable compound that coats all surface areas is formed by the reaction of EcoBond with the oxidizing ferric iron (Fe^{+3}) (Ref. 3).

Several sources provided knowledge of the EcoBond technology and its effectiveness for reducing AMD. These sources had ongoing demonstrations that used the product; the projects involved using EcoBond for microencapsulation of unoxidized waste rock and passivation of AMD in oxidized waste material (Ref. 6). Also, prior to this demonstration, EcoBond had been deployed to stabilize lead (Pb)-contaminated soils for EPA at the DeLatte battery recycling site and at Summitville, Colorado, where a similar product was used to passivate an open-pit highwall, (Ref. 5).

For highwall application, the advantages that assisted with the selection of the technology are listed below.

- The process converts each metal contaminant from its leachable form to an insoluble, stable nonhazardous metallic complex.
- The process forms a stable, insoluble compound that coats the pyrite and any other surfaces that it contacts.
- The process was designed to treat soils in situ, thereby reducing handling, transportation, and disposal costs associated with secondary wastes generated by many conventional technologies.
- The treatment technology can be spray applied to surfaces.
- The viscosity of EcoBond is comparable to water (i.e., 1 cp), allowing the treatment to contact all surfaces contacted by runoff from precipitation events.
- Runoff water from the treated surfaces has an increased pH because of the application of the treatment technology, thus reducing the toxicity of the receiving waters.

3.1.3 UNR/MgO Technology

The Mackay School of Mines at UNR has been researching and developing technologies able to mitigate AMD. The ap-

proach of the UNR technologies was to coat the sulfides present in the ore. Over the past several years, DuPont developed a novel coating method known as a passivation technology. The Dupont Passivation Technology (Refs. 7 and 8) was donated to UNR for further process development and commercialization with the intent of using the technology on fresh rock or waste rock piles without rehandling the mining waste (Ref. 9).

The UNR/MgO technology is a variation of the original technology donated by DuPont. The basic permanganate solution that produces the inert manganese-iron oxide layer was eliminated. The UNR/MgO technology was designed to create an inert coating on the sulfide phase by contacting the sulfide rock with an MgO solution.

For highwall application, the advantages that supported the selection of the UNR/MgO technology are listed below.

- The process creates an inert layer on metal-sulfide minerals when contacting the sulfide with the basic MgO solution, which produces an insoluble, stable layer on the sulfide mineral in the highwall rock.
- The process forms stable, insoluble coating on the pyrite and any other surfaces that it contacts, preventing contact of atmospheric oxygen/water during weathering, thus preventing sulfuric acid generation.
- The process was designed to treat soil and rock material in situ, thereby reducing materials handling, transportation, and disposal, which reduces the costs associated with secondary waste generation and management that occurs when using many conventional technologies.
- The MgO treatment technology can be spray applied to surfaces.
- The viscosity of MgO treatment solution is comparable to water (i.e., 1 cp), allowing the treatment to contact all surfaces contacted by runoff from precipitation events.
- Runoff water from the treated surfaces has an increased pH because of the application of the treatment technology, thus reducing the toxicity of acidic receiving waters.

3.1.4 UNR/KP Technology

The basic permanganate technology (UNR/KP) was the original passivation technology developed and donated by Dupont to UNR. When the UNR/KP technology is applied and contacts the surface of sulfidic material, it creates an inert layer on the sulfide phase of the rocks and produces an inert manganese-iron oxide layer. This layer prevents contact with atmospheric oxygen/water during weathering of the sulfide rock, thus preventing sulfuric acid generation. Another critical element of the process is the addition of trace amounts of MgO during the initial pH adjustment (Ref. 9). Magnesium oxide addition enhances the coating strength.

The UNR/KP was also evaluated in field-scale demonstrations at the Gilt Edge Mine located in South Dakota for an EPA treatability study and at GSM on the surface waste piles, both weathered and nonweathered, and on an approximately 100-ft length of highwall. At the GSM financed field-scale demonstration, the bench above the highwall plot was saturated with the treatment; the solution was then spray applied to the face of the highwall. Results from the demonstrations cited above are in the final reporting stages, and the results will not be provided in this report.

For highwall application, the advantages that supported the selection of the UNR/KP technology are listed below.

- The process creates an inert layer on the sulfide phase by contacting the sulfide with a basic permanganate solution to produce an inert manganese-iron oxide layer. This layer prevents contact with atmospheric oxygen/ water during weathering of the sulfide rock, thus preventing sulfuric acid generation.
- The process was designed to treat soil and rock material in situ, thereby reducing materials handling, transportation, and disposal, which reduces the costs associated with secondary waste generation and management that occurs when using many conventional technologies.
- The UNR/KP treatment technology can be spray applied to surfaces.
- The viscosity of UNR/KP treatment solution is comparable to water (i.e., 1 cp), allowing the treatment to contact all surfaces contacted by runoff from precipitation events.
- Runoff water from the treated surfaces has an increased pH because of the application of the treatment technology, thus reducing the toxicity of acidic receiving waters.
- The costs of the chemicals required in the treatment technology formulation are inexpensive and are commercially available.

3.2 Highwall Technology Evaluation Methods

Several methods were used to evaluate the applied highwall technologies. In this demonstration, both field and laboratory evaluations were performed. The monitoring procedures and evaluation methods were addressed in the project QAPP (Ref. 2) and are described further in this section.

The QAPP was developed and submitted to the EPA Project Manager for review and approval. The QAPP was prepared according to the EPA publication *Preparation Aids for the Development of Category II Quality Assurance Project Plans* (Ref. 10). Additionally, the QAPP served as a standard operating procedure document for sampling; sample preparation, laboratory analysis, and data reduction. A summary of QA related activities is provided in Section 6.

3.2.1 Residual Wash Field Sampling

To validate the objectives of this project, an experimental design was created using the Mine Wall Water Sampling Technique to evaluate the effectiveness of the technologies and to provide an in situ prediction of the water chemistry from the highwall. The technique was developed for the Canadian Mine Environment Neutral Drainage (MEND) Program (Ref. 11).

The initial primary project objective was to determine if the highwall areas treated by the technologies had an impact on the total metal loading per unit area (i.e., Al, Cu, Fe, Mn, Ni, and Zn) in residual wash samples as compared to the total metal loading in wash residual samples from the untreated/background area at Plot A (Figure 2-3).

The second primary project objective was to determine if the highwall areas treated by the technologies were impacted with respect to pH. Results from the residual wash sampling compared the pH in residual samples from the untreated areas to that from the treated areas.

The MEND technique (or the technique developed by Morin) requires that sample ports be attached below the mine wall station and covered with plastic to prevent contamination. However, the mine wall sample stations for this demonstration were not covered to allow weathering effects to occur. Leaving the mine wall sample stations exposed allowed for airborne particulates, erosional material from water flowing from the road above, and earth movement debris to collect in the sample ports. As a result, these factors could have affected the variability and replication of the parameters analyzed.

Mine wall sample stations were installed at five locations on each of the treated and untreated highwall plots. Prior to technology emplacement in September 2001, rinsates were collected for background data at each mine wall sample station. Once all of the technologies had been applied, residual wash water samples were taken from the mine wall sample ports in July, September, and November of 2002 to determine acidity and leachability of metals.

The sampling strategy was included in the experimental design, and quality control (QC) documents. Sample locations and time intervals between sampling events were established to aid in the identification of trends and to produce adequate data to evaluate the overall performance of the technologies. The type of laboratory analysis for each sample was established to ensure there was adequate data. The HKM Laboratory located in Butte, Montana, was selected to perform the necessary analytical testing of the sampling events at GSM.

3.2.2 Laboratory Testing – HC Testing

The HC testing was performed to simulate natural weathering procedures and to accelerate sulfide mineral oxidation. The HC testing procedure is cyclic, during which the sample is subjected to 3 days of dry air permeation, 3 days of water saturated air permeation, and 1 day of water washing with a fixed volume of water. The American Society for Testing and Materials (ASTM) procedure D5744-96 Standard Test Method

for Accelerated Weathering of Solid Materials Using a Modified Humidity Cell requires a minimum test duration of 20 weeks; however, it is recommended that the testing be conducted for at least 40 weeks (Ref. 12).

Representative samples from each technology plot were collected from the highwall and screened using a Gilson laboratory-scale vibratory screen at the GSM laboratory to 1/4-inch by 1/2-inch size fractions. The samples were blended and then split with a riffle splitter to ensure a representative sample was given to each technology provider.

The technology providers applied their technologies to the HC sample at the same time as the field application was conducted on the highwall. The samples were fully saturated, making the dosages to the HC samples much different than from the highwall applications. After the final application of the technologies to the highwall, the samples were shipped to McClelland Laboratories, Inc. (MLI) for modified HC testing. Identical splits of each GSM highwall sample (five in total) were received; one was untreated and designated GSM, and the other four (one per technology) were treated using FARS, EcoBond, UNR/MgO, and UNR/KP. All of the samples were in good condition; however, the FARS sample had to be broken

to reduce the size fractions to fit into the sampling equipment. Because the sample was broken, some of the surfaces were exposed and the uncoated surfaces were visible. All untreated and treated HC samples were conducted in triplicate. An inductively coupled plasma spectrometer (ICP) multielemental scan was performed on the treated and untreated feed sample for characterization.

Test durations were originally scheduled for 21 weeks but were extended to 31 weeks and subsequently to 41 weeks. Test suspension duration was 43 days after week 21 before reinitiation and 131 days after week 31 before reinitiation. Humidity cell test solids were left in the cells and stored in a freezer during test suspensions.

Humidity cell testing samples were monitored on a weekly basis at MLI, and the sampling procedures were included in the sampling plan. The analytical parameters monitored and recorded by MLI personnel from the effluent samples included temperature, pH, oxidation-reduction potential (E_H), electric conductivity (EC), SO_4 , Fe^{3+} and Fe^{2+} , acidity, and alkalinity at maximum contaminant level (MCL). The project-specific QAPP contains a detailed description of the experimental design (Ref. 2).

4. Field Demonstration

This project field demonstration evaluated the ability of the four technologies to decrease or eliminate acid generation from treated areas of the highwall using an untreated highwall area for comparison of results. The following section provides a general description of the field application procedures used by each technology provider. Due to the proprietary nature of some of the applied technologies, some details were not included in this report. If further information on the process is needed, the technology provider should be contacted.

4.1 Technology Application Descriptions

At the GSM project site, each of the four technologies were spray applied to a designated plot area on the face of the highwall. Each technology vendor provided the materials, application equipment, and expertise for the application of their technology. Each technology provider used a different formulation and volume of treatment solution during the application procedure.

Five 50-ft by 50-ft plots were surveyed and cleared of loose and fallen debris by GSM and used for the field application of the technologies (Figure 2-3). Plot A was designated as the background or control plot and was sampled and monitored identically to the technology plots. Sampling results from the technologies were compared to the background plot to determine the effectiveness of each technology. The four innovative technologies and the plots (Figure 2-3) on which each technology was applied were the FARS technology on Plot B, EcoBond on Plot C, UNR/MgO technology on Plot D, and UNR/KP technology using potassium permanganate solution on Plot E.

4.1.1 FARS

The Intermountain Polymers FARS technology is comprised of byproducts from the agricultural and wood industry and is a two-component, acid-catalyzed binder that produces a resistant, stable polymer. For this demonstration, Intermountain Polymers formulated and spray applied the treatment technology to Plot B.

Intermountain Polymers personnel applied a total volume of 200 gallons (gal) of a low viscosity solution (approximately

1 to 3 cp) in two equal applications. The treatment solution was spray applied at a rate of 10 gallons per minute (gpm) on the highwall surface (Plot B). Each 5-gal batch of solution was mixed with 2% by volume proprietary acid catalyst, and the pH of the monitored solution was 4.5 (since the solution is acid catalyzed and the pH of the wall remains slightly acidic). The solution was applied to the surface of the highwall immediately because an exothermic reaction occurs when the catalyst is mixed with the furfuryl alcohol solution. On application, the FARS coating turned the highwall a dark blackish brown color. The FARS formulation for this demonstration allowed for a set time of 20 minutes using 2% catalyst. If the set or cure time needs to be increased, then the amount of catalyst used would be reduced.

To reach the full height of the plot, a person in a manlift sprayed the FARS solution onto the wall using an ordinary, 5-gal capacity, industrial paint sprayer. A second application (still using the initial 200 gal of solution) was spray applied after the initial coat was allowed to set for more than 1 hour. The second coat was applied to seal, provide additional stabilization, and ensure comprehensive coverage of the highwall surface. Figure 4-1 shows the FARS solution being applied to the surface of the highwall.

4.1.2 EcoBond

EcoBond, a phosphate-based AMD treatment process developed to prevent the oxidation of pyrite on mine dumps, highwalls, and in underground mine workings was spray applied in the field by MT². For this demonstration, 300 gal of EcoBond was sprayed on the open-pit highwall using a hydromulch spray cannon. Plot C was coated several times with the EcoBond solution to allow sufficient coverage of the wall surface. The proprietary formulation was sprayed at a high pressure and used a low volume of water. The application method used ensured a comprehensive coverage of the highwall and sufficient contact of the treatment solution on the rock surface.

Once applied, EcoBond is designed to react with the pyrite within 24 to 48 hours. The pH stabilizes at an environmentally safe level and, as a result, the available Fe⁺³ in the system decreases. The minimum required air and surface area tempera-



Figure 4-1. FARS being spray applied on the GSM open-pit highwall at Plot B.

ture was 32°F at the time of installation (Ref. 3). A picture of the spray application of the EcoBond technology is shown in Figure 4-2.

4.1.3 UNR/MgO Technology

UNR developed the MgO passivation technology to create an inert coating on the sulfide phase by contacting the sulfide rock with an MgO solution. Technical personnel from UNR formulated the MgO treatment solution, and the spray application of the treatment solution was performed by UNR's techni-

cal personnel and subcontractor. A Kenworth hauling manlift was retrofitted with a triple-nozzle spray system that did not require a person in a manlift basket for application. This equipment allowed the operator to apply the treatment solution from a metal shielded cab (Figure 4-3).

A total of 2,000 gal of caustic pretreatment wash was spray applied to Plot D of the highwall to raise the wall pH from approximately 3 or 4 to a pH greater than 11. The pretreatment wash was spray applied at a rate of 22 gpm using the spray system attached to a manlift. Once the desired pH was achieved, a final 2,000 gal of MgO solution was sprayed to the highwall. The viscosity of the solution was between 1 and 2 cp, which allowed the solution to penetrate the fractures and completely cover the surface area of the wall. Upon completion of the application, there was no visible indication of the treatment solution application other than the wall rock was clean and washed in appearance.

4.1.4 UNR/KP Technology

Dupont developed and patented a permanganate passivation technology that was donated to UNR. UNR has developed field applications using the passivation technology. UNR's passivation technology is used to create an inert layer on the sulfide phase by contacting the sulfide rocks with a basic permanganate solution to produce an inert manganese-iron oxide layer. This layer prevents contact with atmospheric oxygen/water during weathering of the sulfide rock, thus preventing sulfuric acid generation.

Technical personnel from UNR formulated the permanganate treatment solution, and the spray application of the solution was performed by UNR's technical personnel and subcontractor. As with the MgO technology, a Kenworth manlift was retrofitted with a triple-nozzle spray system that did not require a person in the manlift basket. The equipment allowed the operator to apply the treatment solution from a metal shielded cab (Figure 4-4).

The initial application of the treatment technology to Plot E included spray applying 4,000 gal of caustic pretreatment solution to the highwall to adjust the pH of the wall from approximately 3 to greater than 12. After the pH of the highwall was raised to 12, then the permanganate treatment solution was applied and allowed to cure. Upon initial application of the permanganate solution, the surface of the highwall and the snow in the area were bright pink in color, typical of permanganate solution. However, after several hours, the pink color had faded and there was little indication that the treatment solution had been applied.



Figure 4-2. Spray application of the EcoBond technology onto the GSM highwall at Plot C.



Figure 4-3. Field application of the UNR/MgO technology on the GSM highwall at Plot D.



Figure 4-4. Spray application of the UNR/KP technology on the GSM at Plot E.

5. Site and Technology Characterization Results

The primary objectives of this project were to determine the impact of the treated area for each technology on the total metal loading per unit area and to determine the pH of the rinsates compared to the rinsates from the untreated area. An actual comparison of the four passivation technologies was not one of the objectives. The results from the site characterization, the residual wash field sampling, and the laboratory sampling performed by MLI are provided and discussed in this section.

5.1 Core Drilling and Water Injection Testing Results

The core drilling and water injection testing were performed to characterize the highwall and were performed before the treatment technologies were applied to the wall. The information acquired during characterization of the site was provided to the technology providers so they could refine the technology design, formulations, and application procedures. The information also provided in-depth information of the wall characteristics (i.e., depth of oxidation, fracture density, rock type, hydraulic characteristics). The overall results from the core drilling and mine wall testing established that the geology and wall characteristics at each plot location had similar properties, see Appendix A and C. Thus, all the technologies were applied to highwall surfaces having similar properties.

5.1.1 Pretreatment Core Drilling Results

In June 2001, Bush Drilling Inc., drilled five core holes into the highwall at the project site. Cores measuring 5 ft [1.524 meters (m)] using an NQ drill rod [1-7/8 inch inner diameter (ID)] were drilled and retrieved using a triple-tube core barrel. The five core holes drilled included:

- 1 - 20-ft (6.096-m) vertical core hole (GS3-V);
- 1 - 70-ft (21.336-m) - 45-degree core hole (GS3-45);
- 1 - 50-ft (15.5-m) - 5-degree, near-horizontal core hole (GS3-H); and
- 3 - 20-ft (6.096-m) - 5-degree, near-horizontal core hole (GS2-H and GS4-H).

In general, the Precambrian sedimentary rock drilled and cored at the project site was highly mineralized and impregnated with sulfide minerals, mainly pyrite. The core extracted from the highwall was rubble for approximately the first 3 ft and contained numerous fractures to approximately 10 ft from the drill face. From analyzing the core, it is apparent that the fracture aperture becomes narrow after the first 10 ft and the iron oxide fracture infilling is nonexistent. It could be assumed that the sulfide minerals between 0 and 10 ft into the highwall are being exposed to water and air by mining activities producing AMD (see Appendix A).

The core holes that were drilled before the highwall was treated provided the following information.

- On average, the majority of the Fe-stained fractures were observed from 0 to 9 ft into the highwall. Most of the oxidation of pyrite was associated with fracture flow, and most of the oxidation occurring in the first 9 ft into the highwall can be attributed to more numerous fractures and wider fracture apertures in the wall.
- The lowest pH (between pH 2.7 and 3.8) taken on the highwall were on the wall surfaces that are exposed to fluctuating weather conditions and accelerated oxidation. The pH values corresponded with the depth of visible iron oxide on the fractures. Between 0 and 9 ft, the pH was 4.0.
- The pH measurements taken in the fractures show that from a depth of 9 ft to the end or bottom of the core holes, the pH ranged from 5 to 6 and the pyrite exposed on the fracture surfaces at these depths was not oxidized (see Appendix A).

5.1.2 Water Injection Testing Results

Overall, the permeability of the highwall followed a similar pattern as the fracture filling and pH. At the project site, the permeabilities of the highwall between approximately 5 and 20 ft were hydraulic conductivity (K) = 10^{-4} cm/s and, at greater than 20 ft into the wall, the permeability was K = 10^{-5} to 10^{-6} cm/s. Appendix B provides a summary of the water injection

testing results. Table 5-1 lists the stages or injection intervals, the average pressure applied during the testing, a description of the tested interval using the Lugeon method of analysis, and, finally, the range of permeabilities measured at each interval tested (see Appendix B for more detailed results and descriptions.)

From the water injection testing performed on the core holes, it was determined that the permeability of the wall decreases directly in relation to the depth drilled. From the injection testing results, it can be assumed penetration of the spray-applied, low viscosity, highwall technologies would mainly occur in the area having the highest permeability (i.e., 0 to 20 ft bgs). However, the trends of the iron staining indicate that most of the water movement occurs within 0 to 10 ft into the wall. It also indicates that the surface was fractured during drilling and

blasting, and the resultant fractures propagate to approximately 50 ft into the wall; past this depth, the fractures are usually associated with natural occurring fault systems created during tectonic movement.

5.2 Mine Wall/Rinsate Sampling Results

The mine wall sampling technique was used to determine the kinetic acid rock drainage characteristics of in situ rock or, in this instance, the highwall surface at GSM. The residual wash from the mine wall sampling was analyzed for wall pH, sulfate, and total and dissolved metals. The data were then provided to EPA for statistical analysis (see Appendix D). The three field residual wash sampling events that were evaluated statistically by EPA occurred on July 22, September 19, and November 4, 2002.

Table 5-1. Summary of the variability of the mean and the sample size both before and after the application of the technologies on the test plots

Descriptive Statistic for pH for the September 2001 Highwall Sampling Event taken Prior to the Application of the Treatment Technologies			
Pretreatment	Mean	Variance	Sample Size
Control (GSM)	3.4	0.0325	5
FARS	3.1	0.0099	5
EcoBond	2.9	0.0301	5
UNR/Mg0	3.2	0.2022	5
UNR/KP	3.2	0.1403	5
Descriptive Statistic for H for the July/August 2002 Highwall Sampling Event			
Treatment	Mean	Variance	Sample Size
Control (GSM)	2.9	0.5140	4
FARS	4.6	0.1135	4
EcoBond	4.3	4.3001	3
UNR/Mg0	3.2	NA	1
UNR/KP	4.0	1.1618	5
Descriptive Statistic for pH for the September 2002 Highwall Sampling Event			
Treatment	Mean	Variance	Sample Size
Control (GSM)	3.0	0.0506	2
FARS	4.9	0.0245	4
EcoBond	3.2	0.4714	3
UNR/Mg0	3.2	NA	1
UNR/KP	3.2	0.0107	5
Descriptive Statistic for pH for the November 2002 Highwall Sampling Event			
Treatment	Mean	Variance	Sampling Size
Control (GSM)	3.4	0.0684	2
FARS	4.9	0.0511	4
EcoBond	3.5	0.1314	3
UNR/Mg0	3.4	NA	1
UNR/KP	3.4	0.0062	5

5.2.1 Summary of Statistical Analysis

From the field sampling events, residual wash data were statistically evaluated by EPA to determine if any significant, statistical differences were observed when comparing the background/control plot and the treated plots. The complete data set from the mine wall sampling can be found in Appendix C, and the three EPA statistical analyses are located in Appendix D. The analyzed field parameters included pH, six total metal loadings, and six dissolved metal loadings.

In the EPA reports, 13 statistical analyses were performed and included box plots by treatment level, scatter plots, descriptive statistics, and the results of a Kruskal-Wallis test and multiple comparison procedure. The data were analyzed as a completely randomized design via a one-way treatment structure with five levels using the nonparametric Kruskal-Wallis test.

Results from the analysis determined that there were statistically significant differences between the control (Plot A) and some of the treatments for all analysis variables except the dissolved metal loadings for Al. It was also determined that the FARS treatment technology performed the best; it was statistically different than the control (p -value ≤ 0.05) for all variables except sulfate.

The EcoBond technology appeared to be the treatment that was not statistically different from the control for any variable. It was not possible to draw any conclusions on technology performance regarding the UNR/MgO technology since it only had one sampling port. The detailed statistical reports containing the results are provided in Appendix D. A summary of the variability of the mean and the sample size are presented in Table 5-1 for the pH of the highwall. For each demonstration plot, five randomly selected sampling locations were designated. From the results presented in Table 5-1, it is apparent that the number of sample ports on most of the plots decreased over time. This was due to highwall movement, loss of sample ports, and unsafe conditions in the area of the sample ports.

Because the demonstration involved just one application of each select treatment on one plot/site, the statistical inferences and conclusions extend only to this site. There was no guarantee that the treatments would perform in a similar manner at another site.

5.2.2 Residual Wash pH Results

At the GSM project site, the measured pH of the highwall prior to technology application ranged from 2.7 to 3.8. Listed as a critical parameter in the project QAPP, the pH was used to compare the effectiveness of the technologies. The pH for each of the three sampling events was graphed and is shown in Figures 5-1, 5-2, and 5-3. It should be noted that in the figures, the samples denoted as GSM were taken from the background (Plot A) sample area, and the MT² was the EcoBond technology sample location (Plot C). All other technologies were denoted as they were throughout the text. The final pH of the residual wash from the mine wall sample stations for each treated area averaged were:

- GSM (background), pH = 3.4;
- FARS, pH = 4.9;
- EcoBond, pH = 3.5;
- UNR/MgO, pH = 3.4; and
- UNR/KP, pH = 3.4.

Upon comparison of the data, the average final pH of the background plot (Plot A) remained within the range of the initial pH values taken on the highwall prior to the technology applications.

When comparing the pH values for the FARS technology, it should be understood that this technology creates an acid-catalyzed coating, (i.e., for FARS to cure properly, an acid solution is mixed with the alcohol component of the formulation) and, when all of the components of the sealant are mixed, the pH of FARS ranges between 4 and 5. Throughout this demonstration, the pH of the FARS treated highwall remained between 4 and 5 and did not fall below the expected pH for the technology.

The EcoBond, UNR/MgO, and UNR/KP treatment technologies neutralized the highwall during initial application to achieve a desired wall pH, which would allow the desired chemical reactions to occur. The neutralized highwall pH for the technologies were pH = 9 -10 for EcoBond; pH = 11 for UNR/MgO; and pH = 12 for UNR/KP. Comparing the pH values to the average pH of the background plots and the original pH of the treated plots, the low final average pH values would indicate that the treatment only controlled the formation of acid for a limited amount of time in the field (see Figure 5-1). This statement can be supported by the fact that the average final pH values listed above for EcoBond, UNR/MgO, and UNR/KP range between pH 3.4 and pH 3.5. However, other external factors such as oxidation of airborne particulates from traffic or particulates transported over the wall during runoff events could be affecting these results. Since the plots were too large to be covered and weathering effects on the treatment was part of the evaluation, the transported foreign particles that landed on the wall could potentially reduce the pH on the treated highwall plots. However, if this were the case, the FARS average pH would then be similar to that of the other technologies and the pH from the background (see Figures 5-2, 5-3, and 5-4).

5.2.3 Residual Wash Metals Analysis

Mine wall sampling involved washing the highwall at specified mine wall stations and analyzing the residual wash (rinsate). The data acquired during sampling were used to determine the effect of the treatment technologies on each plot. The six constituents analyzed during the field demonstration were Al, Cu, Fe, Mn, Zn, and Ni. As noted above, to allow for weathering of the rock surface during the in situ testing, the mine wall sample stations were not covered, thus the mine wall stations were exposed not only to the weather but also to runoff conditions and airborne particulate accumulation. The metals loading results from each treated plot were compared graphically to the GSM/background plot and are shown in Figures 5-5

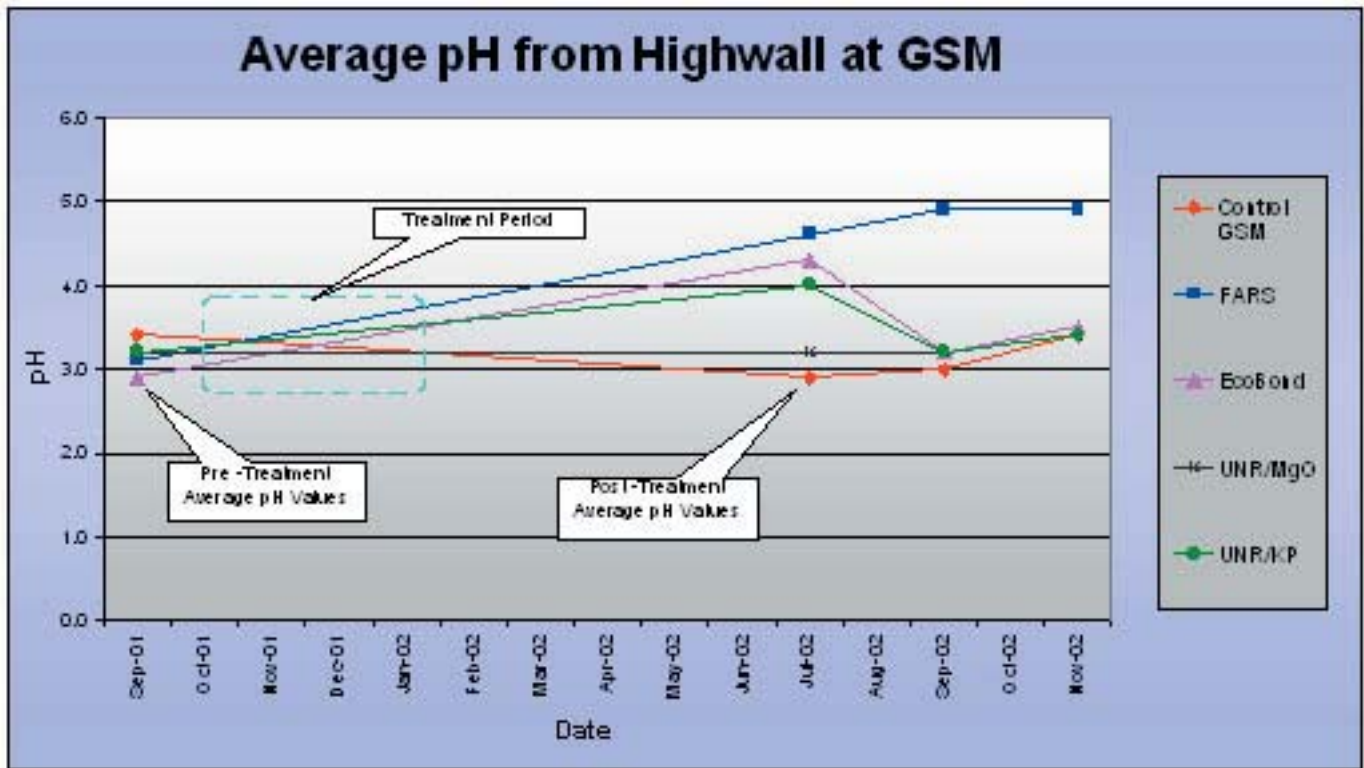


Figure 5-1. Average pH from highwall at GSM.

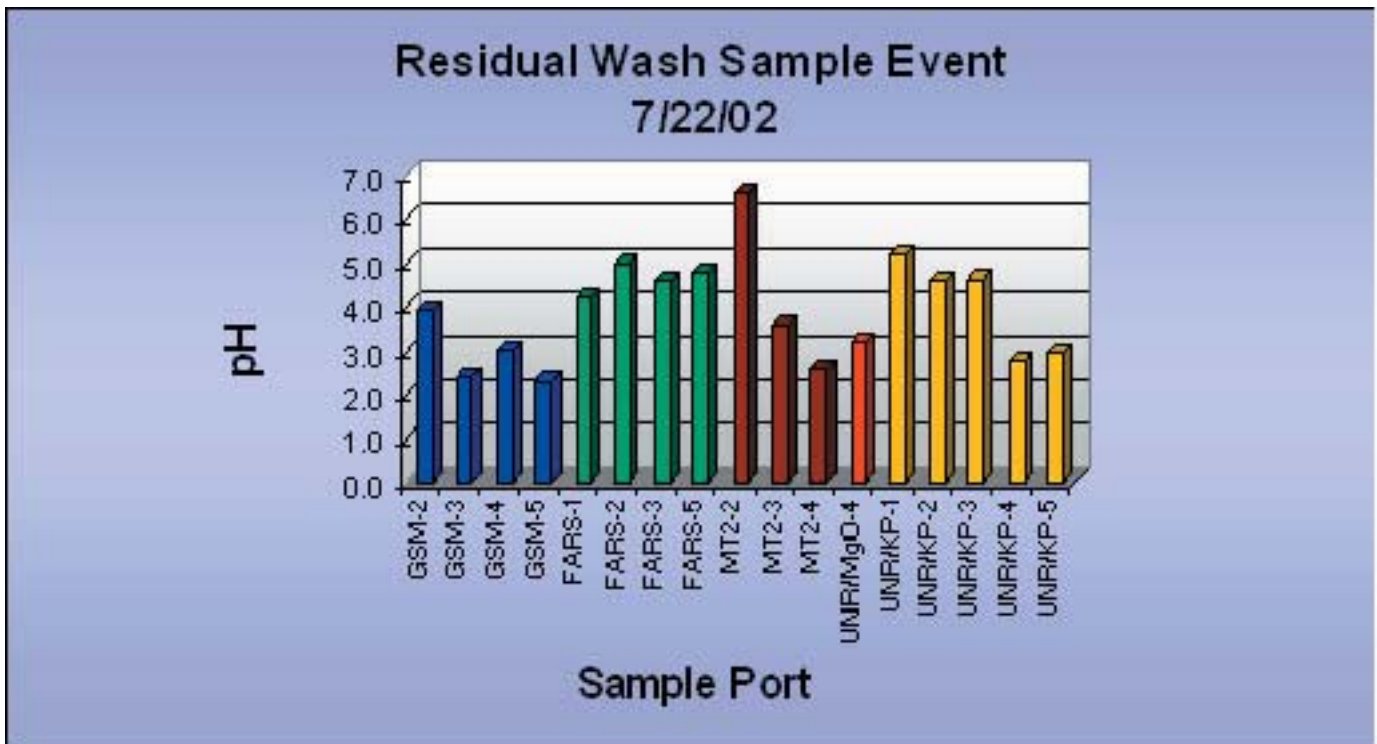


Figure 5-2. pH results for July 22, 2002, residual wash sampling event.

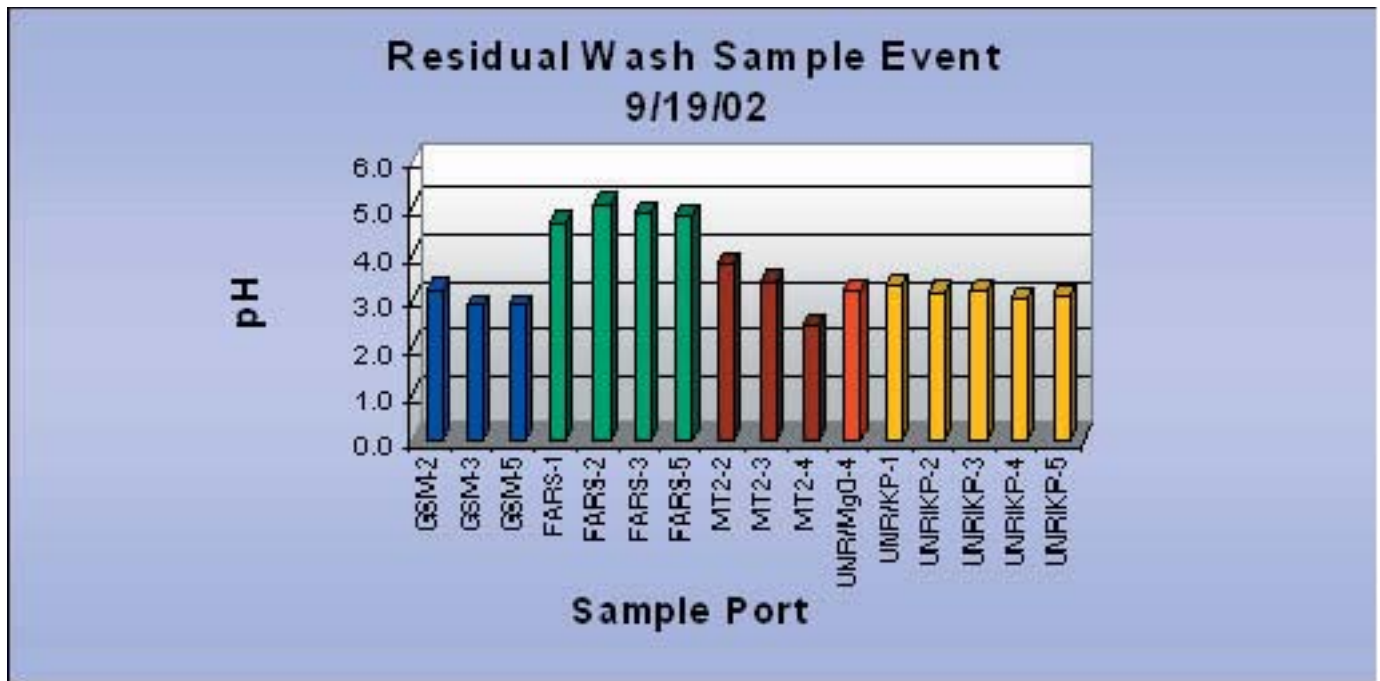


Figure 5-3. pH results for September 19, 2002, residual wash sampling event.

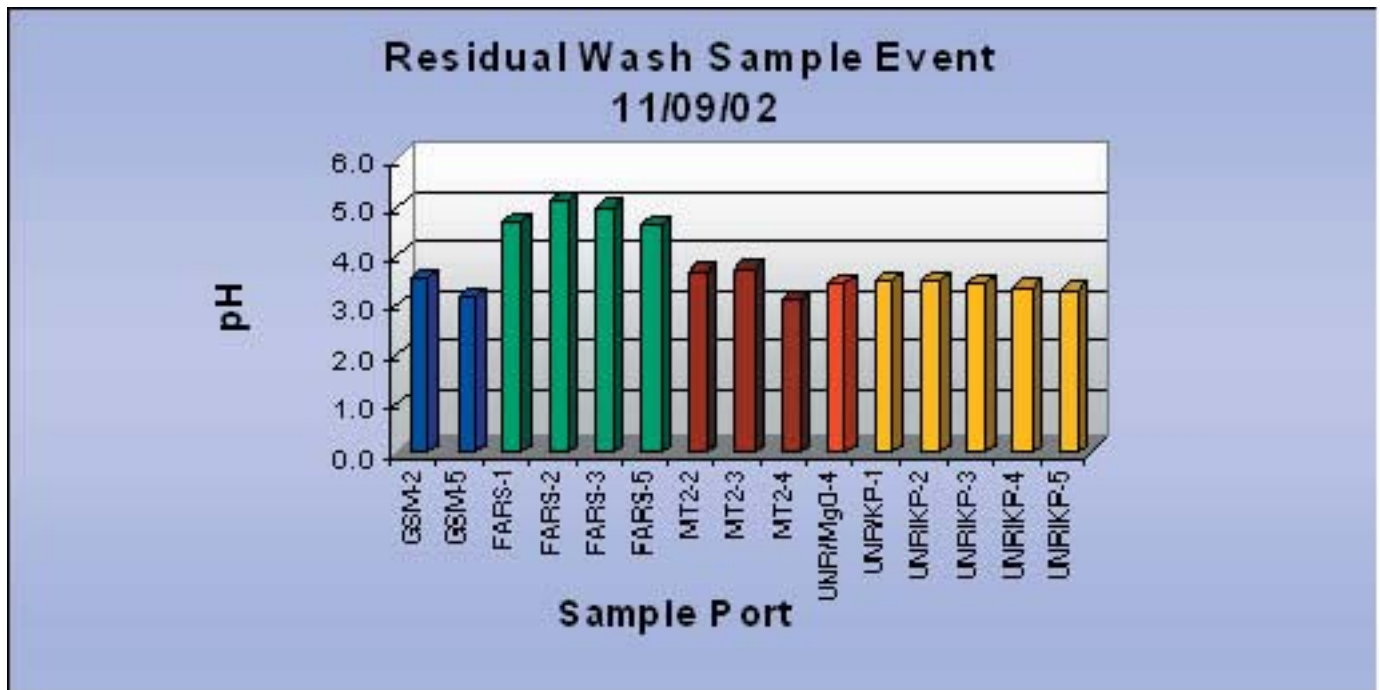


Figure 5-4. pH results for November 9, 2002, residual wash sampling event.

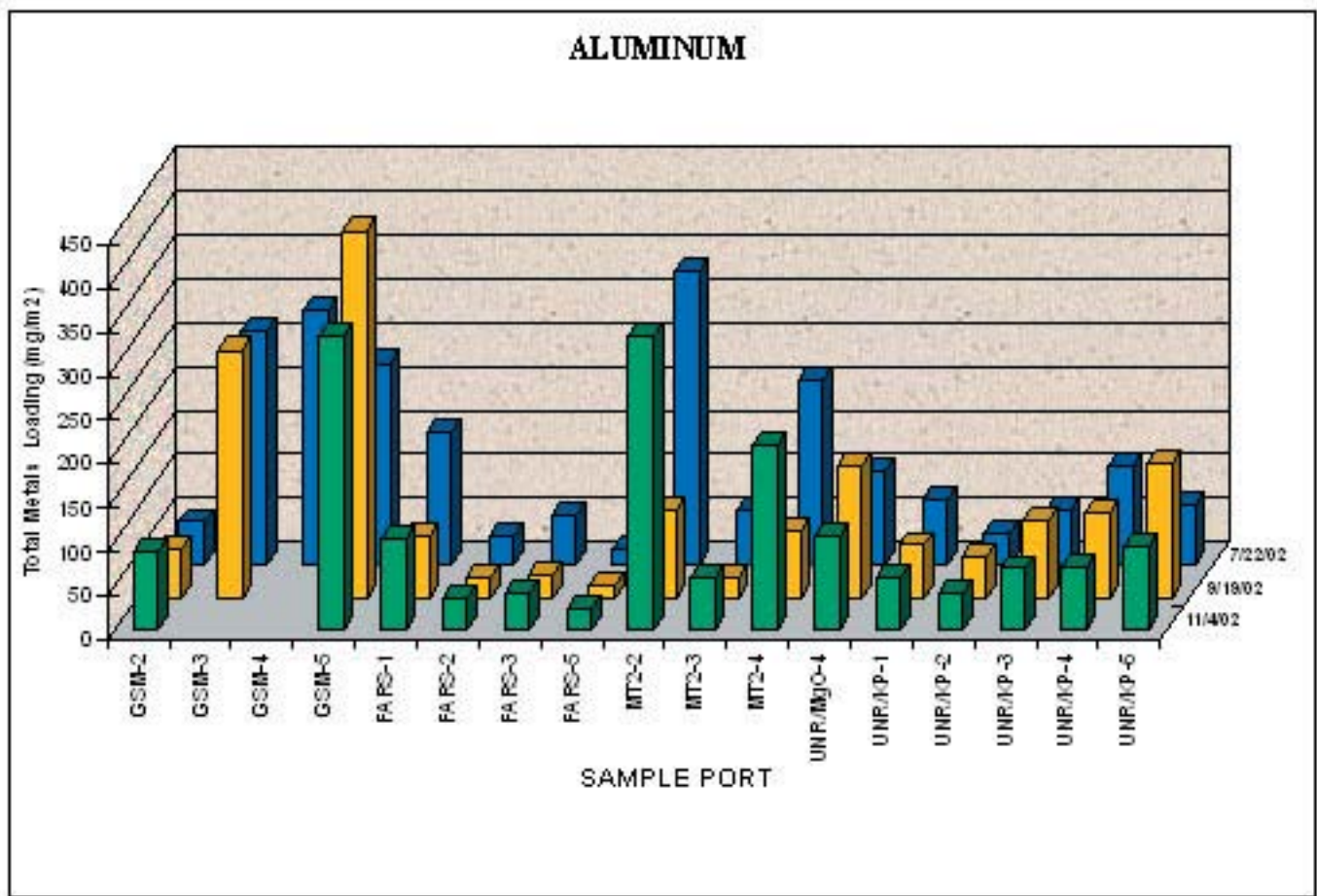


Figure 5-5. Total metals loading results for Al from samples taken from the mine wall sampling stations.

through 5-10. The complete data set used to graph the mine wall can be found in Appendix C.

The following includes the results and evaluation of each technology as compared to the background plot (see Figures 5-5 through 5-10) and the raw sulfate data.

5.2.3.1 FARS Plot

- The average sulfate concentration for FARS was reduced 89% of the background concentration of 10,779 mg/L.
- On average, when comparing the FARS treatment to the background, the FARS technology reduced the total metals loading for all six metal constituents. The metal loading for Al was reduced by 78% of the background loading, Cu by 91%, Fe by 89%, Mn by 88%, Ni by 92%, and Zn by 93%.

5.2.3.2 EcoBond

- The average sulfate concentration for EcoBond was 31% less than the background concentrations of 10,779 mg/L.

- On average, when comparing the treatment to the background, the technology reduced the total metals loading for four constituents (Al, Fe, Mn, and Ni); however, the total loading for Cu and Zn was greater than the total loading for the background plot. This would indicate that the technology may provide limited inhibition of these metals, and additional chemical treatment may be required to reduce the loading for Cu and Zn. EcoBond reduced Al by 7%, Fe by 26%, Mn by 55%, and Ni by 64%.

5.2.3.3 UNR/MgO

- The average sulfate concentration for UNR/MgO was reduced 21% of the background concentration of 10,779 mg/L.
- On average, when comparing the treatment to the background, the technology reduced the total metals loading for five constituents. Iron was not reduced, and Zn and Mn were reduced to the greatest degree. The total metals loading reduction for Al was 21% that of the background loading, Cu by 27%, Mn by 37%, Ni by 34%, and Zn by 71%.

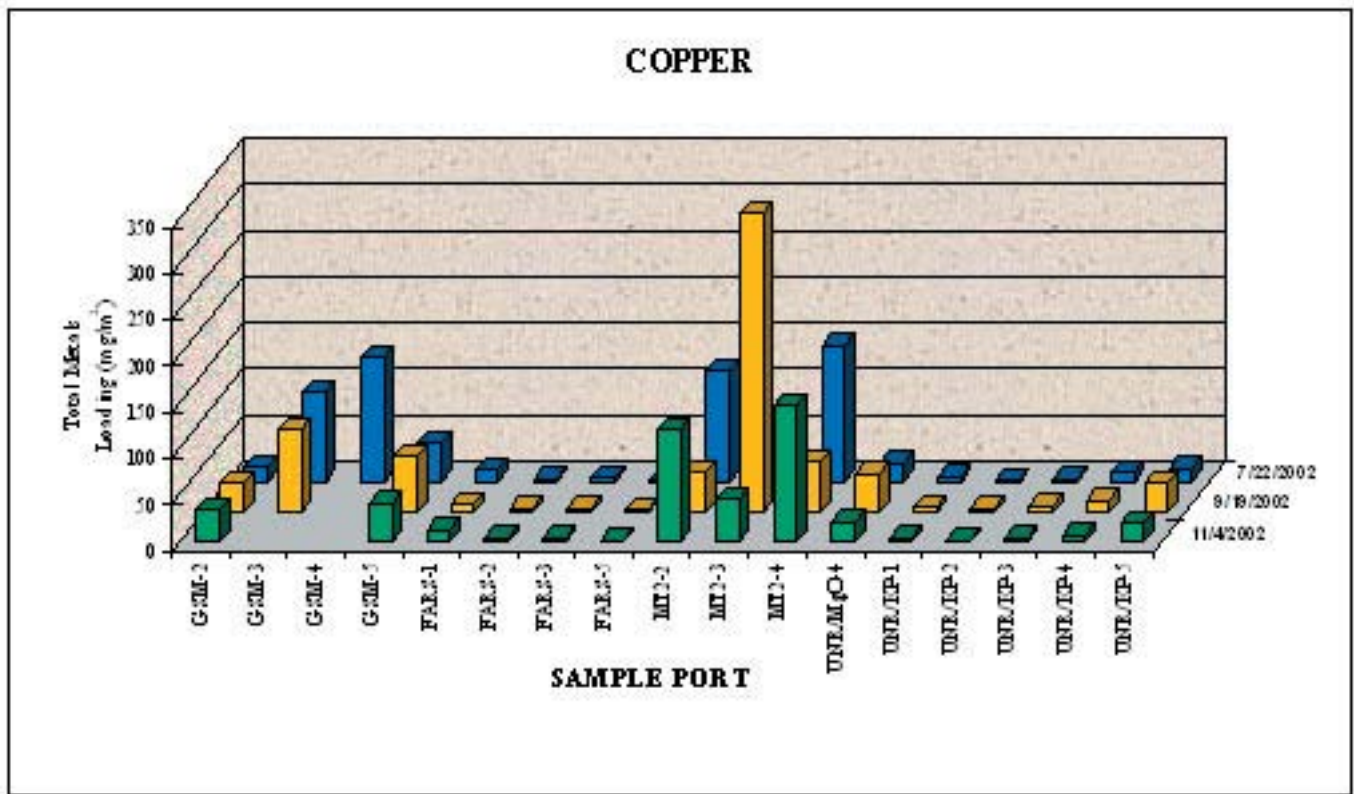


Figure 5-6. Total metals loading results for Cu from samples taken from the mine wall sampling stations.

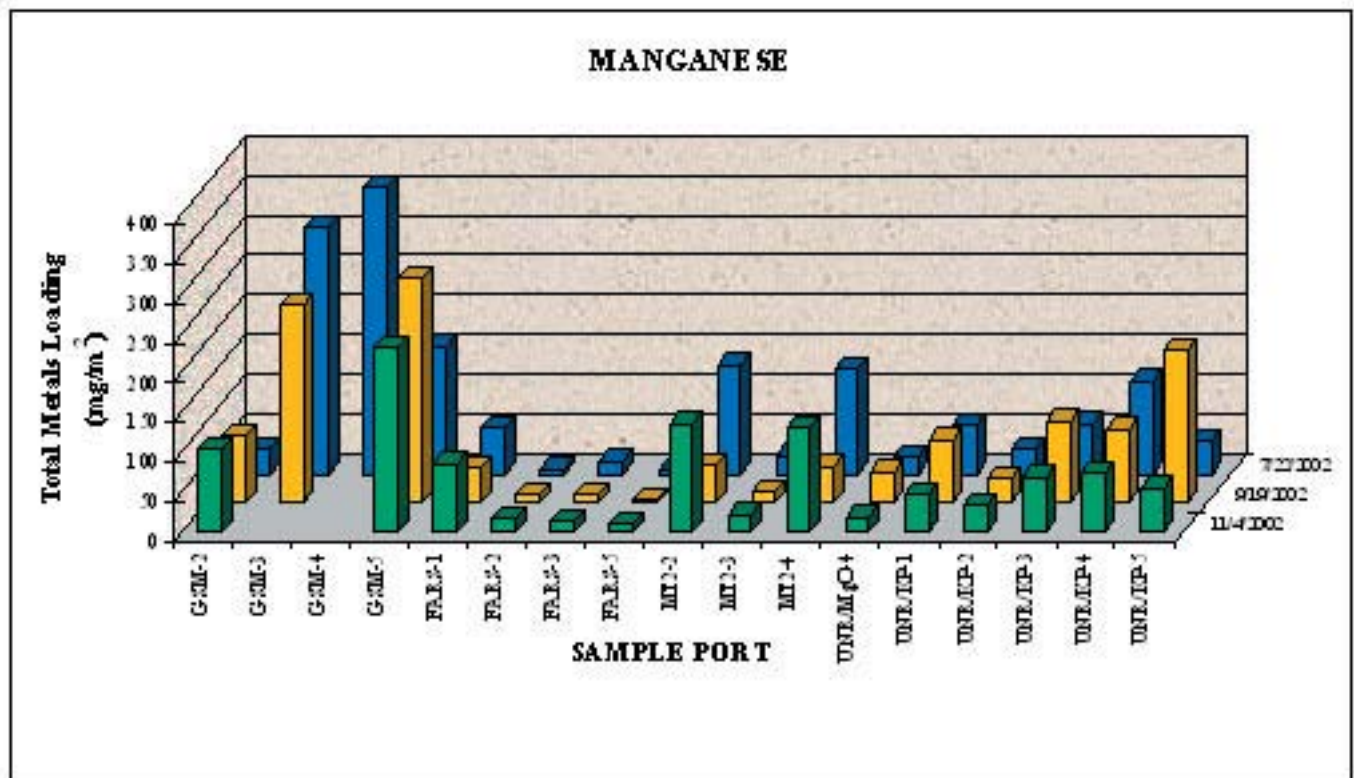


Figure 5-7. Total metals loading results for Mn from samples taken from the mine wall sampling stations.

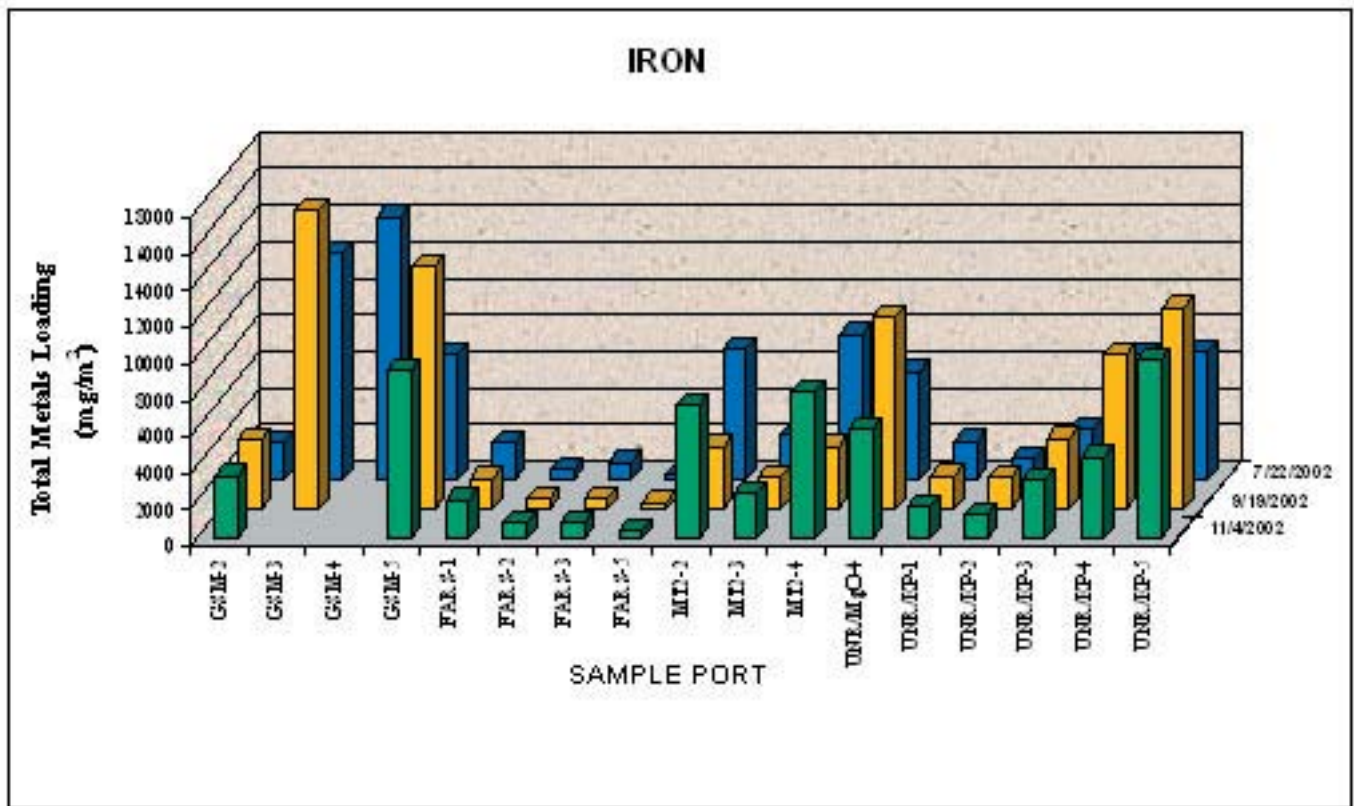


Figure 5-8. Total metals loading results for Fe from samples taken from the mine wall sampling stations.

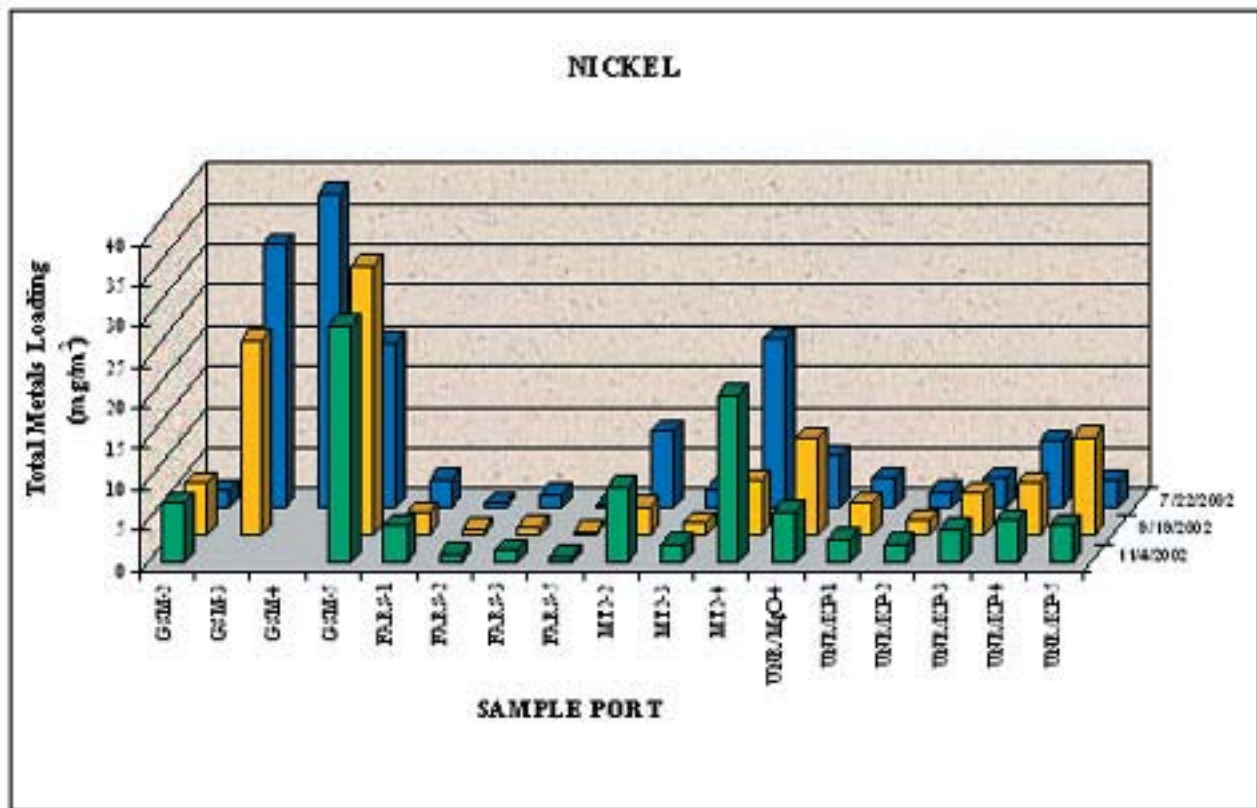


Figure 5-9. Total metals loading results for Ni from samples taken from the mine wall sampling stations.

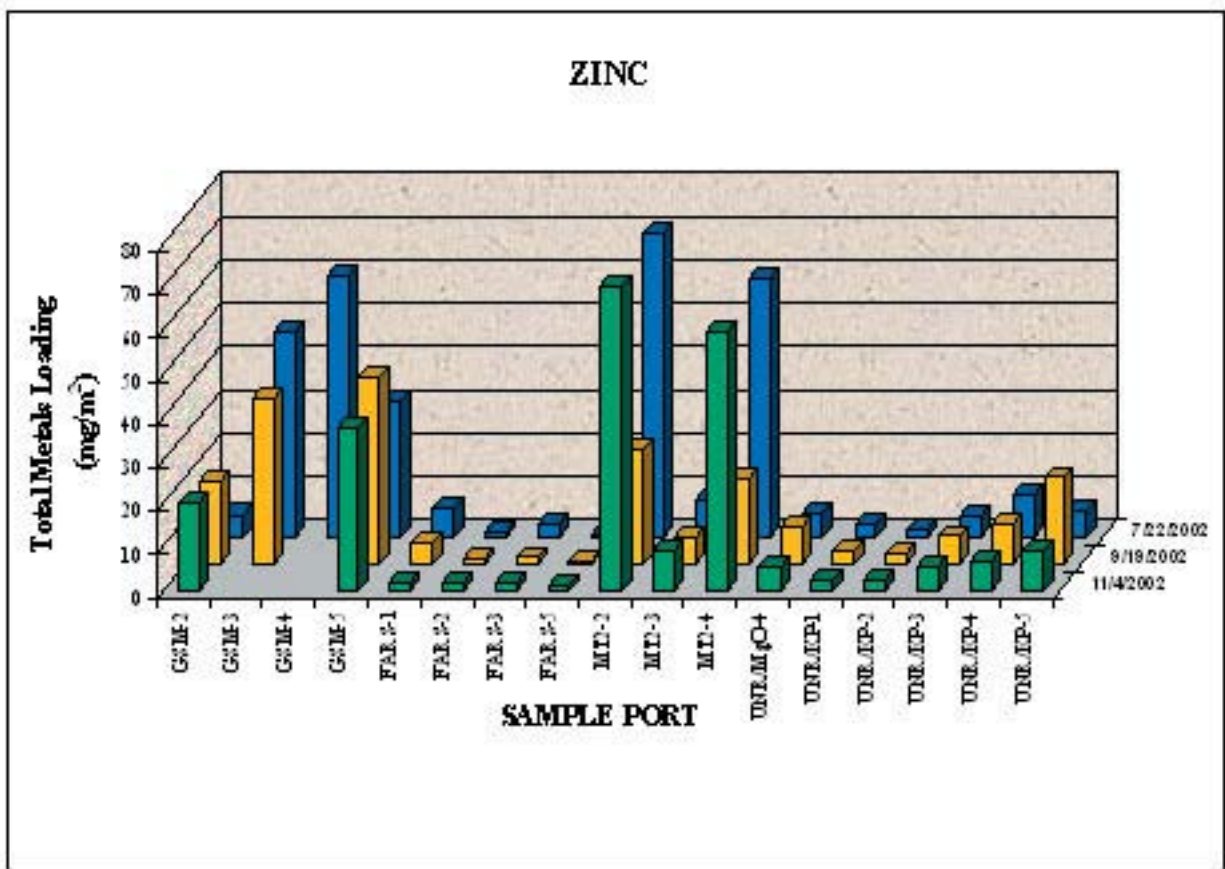


Figure 5-10. Total metals loading results for Zn from samples taken from the mine wall sampling stations.

5.2.3.4 UNR/KP

- The average sulfate concentration for UNR/KP was reduced 34% of the background concentration for sulfate which was 10,779 mg/L.
- On average, when comparing the treatment to the background, the technology reduced the total metals loading for all six constituents. The total loading for Al was reduced by 70% that of the background loading, Cu by 87%, Fe by 64%, Mn by 65%, Ni by 78%, and Zn by 86%.

5.2.4 Percent Reduction of Total Metals Comparison

Each mine wall station was evaluated to determine the percent reduction in the cumulative metal loading per unit area in the rinsate relative to the untreated control area. The concentration of each metal in the rinsates was converted to a mass loading per unit area based on the volume of rinsate and the surface area of the mine wall station. The percent reduction was based on the difference between the average mass per unit area of each metal generated from treated areas relative to the mass per unit area of metal generated from the treated areas relative to the mass per unit area of metal from the untreated

control station. Data were analyzed, and the percent reduction of cumulative metals loading was calculated for each technology. The results are provided in Table 5-2.

The FARS technology reduced all of the metals on the wall by at least 75% and, in some cases, up to 91% compared to the untreated plot (see Table 5-3). The FARS not only reduced the total metals leaching from the highwall, but it physically appeared to stabilize the wall rock.

The maximum percent reduction of total metals from the EcoBond treated plot was less than 50%. The EcoBond was not effective at reducing Zn and Cu on Plot C. This was apparent from results listed in Table 5-3 that indicate a higher concentration of Cu and Zn from the treated plot than the background/control plot. Higher concentrations could result from Plot C having a higher percentage of Cu in the highwall host rock. However, from the results, it would indicate that the treatment does not effectively treat Cu and Zn. Additional testing would need to be performed to determine why the select metals were not chemically bound.

The UNR/MgO technology reduced Mn and Zn by more than 75%; however, with the other metals, only a 50% or less reduction was observed. The concentration for total Fe was actually greater in the rinsate from the UNR/MgO treated plot

Table 5-2. Summary of Water Injection Testing

Stage Interval (feet bgs)	Average Pressure (psig)	Description of the Injection Interval Using a Lugeon Analysis	Permeability (cm/s)
Core Hole Number: GS-3 Horizontal (-5 degrees)			
5 - 17	22	Soft, broken material and fracture washout	7.8×10^{-3} to 1.2×10^{-4}
17 - 35	28	Fractures filled with soft material that restricts fracture flow, tight injection interval	7.9×10^{-6} to 1.6×10^{-5}
39 - 70	70	No flow in this injection interval	2.0×10^{-6}
Core Hole Number: GS-4 Horizontal (-5 degrees)			
5.5 - 20	9	Soft material washed out from fractures during water injection testing	2.4×10^{-4} to 9.9×10^{-4}
Core Hole Number: GS-3 (-45 degree hole)			
14 - 29	18 - 33	Tight fractures, laminar flow, smooth surfaces on cracks	2.4×10^{-5} to 6.3×10^{-5}
29 - 70	15 - 34	Tight fractures, laminar flow, fractures filled with some loose material	1.1×10^{-5} to 9.6×10^{-6}
Core Hole Number: GS-2H Horizontal (-5 degrees)			
7 - 20	17	Material washed out of fractures; broken rock	1.7×10^{-4} to 3.4×10^{-4}

Table 5-3. Percent Reduction of Total Metals from the Treated Technology Plots Compared to the Untreated Plot (Plot A)

Treated Plot vs. Background	FARS	EcoBond	UNR/MgO	UNR/KP
% Reduction of Al	75	20	38	62
% Reduction of Cu	85	-211	26	76
% Reduction of Fe	85	24	-16	30
% Reduction of Mn	84	49	82	51
% Reduction of Ni	90	48	50	72
% Reduction of Zn	91	-40	75	76

than from the untreated plot. This is apparent from the negative value in Table 5-3.

For the UNR/KP treatment, Cu and Zn were reduced the most at 76%, followed by Ni at a 72% reduction. Aluminum was reduced by 62%, and Fe and Mn were reduced by 30% and 51%, respectively.

From the information obtained during the mine wall (residual wash) sampling, the technologies that were the most effective in reducing acid generation and leaching of metals from the highwall area, listed in an increasing order of overall effectiveness, were EcoBond, UNR/MgO, UNR/KP, and FARS.

5.3 HC Testing Results

The HC testing on the untreated GSM material was conducted to establish baseline AMD potential data. Humidity cell testing on the treated material was conducted to determine the

effectiveness of the various treatment technologies in preventing and/or minimizing AMD potential.

Each sample was saturated with the treatment and then remained in the container until transported to MLI (see Figure 5-11). The timeline for treatment of the samples is as follows: FARS (September 2001), EcoBond (October 2001), UNR/MgO (November 2001), and UNR/KP (December 2001). Because of its binding capabilities, the FARS sample had to be physically broken apart so that the coated sample could fit into the HC testing container. Breaking the material coated with FARS allowed some surfaces to be exposed, creating the potential for oxidation to occur on those surfaces.

The original test duration was planned for 21 weeks but was extended to 31 weeks and subsequently 41 weeks. Test suspension durations were 43 days after week 21 before reinitiation and 131 days after week 31 before reinitiation. Humidity cell test solids were left in the cells and frozen during test suspen-



Figure 5-11. Spray application of the material sent to MLI for HC testing.

sions. Several of the technologies responded after the testing had been reinitiated and are shown in the graphical presentation of the data for each technology (see each technology subsection for the relating figure).

Results from the HC testing for each of the treatment technologies replicated very well. The GSM untreated sample duplicated well but did exhibit some interim fluctuations that are believed to be the cause of a sulfide mineral grain “nugget” effect on the active surface of the rock. However, the treated rock is coated with an inert layer inhibiting the “nugget” effect (Ref. 13). The results of the weekly and cumulative HC testing are graphically shown in Figures 5-12 through 5-26. A complete set of data and graphs from replicate HC samples can be found in Appendix E.

5.3.1 ICP Metals Analysis Results for Feed Solids

At the time of the field application to the highwall, the technology providers applied their technologies to prepared samples. After the final application of the technologies to the highwall, the samples were shipped to MLI for testing. An ICP multielemental scan was performed on the treated and untreated

feed samples for sample characterization. These results are shown in Table 5-4.

At MLI, a 1.2-kilogram (kg) composite sample from each technology provider and the background plot were loaded in a 3.5-inch-ID, 9-inch-high HC and were leached weekly with approximately 500 mL of deionized water that was percolated in the cells for 3 hours. The cells were allowed to saturate for an additional hour and then drained. The effluent was analyzed for pH, E_H , EC, SO_4 , Fe^{3+} and Fe^{2+} , acidity, and alkalinity at MCL and submitted to an accredited EPA laboratory to be analyzed for Al, Cu, Fe, Pb, Mn, Ni, and Zn.

The above metal analysis on the feed indicates that the samples provided to the technology providers were similar to the background samples. The variability in some of the metals can be attributed to the analysis of the treatment chemicals and coatings. For example, the EcoBond technology is phosphate based. This is apparent from the phosphate values for the feed, EcoBond, phosphorus (P) = 7,540 mg/kg, while for the other technologies and background, P = 320 to 470 mg/kg.

5.3.2 GSM Untreated Rock

The data collected in the 41 weeks duration of HC testing indicate that the untreated rock would produce acid in a natural weathering and oxidizing environment. The final average pH was 2.81, E_H indicated strong oxidizing conditions and likely bacterial oxidation, and EC was substantially higher than the treated rock. Ferric and ferrous iron (Fe^{3+} and Fe^{2+}) mobility was high after week 15 with bacterial oxidation occurring after week 21. Sulfate generation was high; however, in comparing SO_4 and acidity, it is indicated that most SO_4 was not produced by oxidation of sulfide minerals but rather from sulfide oxidation of the SO_4 , and only 11.1% resulted from oxidation of sulfide minerals ($Ac/SO_4 \times 100$). Figures 5-12, 5-13, and 5-14 provide a graphic representation of the biweekly HC tests and cumulative mass data for the constituents available in the GSM HC. Also, an immediate increase in SO_4 and decreases in pH were seen on the figures, indicating the effect of the sample suspension on weeks 21 and 31.

5.3.3 FARS

The FARS treatment was replicated in the three HCs. There were no spikes observed, and pH and E_H increased slightly over the duration of the testing period with an overall pH range of 4 to 4.5 (see Figures 5-15, 5-16, and 5-17). A decrease was observed in E_H , Fe, SO_4 , and acidity concentrations at the beginning of the testing; however, over the 31 weeks, the SO_4 generated was 2,400 mg/L, with approximately 26% of SO_4 resulting from sulfide oxidation. The mobility of Fe was substantial, but the ratio of Fe^{3+} and Fe^{2+} was less than 1. Acidity was noted with no alkalinity. The HC results from the FARS treatment is shown graphically in the figures listed above. From the figures, it is apparent that the FARS was not affected by the period of suspension. In fact, upon reinitiation, the pH increased to 4.5.

Mass data for FARS treated tests show that significantly less acidity and sulfate was produced in 41 weeks of kinetic

Table 5-4. ICP Metals Analysis Results on Treated and Untreated Feed Samples for HC Testing

ICP Metals Analysis Results - Feed Solids Treated and Untreated Highwall Samples						
Metal, mg/kg	GSM	FARS	EcoBond	UNR/KP	UNR/MgO	Average
Ag	0.5	0.5	1.5	1	0.5	0.8
Al	51,000	61,600	64,000	53,100	53,900	56,720
As	15	15	30	15	15	18
Ba	50	60	50	40	50	50
Be	1.5	1.5	1.5	1	1.5	1.4
Bi	<2	14	16	<2	<2	6
Ca	1,200	1,600	1,600	1,100	1,200	1,340
Cd	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Co	16	18	22	17	15	17.6
Cr	105	143	114	110	113	117
Cu	54	72	94	71	71	72.4
Fe	36,700	43,500	56,500	38,800	37,300	42,560
K	29,300	39,800	62,000	36,500	38,400	41,200
Mg	7,100	8,900	9,500	9,100	9,000	8,720
Mn	105	145	170	180	105	141
Mo	5	7	7	5	13	7.4
Na	14,500	14,300	17,600	13,800	13,200	14,680
Ni	34	52	67	52	44	49.8
P	370	440	7,540	470	320	1,828
Pb	22	16	34	18	30	24
S total	28,600	33,500	47,600	33,100	30,300	34,620
Sb	10	5	20	10	5	10
Sr	189	228	218	177	187	199.8
Ti	1,600	2,100	2,100	1,800	1,700	1,860
V	63	84	100	86	73	81.2
W	<10	<10	<10	<10	<10	<10
Zn	30	38	44	34	28	34.8

testing; however, the percentage of sulfate resulting from oxidation of sulfide minerals was higher (23.5%). Alkalinity production for FARS was low.

In summary, HC test data showed that the treatment minimized acid production from the GSM material. Effluent pH was generally above 4, which is the pH of the original treatment solution. The redox potential increased slightly during the test but remained about 300 millivolts (mV); EC values were low; the iron mobility was minimal and the Fe³⁺:Fe²⁺ ratio was less than 1 (0.3 average); and SO₄ and acidity production was much lower than the untreated material; however, the percentage of SO₄ produced by oxidation of sulfides was higher at 23%. This generation of acid may be a result of weathering of the surfaces exposed when the sample was broken to get the sample in the

test container. Essentially no alkalinity was consumed during the test (0.01% of total).

5.3.4 EcoBond

The three HC tests for EcoBond had comparable replication. Slight spikes were noted in E_H, EC, Fe, and SO₄ with a slight decrease in acidity and alkalinity after the 3-week rest period (see Figures 5-18, 5-19, and 5-20). The overall results show that the EcoBond technology prohibits acid production as the pH decreased slightly at the beginning; however, final pH readings were greater than 7. The original pH when the technology was spray applied to the highwall and the test sample material was 11. Oxidation-reduction potential remained in the normal range, and EC and Fe mobility was low after 11 weeks.

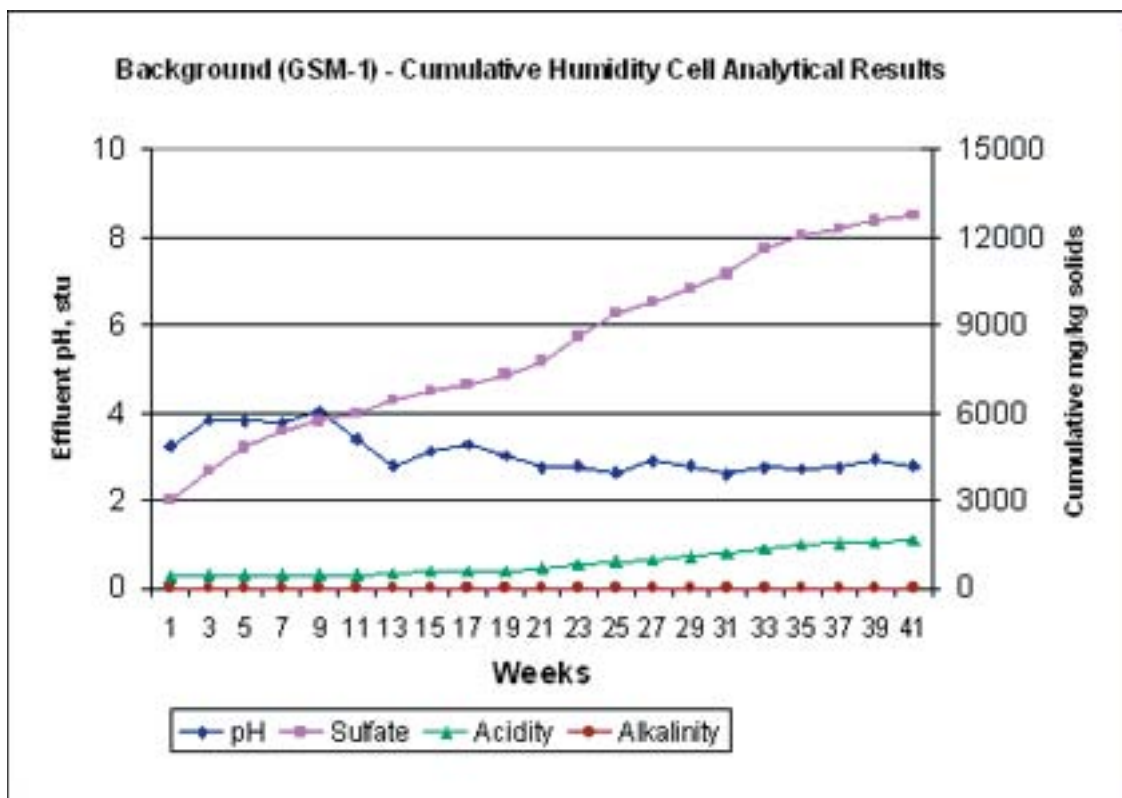
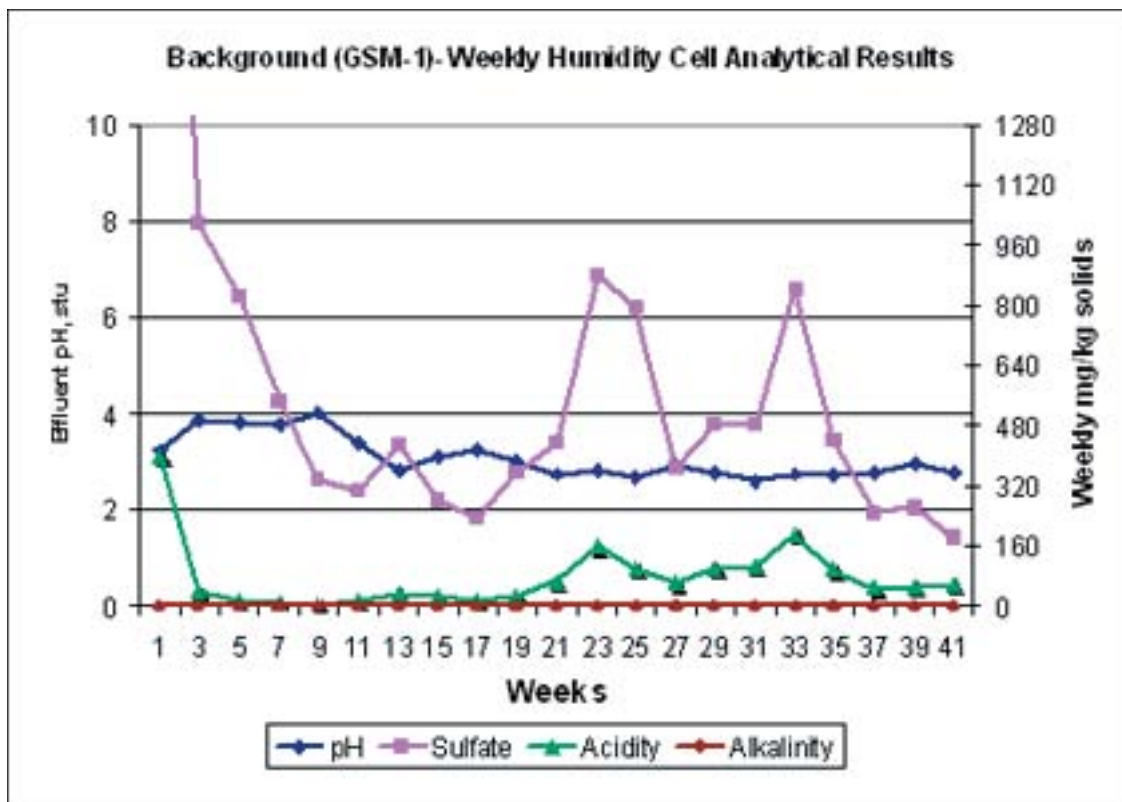


Figure 5-12. Weekly and cumulative HC analytical results for sample 1 from GSM background plot (Plot A).

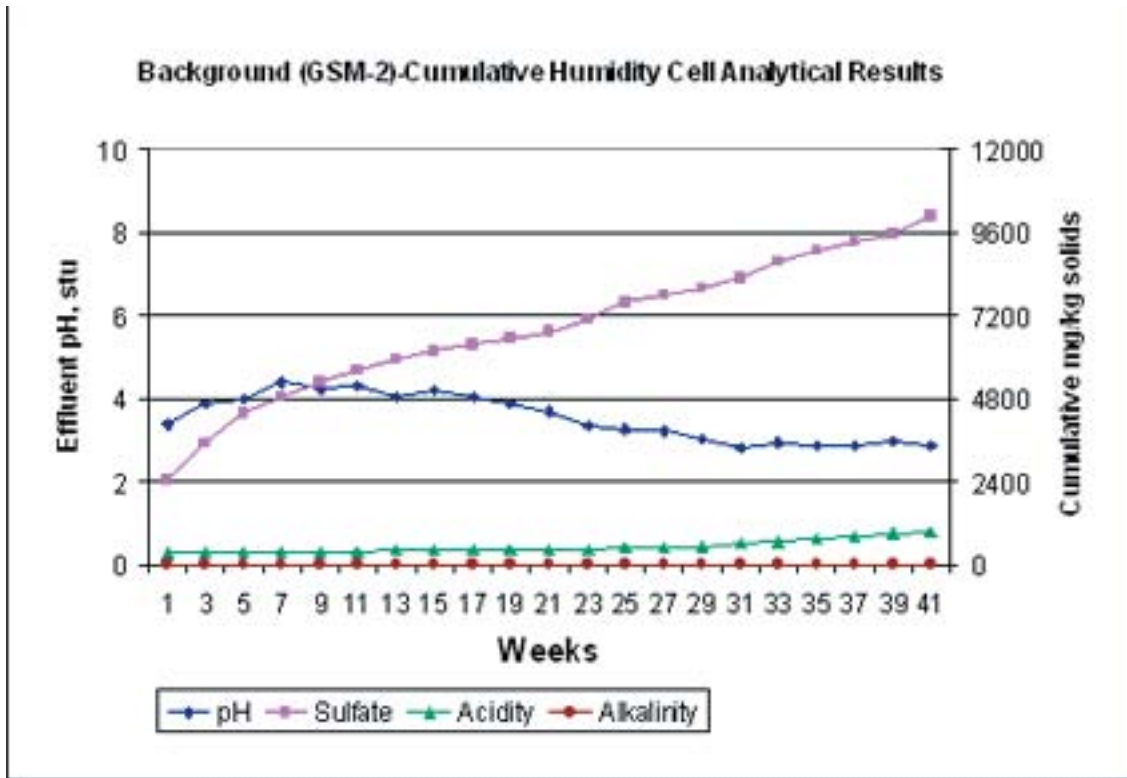
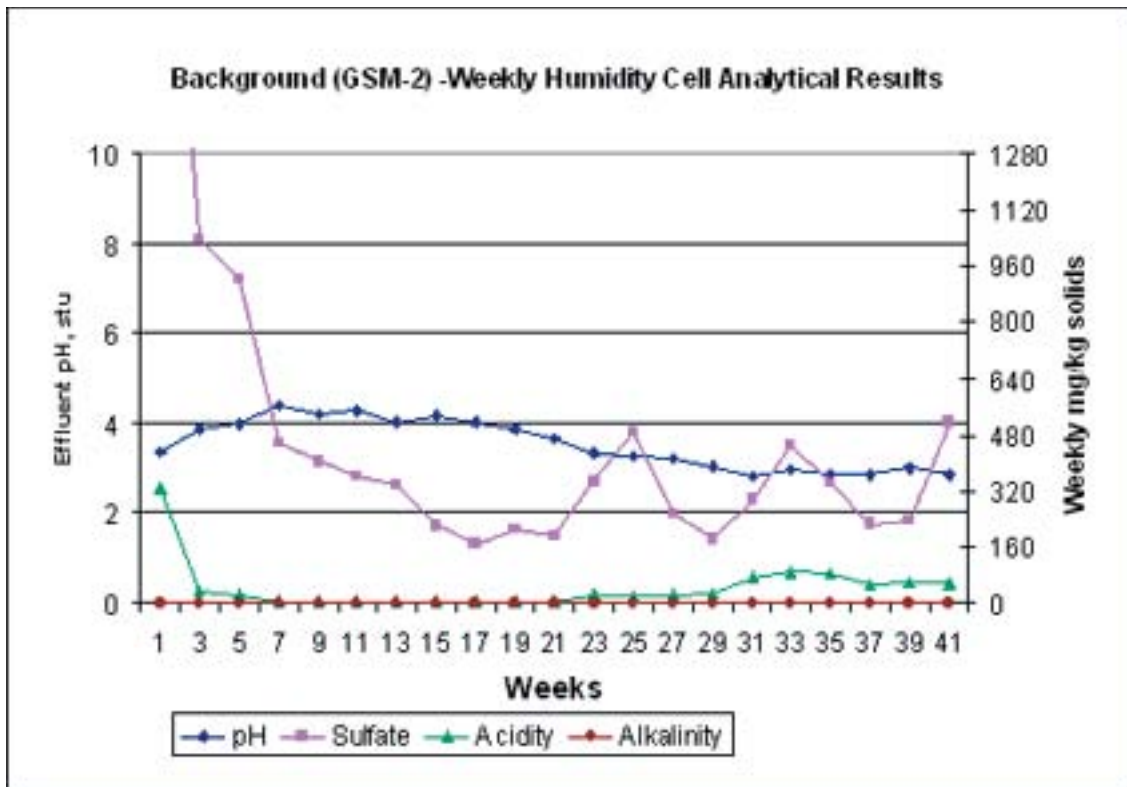


Figure 5-13. Weekly and cumulative HC analytical results for sample 2 from GSM background plot (Plot A).

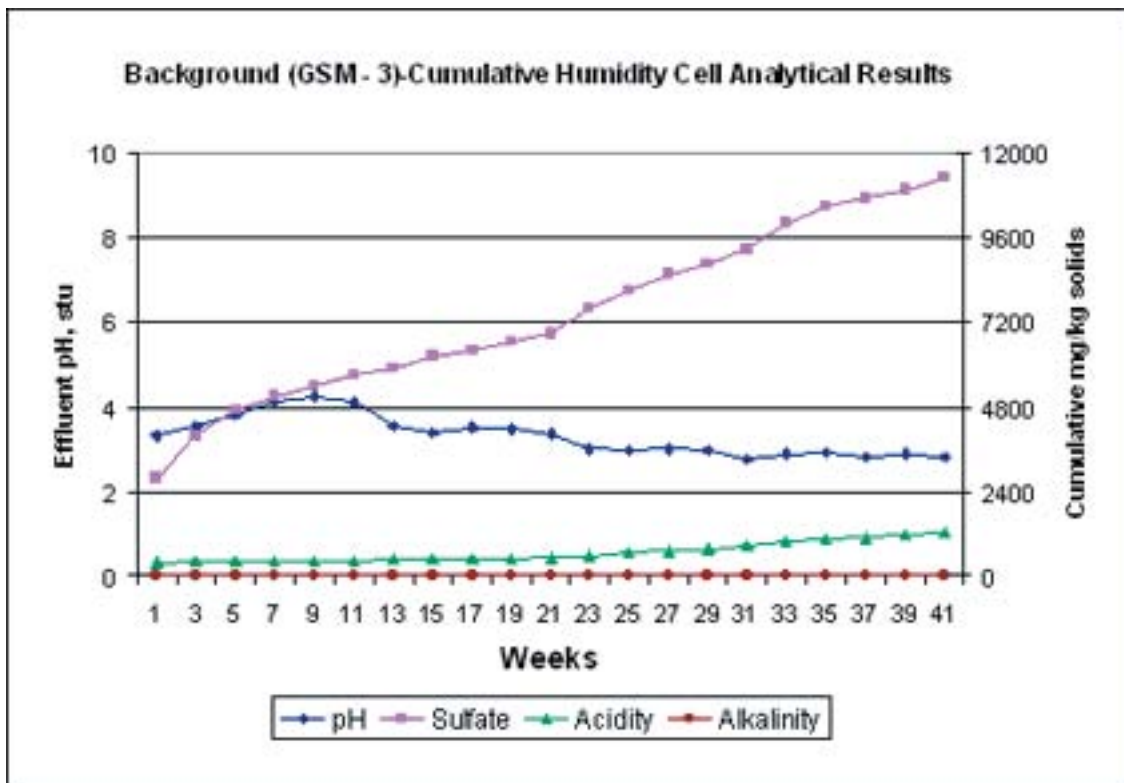
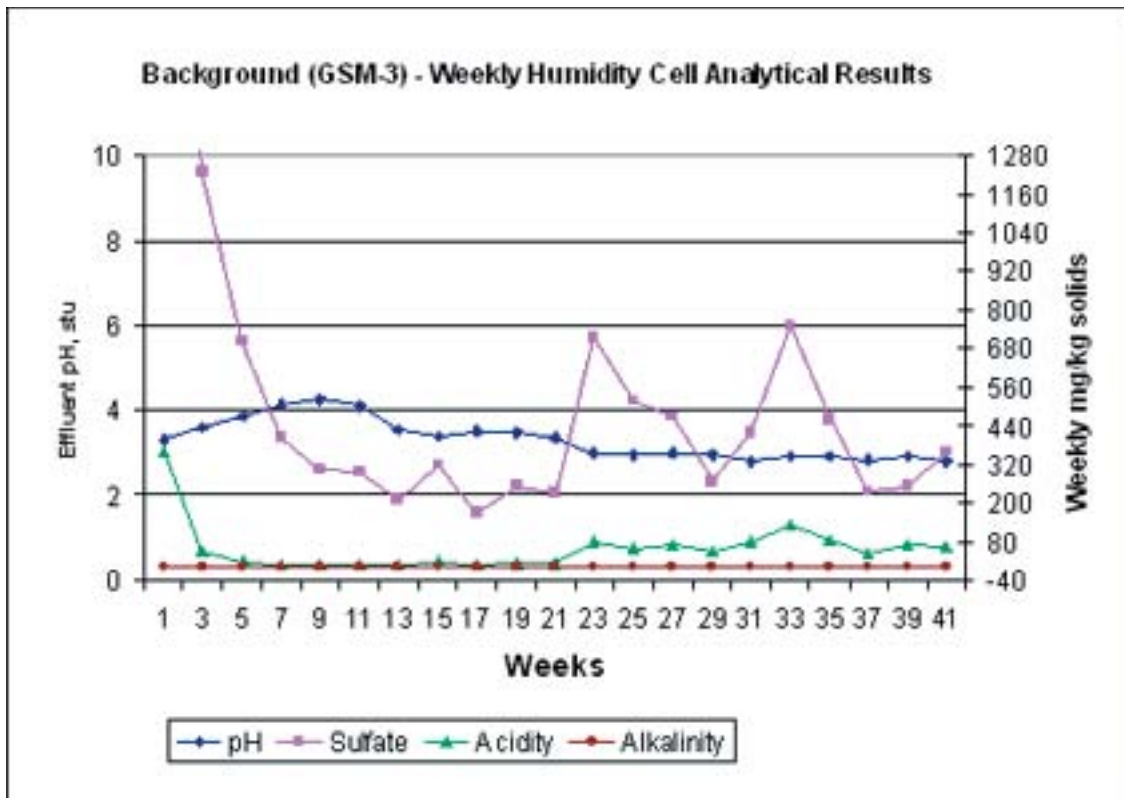


Figure 5-14. Weekly and cumulative HC analytical results for sample 3 from GSM background plot (Plot A).

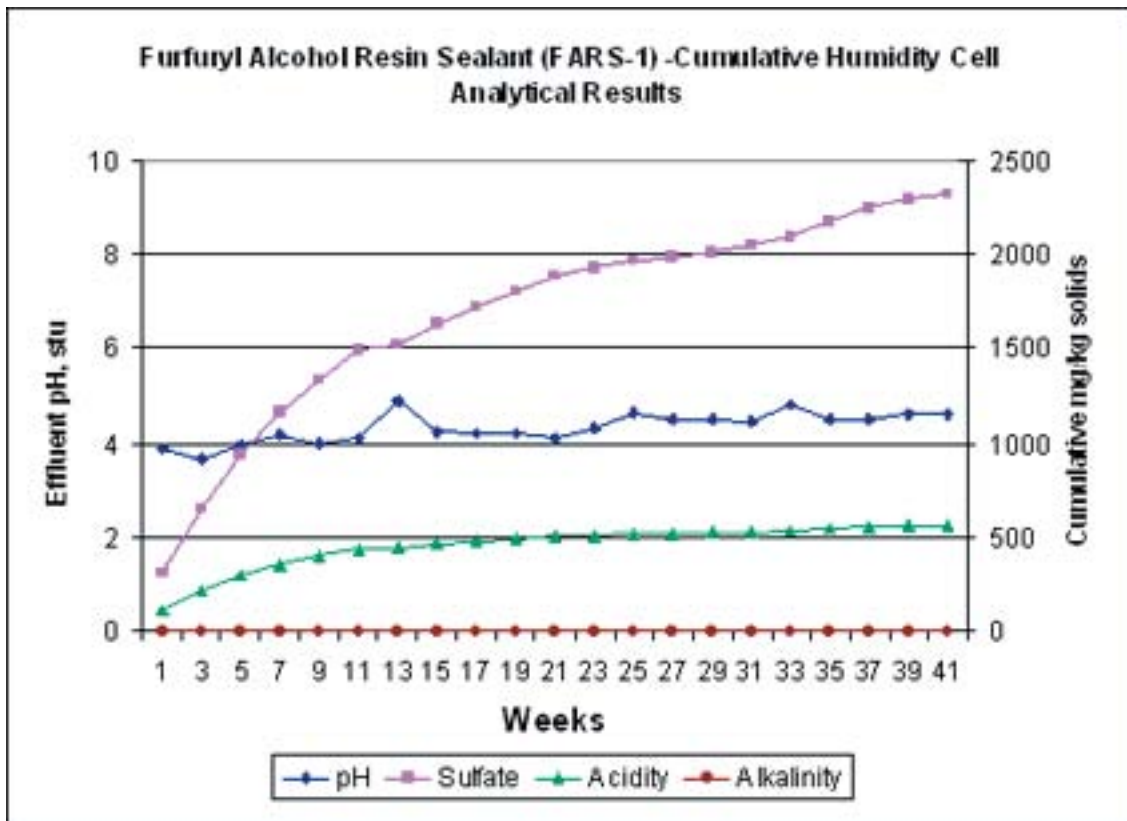
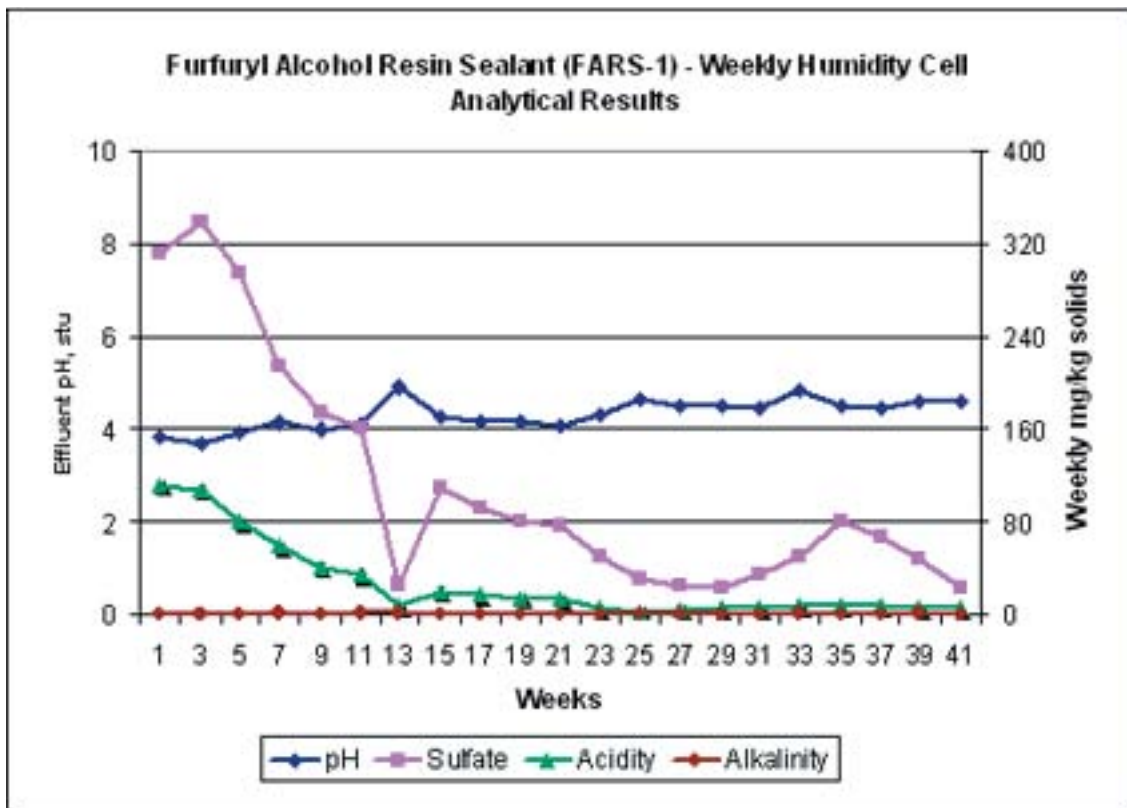


Figure 5-15. Weekly and cumulative HC analytical results for sample 1 from FARS plot (Plot B).

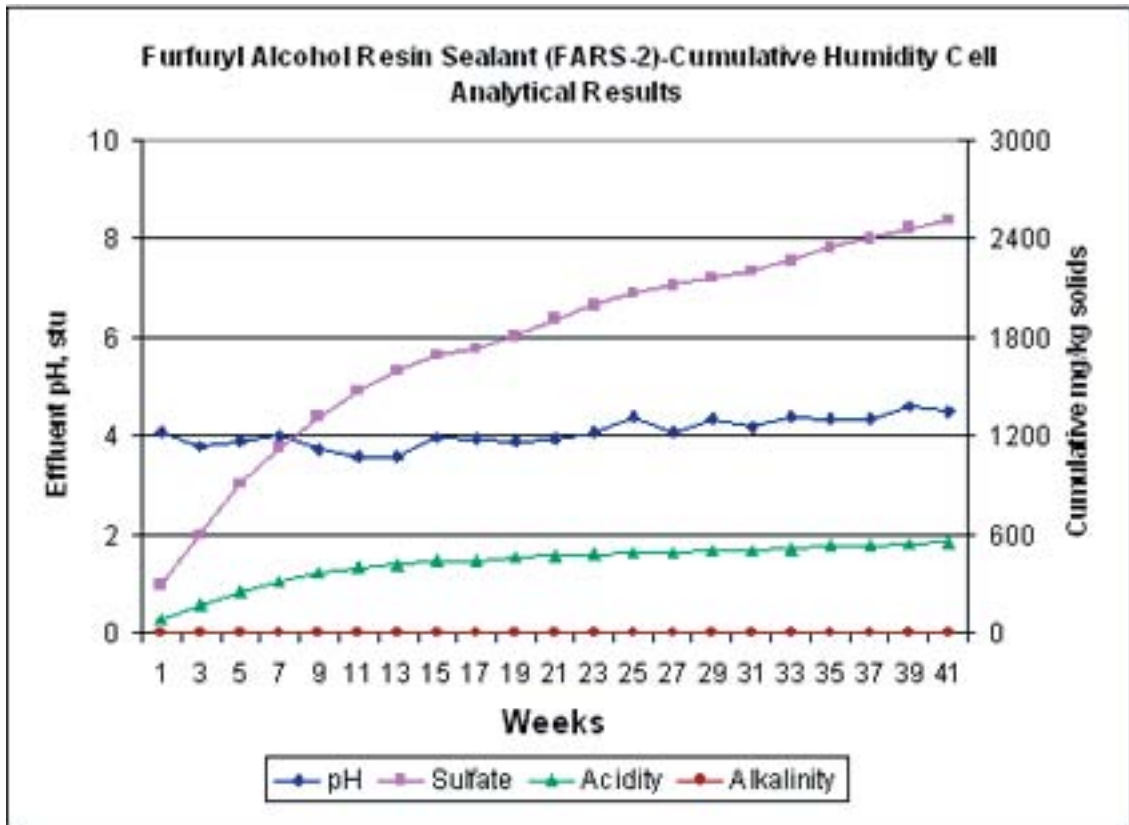
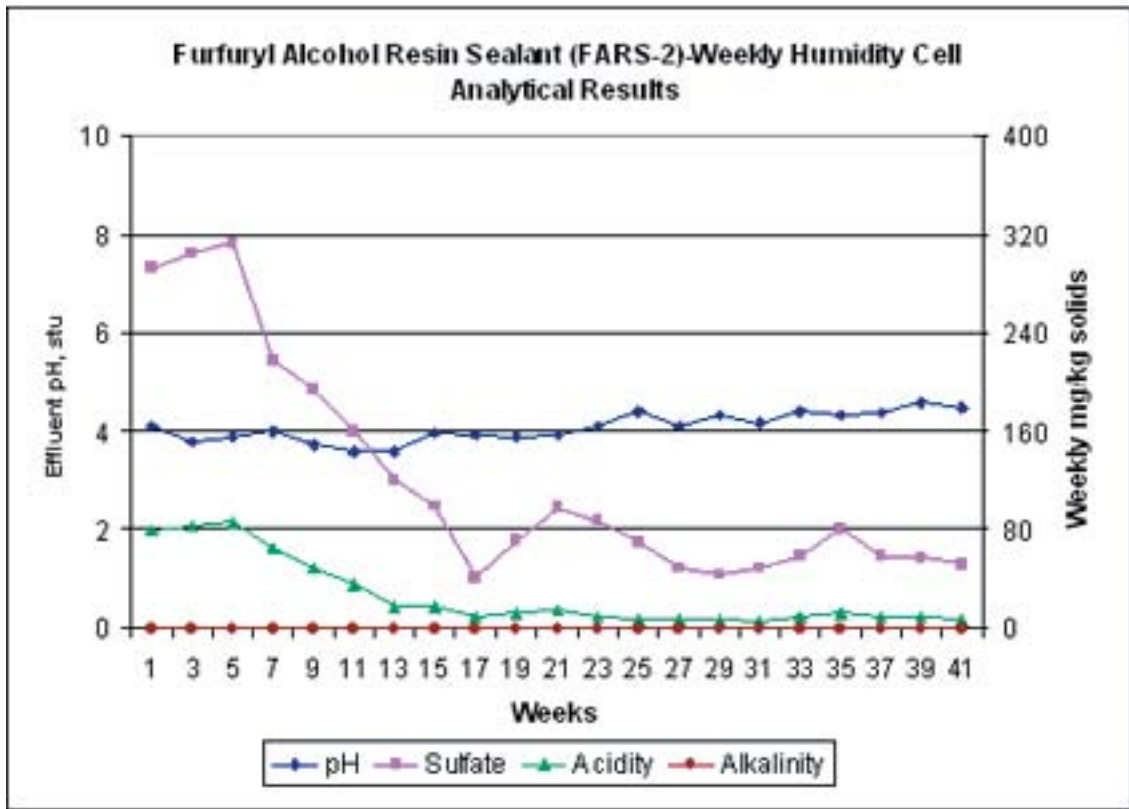


Figure 5-16. Weekly and cumulative HC analytical results for sample 2 from FARS plot (Plot B).

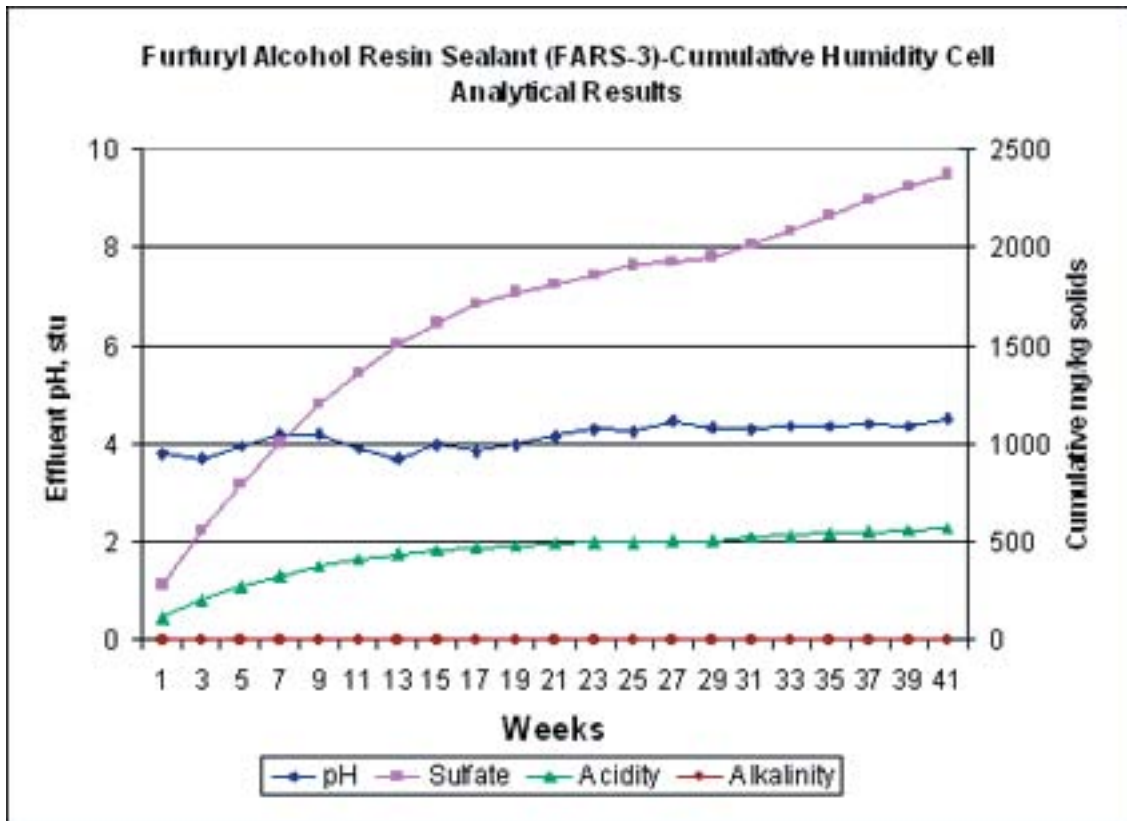
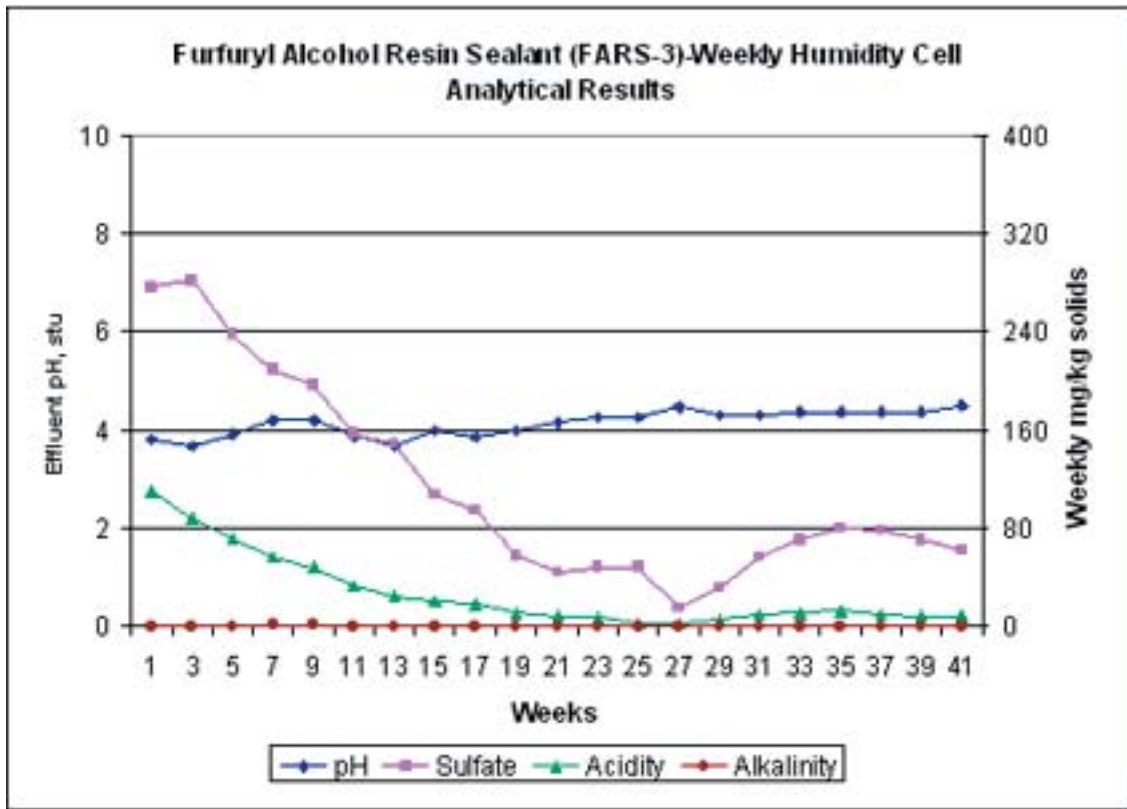


Figure 5-17. Weekly and cumulative HC analytical results for sample 3 from FARS plot (Plot B).

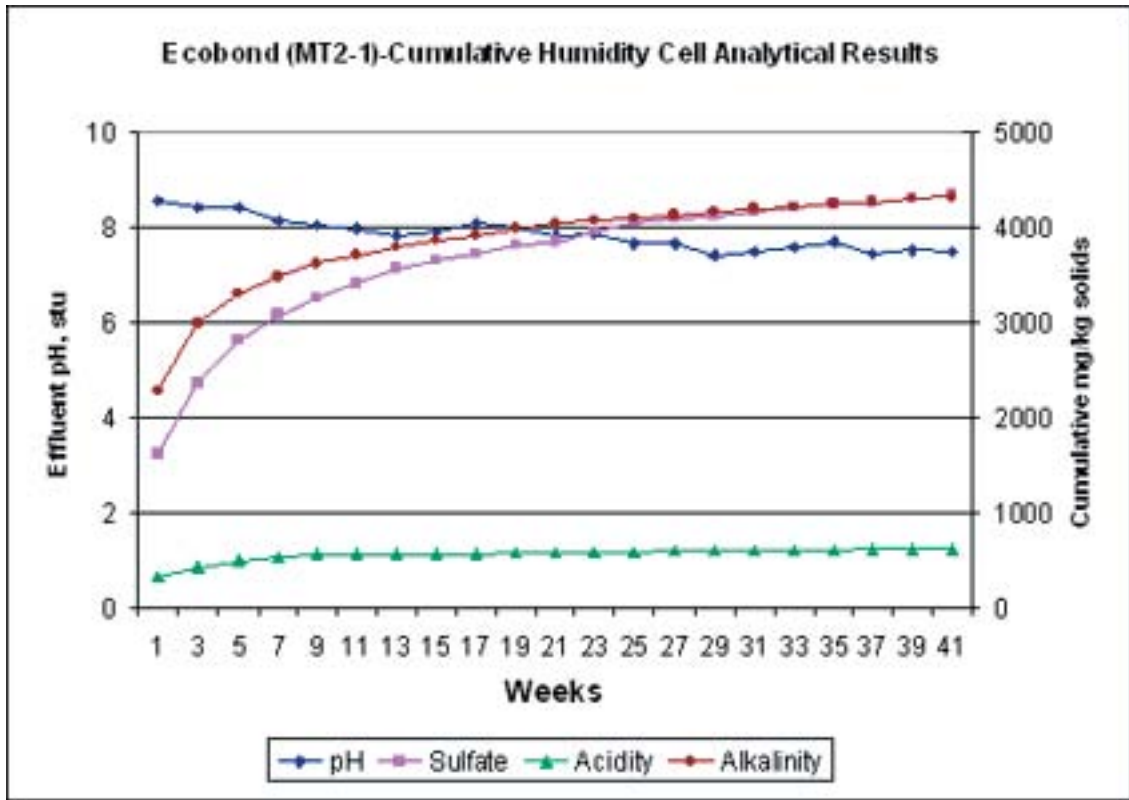
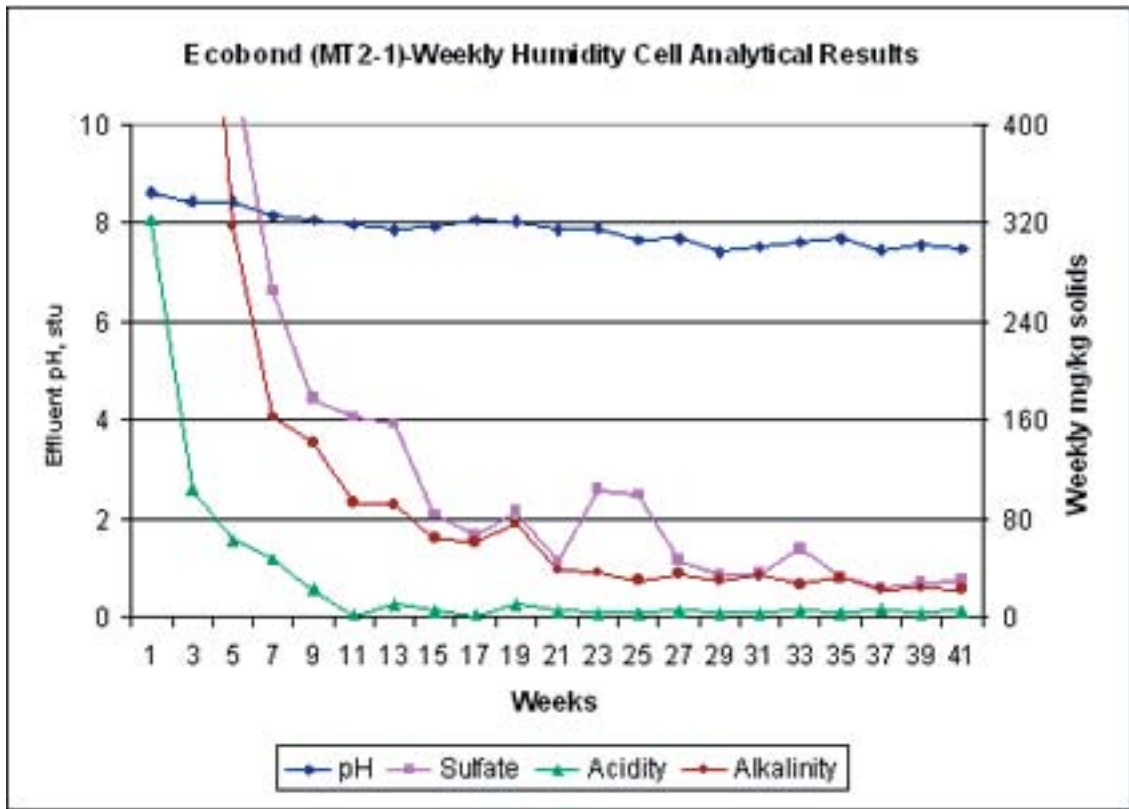


Figure 5-18. Weekly and cumulative HC analytical results for sample 1 from EcoBond plot (Plot C).

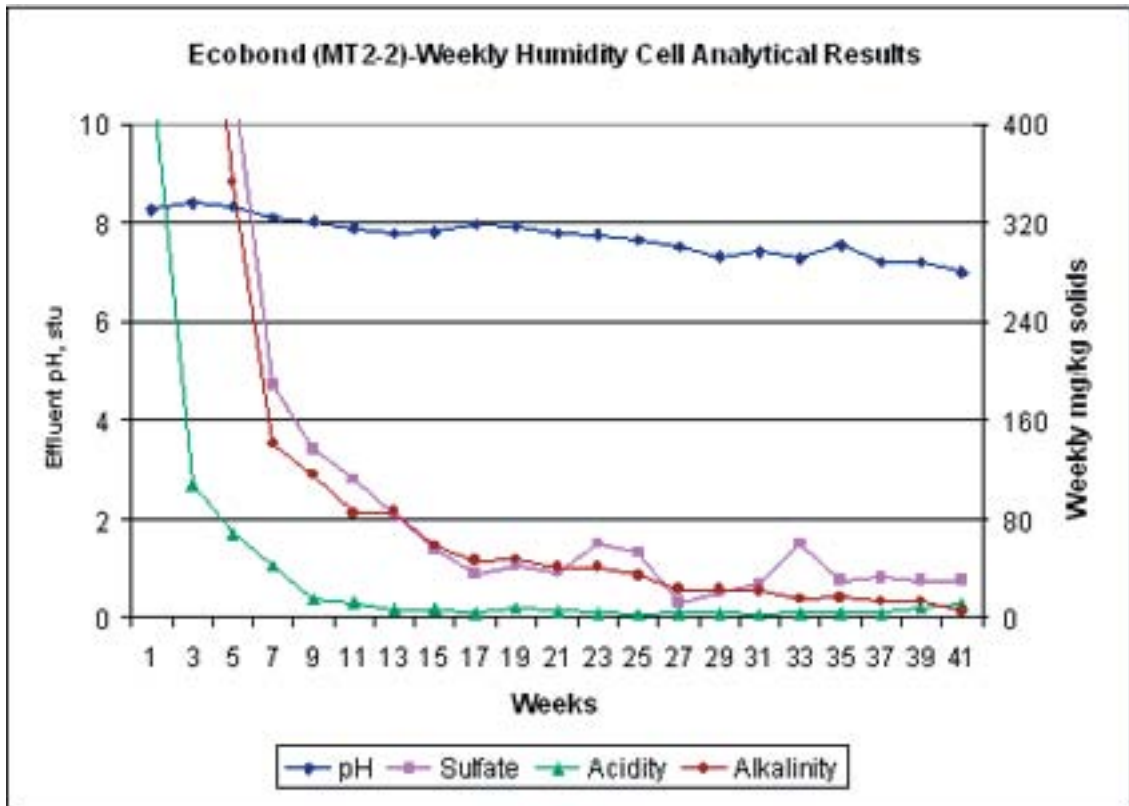
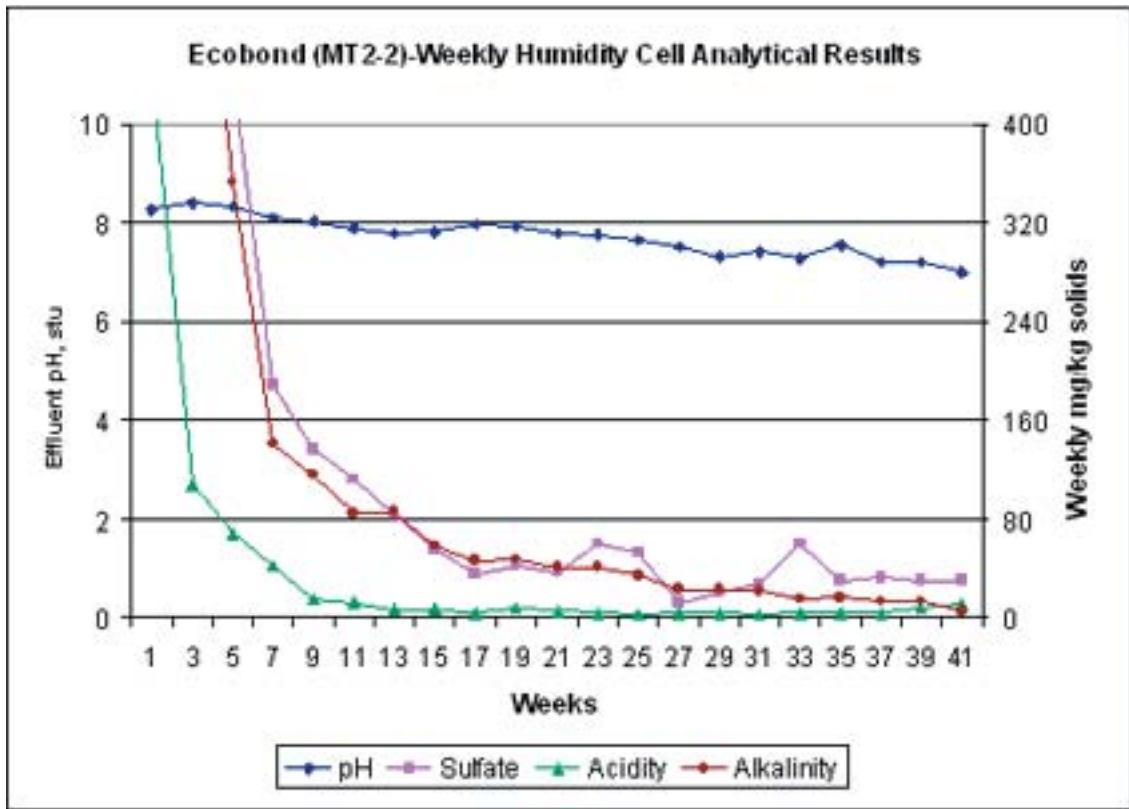


Figure 5-19. Weekly and cumulative HC analytical results for sample 2 from EcoBond plot (Plot C).

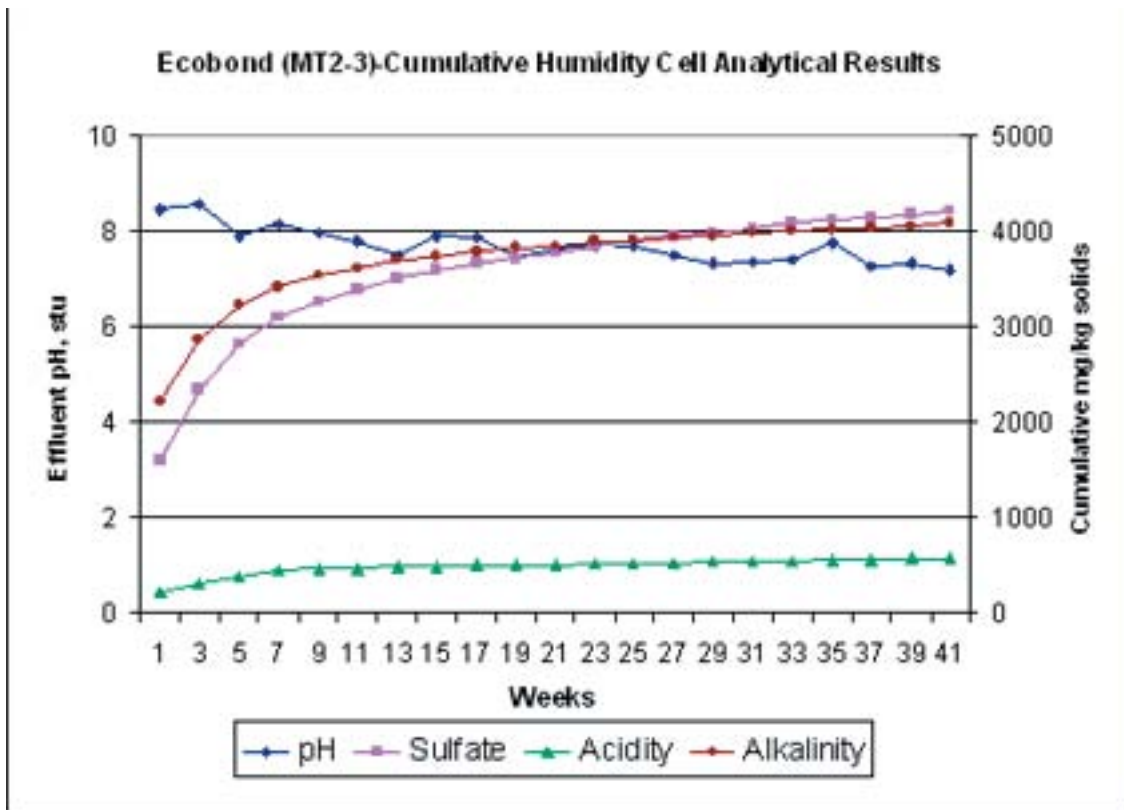
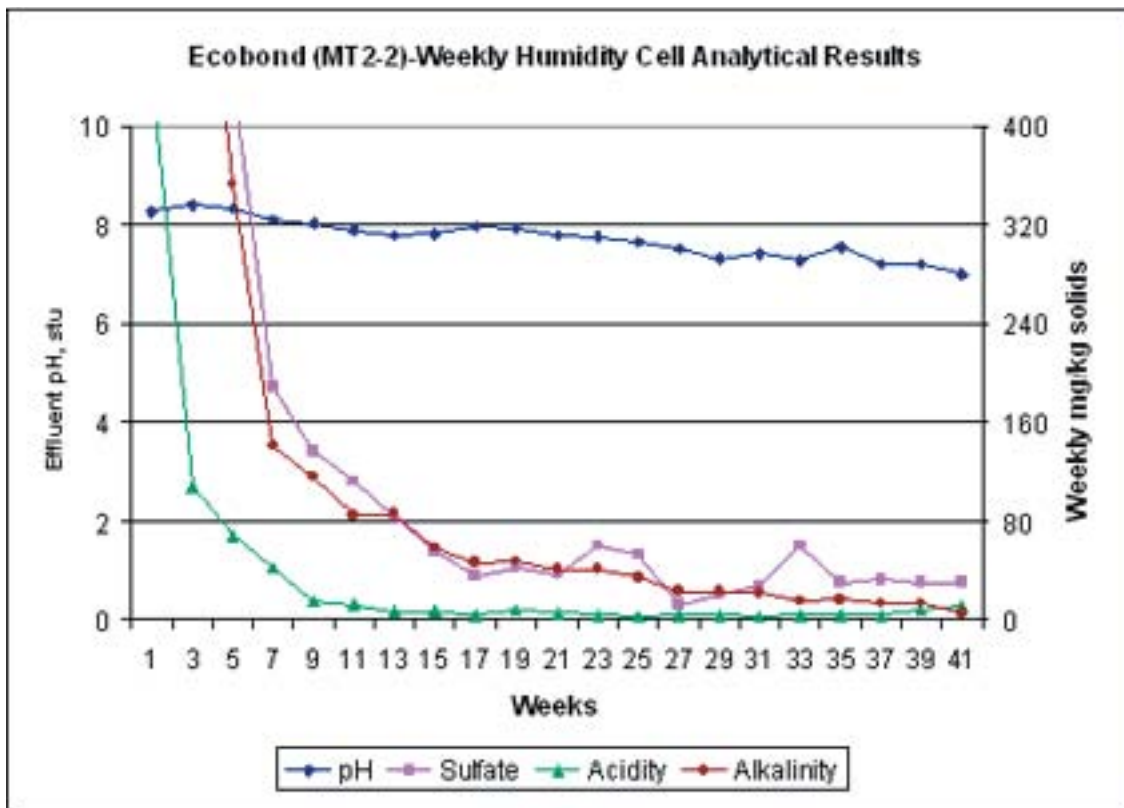


Figure 5-20. Weekly and cumulative HC analytical results for sample 3 from EcoBond plot (Plot C).

The SO_4 generation was high with approximately 15% resulting from sulfide oxidation. Results from the HCs for EcoBond are shown in Figures 5-18, 5-19, and 5-20.

Mass data for EcoBond treated tests show that significantly less acidity and sulfate was produced in 41 weeks of kinetic testing; however, the percentage of sulfate resulting from oxidation of sulfide minerals was higher (15.5%). Alkalinity production for EcoBond was 4,263 mg/L (21.2%). It was determined that if the rate of alkalinity production versus acidity production were to continue at a constant rate for EcoBond, data indicate that neutralizing capacity would be consumed before available acidity would be produced.

Humidity cell test data showed that the EcoBond treated GSM material would not produce acid in a natural environment. Effluent was above pH 7.4 during the test but did decrease from pH 8.58 (week 1) to pH 7.47 (week 41). The original pH of the treated material was 11. Redox potential varied slightly but remained fairly constant during the test at approximately 200 mV. The potential is typical for neutral pH systems exposed to air. Electric conductivity values were high initially but decreased to low levels the remainder of the test. Iron mobility was low; however, the $\text{Fe}^{3+}:\text{Fe}^{2+}$ ratio averaged about 3 after week 11; the higher ratio may have resulted from the treatment chemistry. Sulfate and acidity production was highest the first 5 weeks but steadily decreased thereafter. The overall results indicate that the EcoBond technology prohibited acid production under HC testing conditions.

5.3.5 UNR/MgO

During the 41 weeks of kinetic testing, none of the available acidity was produced for the MgO treatments, indicating that acid production for oxidation of sulfide minerals was essentially prevented. The percentage of sulfate resulting from sulfide oxidation was extremely low. The cumulative sulfate generated averaged 3,075 mg/L and was beginning to rise in weeks 37 through 41 (see Figures 5-21, 5-22, and 5-23). Alkalinity production was also low (MgO at 1.27%), indicating that the neutralizing capacity would be available over a long term, especially since no acid was produced.

Effluent pH was above 6 throughout the test; however, the pH tended to decrease with time, and the original pH of the material was 12. The MgO technology was responsive to the periods of testing suspension (i.e., the sulfate generation increased and the pH responded by either increasing or decreasing sufficiently). The EH decreased with time; however, it is typical of an aerated system and did not reach strong oxidizing conditions. Iron mobility was slight, yet the $\text{Fe}^{3+}:\text{Fe}^{2+}$ ratio was fairly high (0.4 late in the test cycle). Acidity was detected only late in the test cycle; however, alkalinity concentrations were 3 to 4 times higher during that period. Overall, under the HC testing conditions, the MgO reduced the acid production and leaching of metals from the highwall rock sample material.

5.3.6 UNR/KP

Comparable replication was noted with both the UNR/KP and UNR/MgO cells. A decrease in pH and alkalinity and an

increase in E_H , EC, and SO_4 were observed at the beginning of the testing (see Figures 5-24, 5-25, and 5-26). No mobility of metals was noted with the exception of Mn from the potassium permanganate. At the end of the 31 weeks, analytical results showed a pH of greater than 6, E_H in the normal range, and a low EC. The mobility of Fe was low as was the ratio of Fe^{3+} and Fe^{2+} . The low SO_4 generation (2,379 mg/L) indicates that the SO_4 is nonacidic. The UNR/KP technology was responsive to the periods of suspension, and sulfate generation increased and pH decreased upon reinitiation of the HC testing.

During the 41 weeks of kinetic testing, none of the available acidity was produced for the UNR/KP treatment, indicating that acid production for oxidation of sulfide minerals was essentially prevented. The percentage of sulfate resulting from sulfide oxidation was extremely low at less than 0.2%. Alkalinity production was also low at 0.9%, indicating that the neutralizing capacity would be available over a long term, especially since no acid was produced. From results shown in the HC tests, GSM material treated with the UNR/KP technology would not produce acid in a natural environment.

Effluent pH was above 6 throughout the test; however, the pH tended to decrease with time, and the original pH of the material was 12. The EH decreased with time, although this is typical of an aerated system and did not reach strong oxidizing conditions. Iron mobility was slight, yet the $\text{Fe}^{3+}:\text{Fe}^{2+}$ ratio was fairly high (.4 late in the test cycle). The higher ratio may be explained by the treatment chemistry (potassium permanganate is an oxidant) and by the fact that Fe concentrations were extremely low. Acidity was detected only late in the test cycle; however, alkalinity concentrations were 3 to 4 times higher during that period.

5.3.7 Summary of the HC Testing Results

An overall summary of HC test data is provided in Table 5-5. Oxidation-reduction potential, pH, and EC data are averages for the week 41 HC test extracts only. All other data in the table are an average of the triplicate tests conducted on each rinsate water sample from the HC testing.

In summary, the data show that the untreated GSM highwall sample would produce acid in a natural weathering and oxidizing environment. The final pH was 2.81; E_H indicates strong oxidizing conditions and likely bacterial oxidation; EC indicates substantial metal mobility; and SO_4 and acidity production was high; however, alkalinity production was low (0.02% of total). Of the SO_4 produced, only 11.1% resulted from oxidation of sulfide minerals ($\text{Ac} \div \text{SO}_4 \times 100$). The calculated alkalinity and acidity ratio ($\text{Alk} \div \text{Ac}$) of the rinsate water from the HC testing was less than 0.001.

It should be noted that the rock from the treated highwall plots could potentially produce acid. This was apparent from the solids data evaluated and presented in Appendix E, Table 5. Results of the static test performed to predict the acid production potential of the highwall rock (note: untreated and treated samples were crushed, allowing untreated surface area to be exposed) indicated that the difference between the acid neutralization potential (ANP) and the acid generating potential

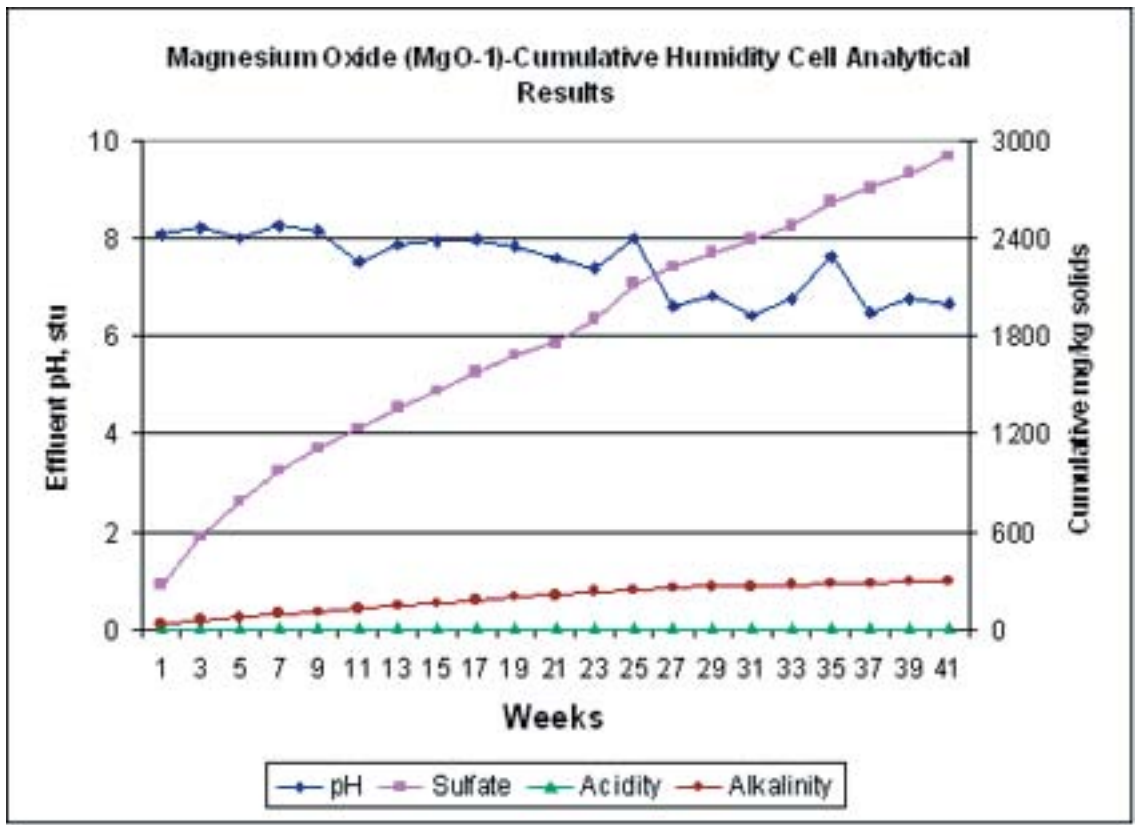
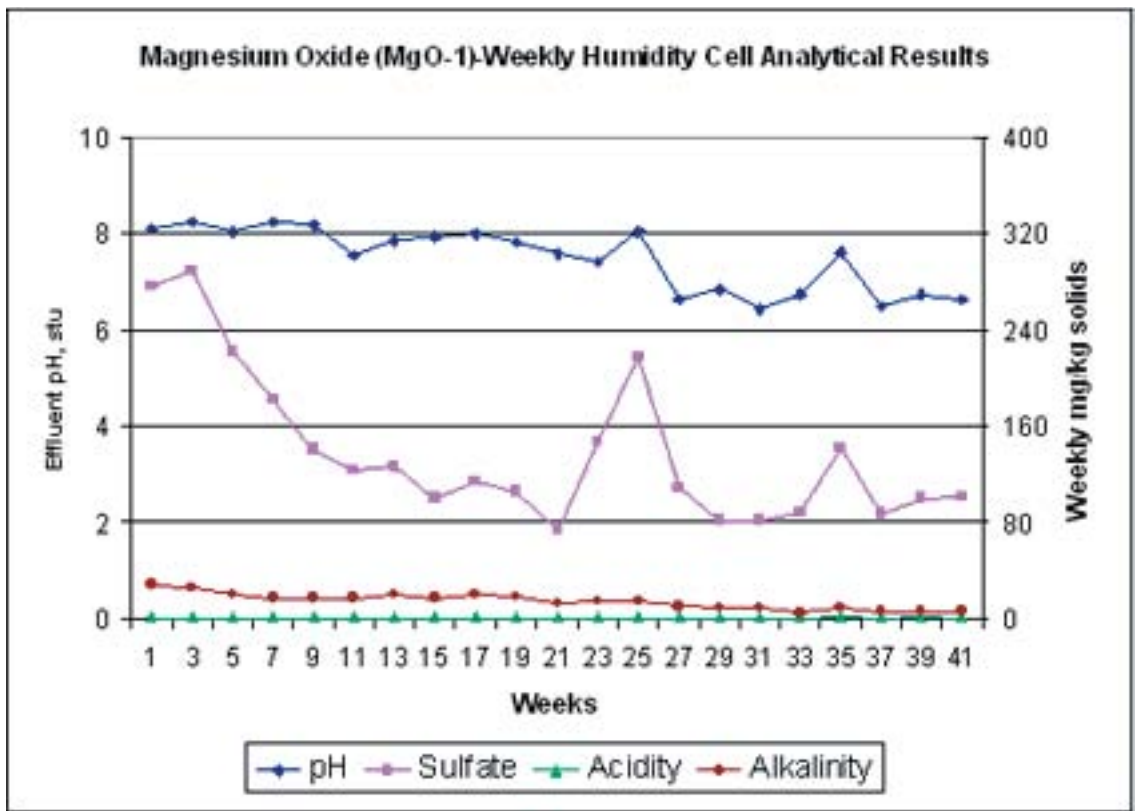


Figure 5-21. Weekly and cumulative HC analytical results for sample 1 from UNR/MgO plot (Plot D).

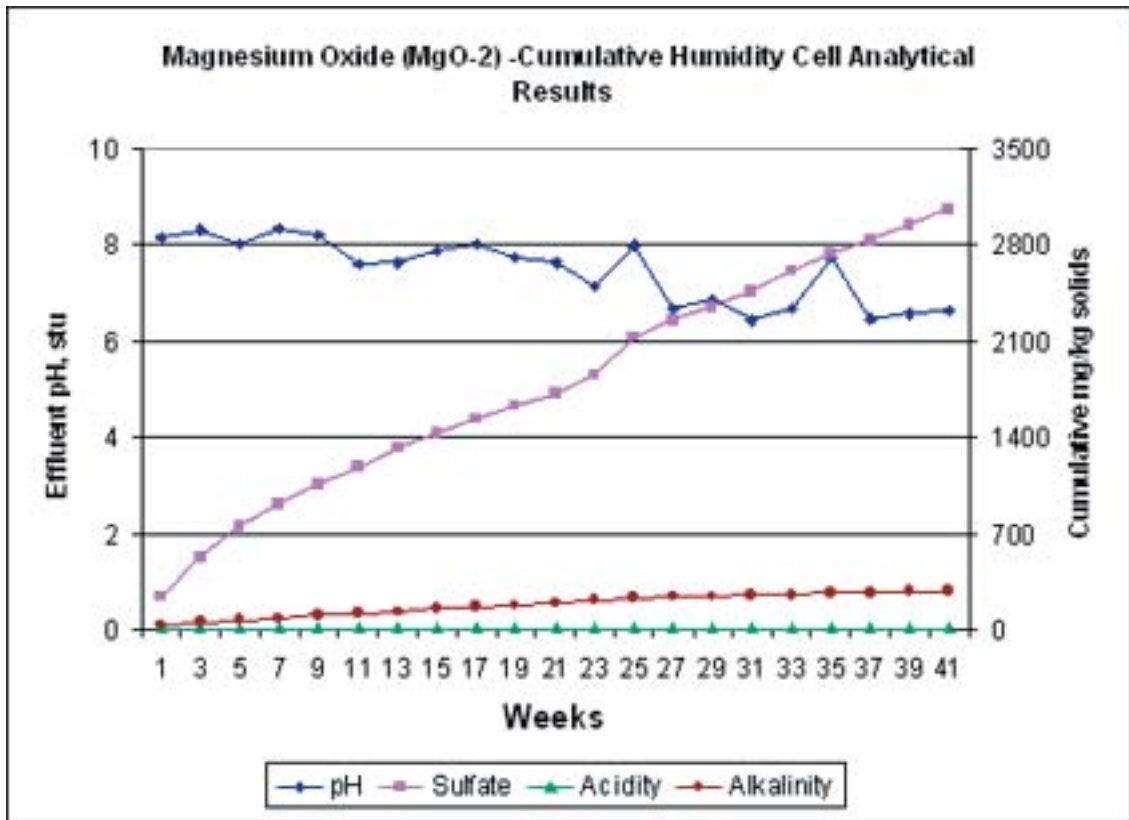
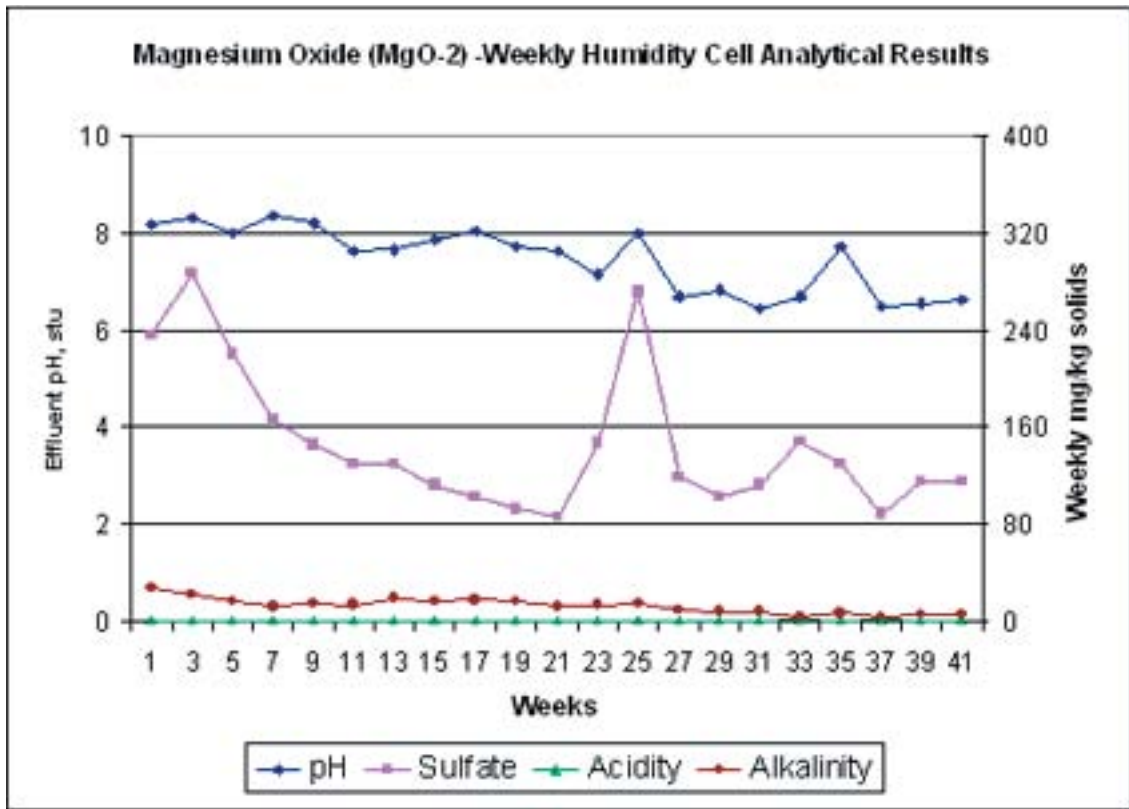


Figure 5-22. Weekly and cumulative HC analytical results for sample 2 from UNR/MgO plot (Plot D).

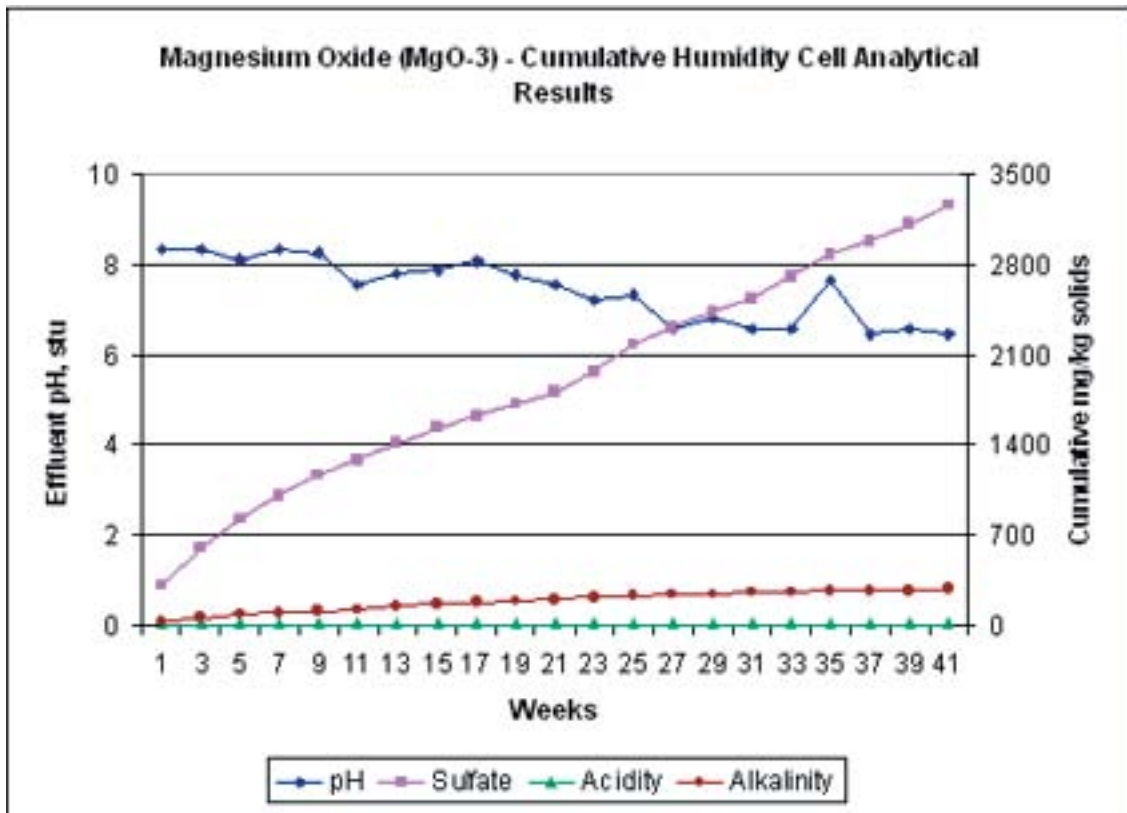
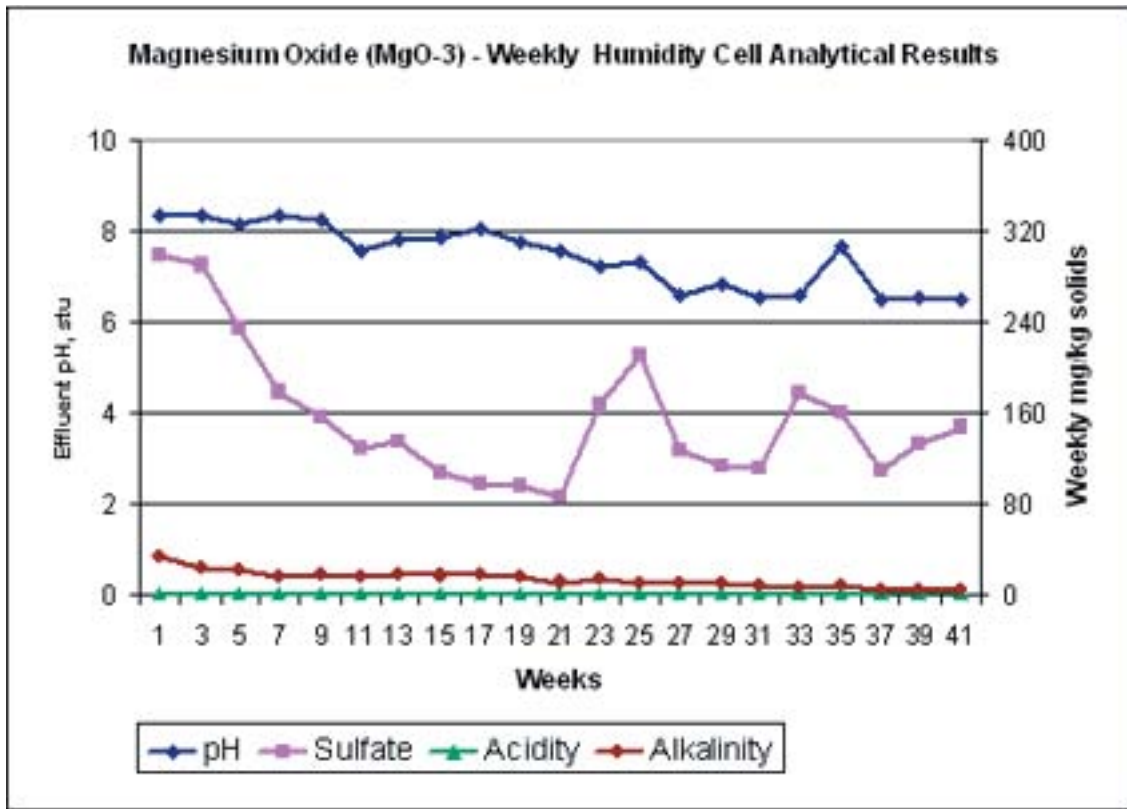


Figure 5-23. Weekly and cumulative HC analytical results for sample 3 from UNR/MgO plot (Plot D).

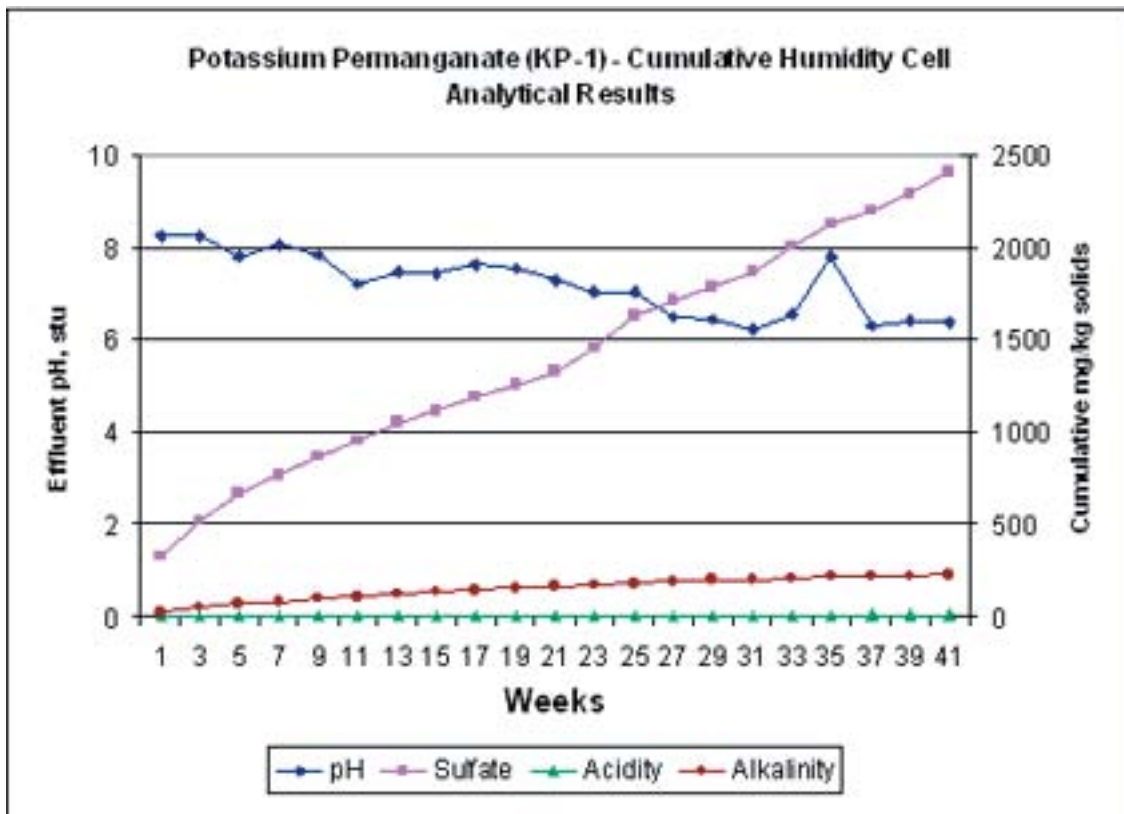
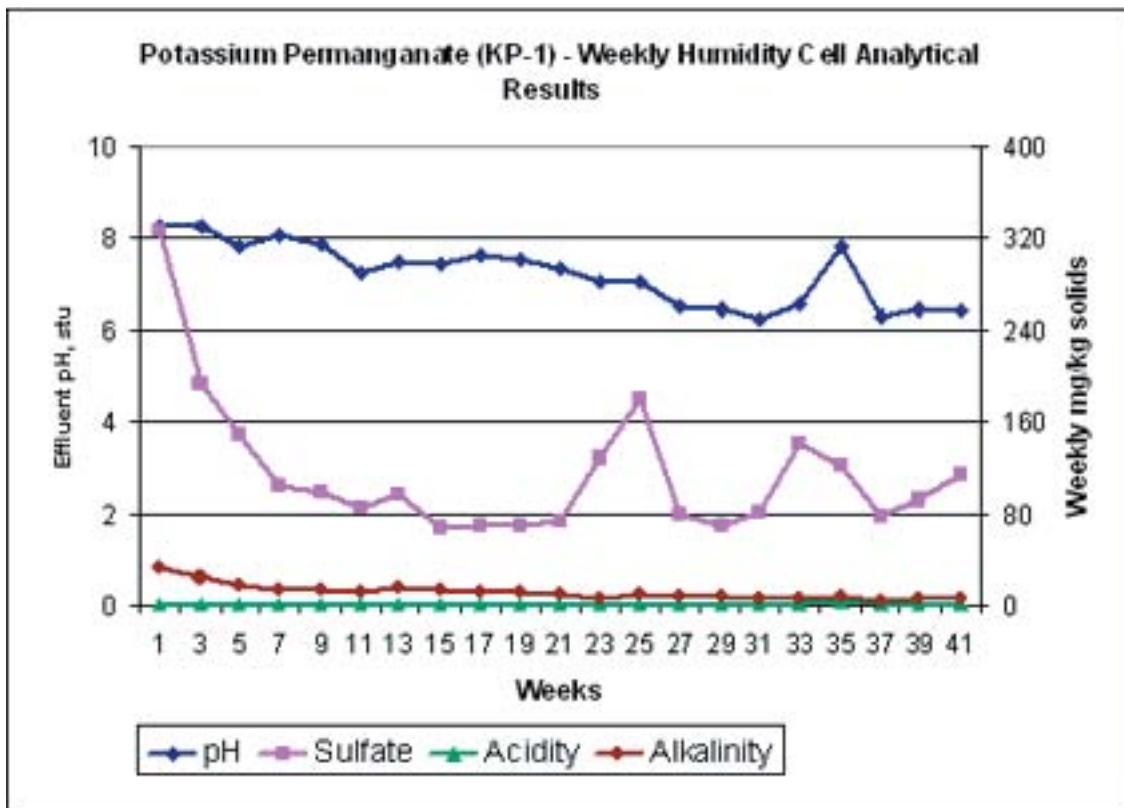


Figure 5-24. Weekly and cumulative HC analytical results for sample 1 from UNR/KP plot (Plot E).

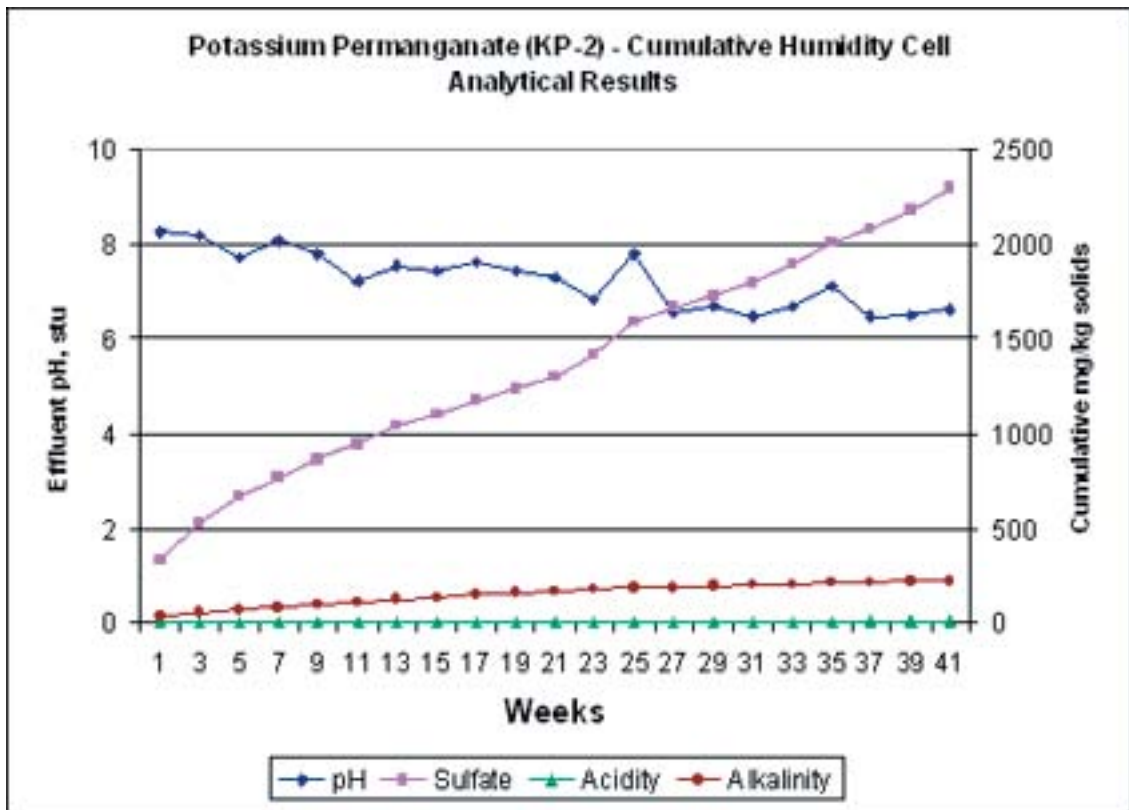
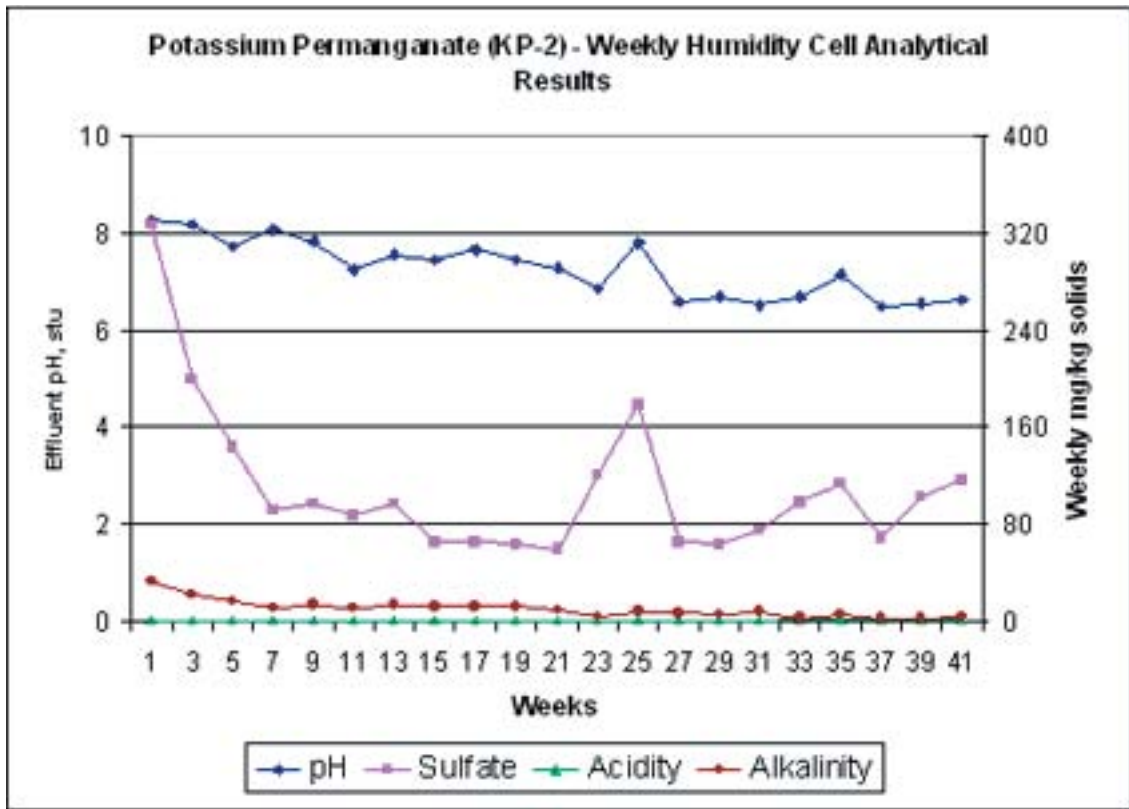


Figure 5-25. Weekly and cumulative HC analytical results for sample 2 from UNR/KP plot (Plot E).

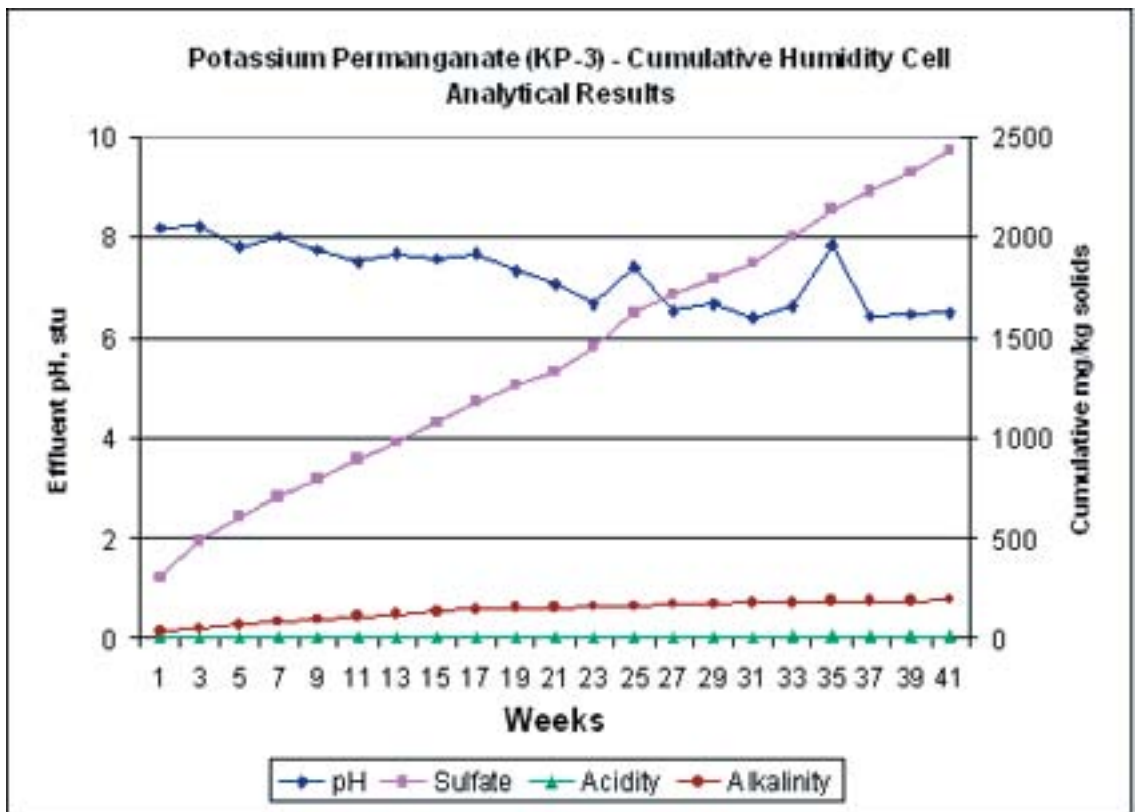
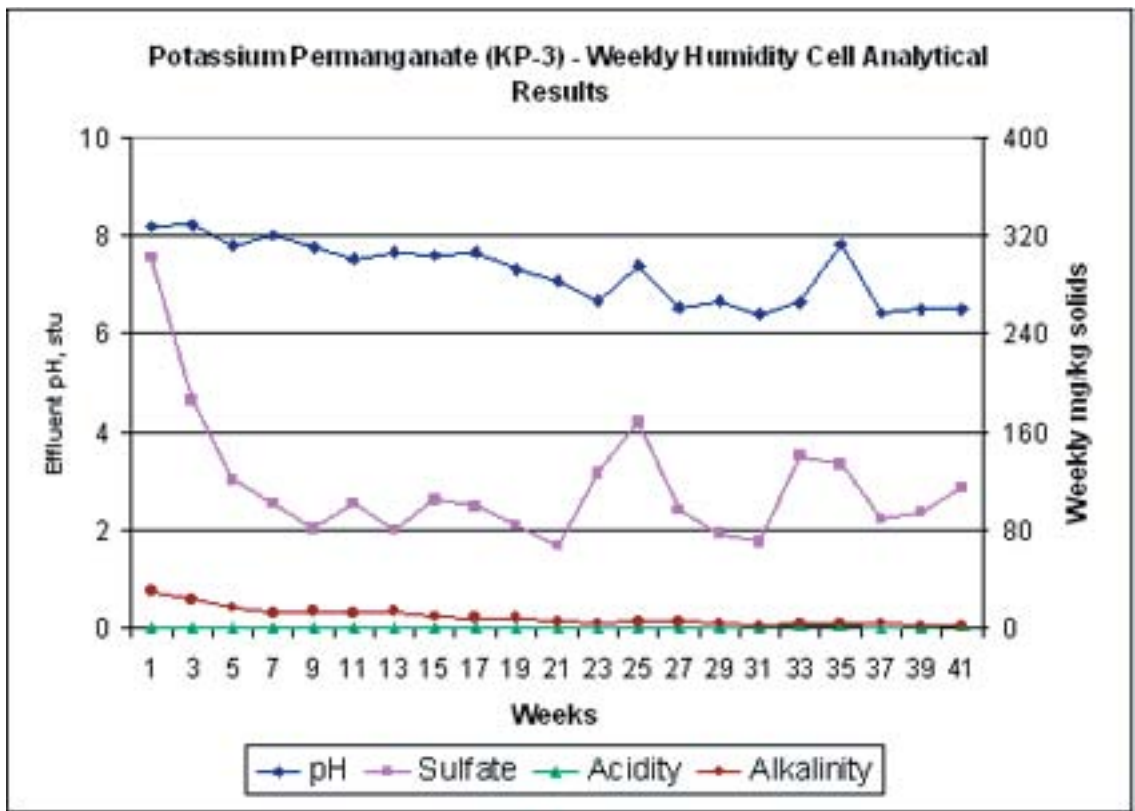


Figure 5-26. Weekly and cumulative HC analytical results for sample 3 from UNR/KP plot (Plot E).

Table 5-5. Summary HC Test Data for Untreated and Treated GSM Highwall Samples (data are an average of respective triplicate HC tests)

		Week 41 Data			Generated, mg/kg				% of SO ₄ ⁻² from S=	Calculated Alkalinity/Acidity Ratio
Sample	Treated	pH	Eh	EC	FE	SO ₄	Acidity	Alkalinity	Oxidation	Ratio
GSM	No	2.81	515	1.21	263	11,373	1,263	1.0	11.1	<0.001
FARS	Yes	4.52	307	0.25	199	2,400	562	2.1	23.4	0.004
EcoBond	Yes	7.22	227	0.29	2.6	4,206	651	4,263	15.5	6.548
UNR/KP	Yes	6.50	275	0.44	2.2	2,379	7.8	214	0.3	27.820
UNR/MgO	Yes	6.57	274	0.47	1.3	3,075	2.8	282	<0.1	100,714

(AGP) were negative. Consequently, the potential exists for all the samples (taken from each plot) to form acid. (The net neutralization potential (NNP) was negative for all samples).

Using the same data comparisons, all treatment technologies were effective in decreasing potential for AMD. For EcoBond, UNR/MgO, and UNR/KP, pH was near neutral; E_h was typical for systems exposed to air; EC indicates minimal metal mobility; Fe, SO₄, and acidity production were lower than the background sample and the MCL standards; alkalinity production was higher than the background samples; and calculated ratios for alkalinity and acidity were positive and substantially greater than the background ratio, reflecting a nonacid producing environment after treatment of the samples.

The FARS technology has a pH of 4.52, which is the pH of the acid-catalyzed solution sprayed as treatment on the highwall. The E_h was typical of systems exposed to air. Electric conductivity indicated minimal mobility; however, it did generate some iron and acidity (acid catalyzed material); however, the SO₄ production was low. To get the FARS sample into the HC for testing, the sample had to be broke apart, which exposed some untreated surface areas. This could account for some of the higher mobility data values.

Potential for metals mobility increases when acid production from oxidation of sulfide minerals occurs. A comparison of metals mobility in the HC extract, on a concentration basis from the various HC tests with respect to the National Primary and Secondary Drinking Water Standards (MCLs and secondary MCLs), are provided in Table 5-6. Metal analytical results are an average of the respective triplicate tests. All treatment technologies were effective in decreasing the concentration and mobility of metals from the GSM highwall sample material.

5.4 Technology Cost Analysis

For this demonstration project, each technology vendor was subcontracted to apply their technology on the highwall at GSM. All aspects of applying the technology were integrated into the subcontract (i.e., materials, equipment, labor, technical expertise, mobilization/travel, etc.). The cost included applying each technology to the 50-ft by 50-ft test plot to provide optimal coverage and maximum effectiveness of the technology.

The costs that are presented in Table 5-7 reflect the cost to apply the technologies on the open-pit highwall at GSM for this MWTP demonstration only. Application of these technologies at a different location or mine would require the technology vendor be contacted for an appropriate price quotation. From the costs listed, FARS was the most cost-effective treatment technology for this demonstration. However, under different situations, the other technologies may be more cost effective.

The costs associated for each technology tested are delineated in Table 5-7. Note that in Table 5-7, Intermountain Polymers did not report any oversight charges. Also, UNR combined the costs for its two technologies. For purpose of this discussion, it is assumed that the cost of each UNR technology was half of the total for each cost element except mobilization. The mobilization cost will remain the same, no matter which technology is applied.

The core cost elements for the four different technologies demonstrated appear to be materials, installation, and oversight. Mobilization and shipping costs appear to be distance driven and not driven by special equipment or other needs. The core cost elements are listed in Table 5-8. The percentage of the total cost of each cost element, as well as the total unit cost per square foot of area treated for each technology, is also listed.

As can be seen in Table 5-8, material costs contribute from one-half to two-thirds of the total cost of using these technologies. Approximately one-third of the cost will be in installation, and the remainder (from 15% to 25%) will be in oversight. Unit costs will vary from \$2.00 to \$8.00 per square foot treated.

EcoBond's unit cost is more than double that of the other vendors. This higher cost may be justified if EcoBond's treatment lasts upwards of three times as long as the treatments of the other vendors. However, life-cycle costs for each of these technologies cannot be calculated at this time since determining the effective longevity of the respective treatments was beyond the scope of this study. As an example, the FARS technology might be the most cost effective, all things considered, because of its low application cost, and, as a polymer, it may stand up well to yearly weathering cycles. The life of each technology application is an area for future research.

The material costs are dependent on the market costs of the products used in the technology formulations and the cost

Table 5-6. Current National Drinking Water MCLs and SMCLs vs. HC Test Extract Composite Data (mg/L) Untreated and Treated GSM Highwall Samples for Regulated Metals Analyzed

		Extract Composite ¹			
		Wks 1-9	Wks 10-21	Wks 22-31	Wks 32-41
GSM Untreated					
Al	0.05-0.2	5.03	0.86	4.73	3.37
Cu	1.0	0.26	<0.06	0.14	0.11
Fe	0.3	70.33	2.28	29.67	29.00
Pb	0.05	<0.025	<0.015	<0.010	<0.010
Mn	0.05	10.46	1.30	2.57	2.03
Zn	5.0	1.20	0.17	0.34	0.26
Ni	0.1	0.89	0.10	0.28	0.24
FARS Treated					
Al	0.05-0.2	0.56	0.079	<0.045	<0.045
Cu	1.0	<0.10	<0.050	<0.050	<0.050
Fe	0.3	71.00	14.00	3.13	3.73
Pb	0.05	<0.020	<0.010	<0.010	<0.010
Mn	0.05	2.77	0.93	0.39	0.54
Zn	5.0	1.17	0.18	0.11	0.21
Ni	0.1	0.24	0.076	<0.017	0.028
EcoBond Treated					
Al	0.05-0.2	<0.090	<0.045	<0.045	<0.045
Cu	1.0	<0.10	<0.050	<0.050	<0.050
Fe	0.3	<0.10	<0.027	<0.010	<0.015
Pb	0.05	<0.020	<0.010	<0.010	<0.010
Mn	0.05	0.022	0.011	<0.005	<0.005
Zn	5.0	0.025	<0.010	<0.010	<0.010
Ni	0.1	<0.020	<0.010	<0.010	<0.010
UNR/KP Treated					
Al	0.05-0.2	<0.045	<0.045	<0.045	<0.045
Cu	1.0	<0.050	<0.050	<0.050	<0.050
Fe	0.3	0.069	<0.020	<0.010	<0.010
Pb	0.05	<0.010	<0.010	<0.010	<0.010
Mn	0.05	0.013	0.026	0.068	0.180
Zn	5.0	<0.010	<0.010	<0.039	<0.010
Ni	0.1	<0.010	<0.010	<0.010	<0.010
UNR/MgO Treated					
Al	0.05-0.2	<0.045	<0.045	<0.045	<0.045
Cu	1.0	<0.050	<0.050	<0.050	<0.050
Fe	0.3	<0.010	<0.010	<0.010	<0.010
Pb	0.05	<0.010	<0.010	<0.010	<0.010
Mn	0.05	<0.005	0.010	0.009	0.020
Zn	5.0	<0.010	<0.010	<0.017	<0.010
Ni	0.1	<0.010	<0.010	<0.010	<0.010

¹ Metal concentrations are an average of the triplicate tests.

Table 5-7. Cost Breakdown for Demonstrated Technologies

Technology	Vendor	Mobilize	Materials	Install	Shipping	Oversight	Total
FARS	Intermountain Polymers - Idaho Falls, ID	\$2,200	\$3,600	\$1,695	\$300	(1)	\$7,795
UNR/MgO	UNR - Reno, NV	\$3,780	\$1,890	\$2,948	\$630	\$2,394	\$11,642
UNR/KP	UNR - Reno, NV	\$3,780	\$1,890	\$2,948	\$630	\$2,390	\$11,642
EcoBond	MT ² - Wheat Ridge, CO	\$5,723	\$10,250	\$5,844	\$1,000	\$2,910	\$25,727
(1) Oversight assumed to be part of the installation cost.							

Table 5-8. Core Cost Elements

Technology	Material	% of Total	Install	% of Total	Oversight	% of Total	Total	Unit Cost*
FARS	\$3,600	68%	\$1,695	32%	(1)	0%	\$5,295	\$2.12
UNR/MgO	\$3,780	41%	\$2,948	33%	\$2,394	26%	\$9,155	\$3.65
UNR/KP	\$3,780	41%	\$2,948	33%	\$2,394	26%	\$9,122	\$3.65
EcoBond	\$10,250	54%	\$5,884	31%	\$2,910	15%	\$19,044	\$7.63
* Basis, 2,500 square feet								
(1) Oversight assumed to be part of the installation cost.								

to transport those products. Fluctuations in the market are dependent on the conditions of the economy and the demand for the products.

Another factor that affects the cost of applying these technologies includes the size of the plots. The cost to implement a technology on a small test plot is usually higher than applying the technology to a large area. Some of the reasons are noted below.

- The cost for mobilization and demobilization of the application equipment is the same whether it is a large or small technology application. With a large application, the cost is a small percentage of the total cost, whereas for a small application (like this demonstra-

tion), the mobilization and demobilization cost could be almost 10% of the total cost.

- When purchasing the chemicals or other materials used for the technology formulations, the cost of a small quantity of material is usually higher than a larger or bulk quantity purchase (i.e., the more product ordered, the less the cost per container).
- In this demonstration, the technology vendors applied the technologies. However, in certain applications or for large applications, it would be cost effective to train company personnel to apply the technology, which would reduce the equipment mobilization/demobilization, labor, travel, and procurement costs, thus reducing application cost.

6. Quality Assurance/Quality Control

A QAPP was prepared specifically for the MWTP, Activity III, Project 26 (Ref. 2). The QAPP met the requirements of an applied research *QAPP* and was developed using the EPA documents *QAPP Requirements for Applied Research Projects (Ref. 14)* and *Preparation Aids for the Development of Category II Quality Assurance Project Plans* (Ref. 10) as guides.

6.1 Project Background

Following is a summary of QA activities associated with MWTP, Activity III, Project 26, *Prevention of Acid Mine Drainage from Open-Pit Highwalls*. This section summarizes the activities used to determine the usability of the data generated for this project. The intent of the project was to obtain performance data on the ability of four technologies to prevent the generation of AMD from the open-pit highwall at GSM.

To be able to evaluate the technologies, the project site was characterized prior to the technology application. During the site characterization activities, water injection test data, core logs, and preapplication mine wall data were evaluated to determine the usability of the data and provide additional baseline data. The data were collected according to the schedule outlined in the approved project-specific QAPP.

The technologies that were applied to the highwall included the four listed below.

- EcoBond developed by MT² of Denver, Colorado
- UNR/MgO developed by UNR
- UNR/KP Passivation technology developed by Dupont and presently owned by UNR
- FARS developed by Intermountain Polymers of Idaho Falls, Idaho

To determine the effectiveness of the highwall treatment technologies, two evaluation methods were used. The mine wall sampling method was used in the field, and the HC testing method was performed in the laboratory.

Background data were collected at each mine wall station prior to technology emplacement in September 2001. Per-

formance data were collected during four planned sampling events; the events were scheduled for April, July, September, and November 2002. All field and laboratory data available for the critical analyses were evaluated to determine the usability of the data. The area of the mine wall stations, volume of residual mine wall wash, field pH, and total metals (Al, Cu, Fe, Mn, Ni, and Zn) analyses were classified as critical analyses for this project. The HC testing data were classified as a critical analysis for the project in July 2002. A critical analysis is an analysis that must be performed in order to determine if project objectives were achieved.

6.2 Project Reviews

During the project, the evaluations performed were:

- internal field systems review at the demonstration site; and
- external technical systems audit (TSA) at the demonstration site and the HKM Laboratory.

6.2.1 Internal Field Systems Review at the Demonstration Site

A field systems review was performed on April 23 and 24, 2002, at GSM. The field systems review included a review of:

- personnel, facilities, and equipment;
- calibration of equipment; and
- sampling procedures.

The following findings were identified during the internal audit.

- The QAPP referenced the removal of plastic sheets on each sample station. No such plastic sheets existed.
- One sample in Plot E contained some headspace in each of the two 500-mL sample bottles; the shortfall in each subject bottle was estimated at 20 mL.

The following observations were identified during the internal audit.

- There was difficulty in calibrating the pH meter on day 2 as written instructions were not available. After some time, the meter responded favorably (within the 0.1 accuracy requirement) when tested against known pH buffer solutions.
- The physical conditions of the highwall sample stations were documented. Plots A, B, and C contained significant sediment and fines with fewer visible fractures while plots D and E were comprised of hard rock surfaces that contributed to low fines but significant surface fractures.
- Five sample stations were either partially damaged beyond use or torn off by rock falling over the course of the winter (one on each of the five plots), in which case the station was not sampled. Two sample stations were slightly damaged (one each on plots D and E) but not beyond use for sampling.

The results of the audit were discussed with the Project Manager. The generation of a QAPP addendum was recommended; however, the addendum development was postponed pending the outcome of the scheduled external TSA by EPA.

6.2.2 External Technical Systems Audit

In addition to the internal field systems review conducted by MSE, an external TSA of the project and the HKM Laboratory was performed by Science Applications International Corporation under subcontract to Neptune and Co. (subcontractor to EPA) during the week of July 22, 2002.

6.2.2.1 Summary TSA Procedures, Findings, and Resultant Actions

The field portion of the TSA consisted primarily of observations and questions during the activities. Observed field activities included quarterly sampling, field measurements, and sample delivery. The laboratory portion of the TSA consisted of reviewing the April sampling event data package, viewing the applicable laboratory activities, and interviews with HKM Laboratory personnel. Five findings, seven observations, and five additional technical comments were identified during the audit.

The initial corrective action response to the TSA corrective action comments was not considered sufficient by EPA; therefore, a detailed data evaluation was undertaken by MSE to determine the validity of the collected data (evaluated were the April and July 2002 sampling events). The data evaluation was submitted to EPA, as well as the data from the July 2002 sampling event. EPA performed a statistical analysis on the July 2002 data to evaluate the success of the treatments and recommended that the additional planned sample events (September and November 2002) proceed (see Appendix D).

Summarized below are the TSA findings and approved corrective actions taken as a result of the findings.

Finding 1 – The collection of samples from the highwall test plots was performed in the April 2002 and September 2001

sampling events using two 500-mL sample containers instead of one 1-liter container as specified in the project QAPP. *Corrective Action:* After evaluation of the data, it was determined that the results from the April 2002 sampling event could not be included in the evaluation of the technologies.

Finding 2 – The QAPP required the establishment of five mine wall sampling stations for each treated and nontreated plot. Five sampling stations were originally established in each plot. However, due to operating mine conditions and nature, several of the sample ports were lost. *Corrective Action:* A statistical analysis was performed by EPA to determine the minimum number of sampling stations required per area and if there was a significant statistical difference between the treated and nontreated data generated in July 2002. It was found that there was some significant difference (see Appendix D). Also, MSE reestablished all sampling stations that could be safely adhered, and all reestablished stations were sampled (Ref. 15).

Finding 3 – The dimensions of the sample station areas were a critical measurement and, during the sampling events, were assumed to be 1 m by 1 m. This was not the case, and the areas rinsed were not measured. The rinsed area is critical for the metals loading calculation. *Corrective Action:* For each sampling event, the mine wall sample ports were repaired, remarked, and measured to obtain the calculated loading values as specified in the revised QAPP (Ref. 2).

Finding 4 – As required by the QAPP, the samples were required to be split and preserved in the laboratory on the same day the samples were received. This was not performed for the April 2002 sampling event. *Corrective Action:* All samples were split, filtered (if necessary), and preserved appropriately the same day the samples were delivered to the laboratory.

Finding 5 – According to the QAPP, four sampling events were to be performed on a quarterly basis after the technologies had been emplaced in January 2002. However, the final sampling event was scheduled in October 2002, which would not allow for a fourth sampling event. *Corrective Action:* As decided during the TSA debriefing meeting, two sampling events would be performed during September and November 2002. These sampling events were reflected in the addendum to the QAPP, and the data from the events were sent to EPA to determine the usability of the data (see Appendix D).

The detailed data evaluation was performed to determine the usability of data from each mine wall sampling event (September 2001, April 2002, July 2002, and August 2002) for evaluating project objectives. After reviewing the project data from the mine wall sampling, the following observations were made.

- The mine wall sampling procedure is difficult to implement and perform because of the instability of the highwall and the safety aspects involved.
- The area measurements in the procedure assume a two-dimensional surface while in many instances the surface is three-dimensional, which can vary from one location to another.

- Measuring the natural effects on the treated and non-treated stations is difficult at an operating mine because factors like airborne particulates and untreated waste material placed on the bench above the test plots place another variable into the evaluation of the technologies.

The above reasons indicate that even if all of the mine wall samples were collected perfectly, the data may not provide all the quantitative information required to fully evaluate the performance of the technologies. Since these observations were noted, all project data were forwarded to the EPA National Risk Management Research Laboratory for statistical analysis, and the HC data were elevated in importance and became a critical parameter.

6.3 Data Validation

An analytical evaluation of all data was performed to determine the usability of the data that were generated by HKM Laboratory for the project. Laboratory data validation was performed using *USEPA Contract Laboratory Program National Functional Guidelines for Inorganics Data Review* (Ref. 17) as a guide. The QC criteria outlined in the QAPP, which are summarized in Table 6-1, were also used to identify outlier data and to determine the usability of the data for each analysis. A summary of QC checked results for the critical dissolved metals and pH analyses of all the usable data are presented in Table 6-2. All data requiring flags are summarized in Table 6-3.

6.4 Program Evaluation

In addition to the data validation, a program evaluation was performed. Program evaluations included an examination of data generated during the project to determine that:

- all samples, including field QC samples, were collected, sent to the appropriate laboratory for analysis, and were analyzed and reported by the laboratory for the appropriate analyses; and
- all field blanks contain no significant contamination.

Field duplicates are typically included in the program evaluation; however, the nature of the sampling technique precluded the collection of field duplicates.

While certain analytes were detected in field blank samples, the sample concentrations were at least 10 times the contamination concentration; therefore, no data were flagged for out-of-control field blanks.

6.5 HC Data Evaluation

The data collected by MLI in Sparks, Nevada, were also reviewed for usability. The HC data were elevated in importance due to the difficulties associated with the data collected in the field. MLI submitted its report including raw data. MSE requested information on QC checks to complete a thorough data review. MLI responded, and MSE completed the data review. MLI performed analyses on the HC rinse waters for:

- pH;
- E_H ;
- conductivity;
- total Fe;
- Fe speciation;
- SO_4 ;

Table 6-1. Data Quality Indicator Objectives

Parameter	Matrix	Unit	Minimum Detection Limit (Instrument Detection Limit)	Precision ^a	Accuracy ^b	Completeness ^c
Area of Mine Wall Station	N/A	m ²	N/A	0.1m ^{2d}	N/A	95%
Volume of Residual Wash	Aqueous	mL	25 mL	N/A	±25 mL	95%
pH	Aqueous	SU ^c	1.0	±0.1 ^d	±0.1 ^d	95%
Al	Aqueous	µg/L	50 (18.9)	≤20%	75-125%	95%
Cu	Aqueous	µg/L	50 (1.3)	≤20%	75-125%	95%
Fe	Aqueous	µg/L	50 (7)	≤20%	75-125%	95%
Mn	Aqueous	µg/L	50 (1.3)	≤20%	75-125%	95%
Ni	Aqueous	µg/L	50 (10.5)	≤20%	75-125%	95%
Zn	Aqueous	µg/L	50 (3.5)	≤20%	75-125%	95%

^a Relative percent difference (RPD) of analytical duplicates, unless otherwise indicated.

^b Percent recovery of matrix spike, unless otherwise indicated.

^c Based on the number of valid measurements compared to the total number of samples.

^d Absolute difference of consecutive measurements.

^e SU – standard unit.

Table 6-2. Summary of QC Checks for Critical Total Metals Analysis

Analysis	Mean RPD for Sample Duplicates	Range of RPD for Sample Duplicates
Al	13.0	4.6-21.9
Cu	21.8	1.5-44.9
Fe	29.2	0.6-70.8
Mn	1.2	0.2-2.6
Ni	9.6	1.2-18.7
Zn	7.8	1.7-12.2
Analysis	Mean Percent Recovery for Matrix Spikes	Range of Percent Recovery for Matrix Spikes
Al	89.1 ^{aa}	89.1-89.1
Cu	94.4	81.1-107.6
Fe	NA ^a	NA ^a
Mn	101.9	96-107.8
Ni	88.7	78.3-95.1
Zn	82.4	65.1-92

^{aa} None of the samples for Fe and only one sample for Al were evaluated for matrix spike recovery because the sample concentration exceeded the spike concentration by a factor of 4 or more.

- acidity; and
- alkalinity.

The Western Environmental Testing Laboratory performed metals analyses on the HC rinsates for metals analysis (Al, Cu, Fe, Pb, Mn, Zn, and Ni).

Solid samples were analyzed by SVL Analytical, Inc., for:

- total sulfur;
- nonextractable sulfur;
- pyritic sulfur;
- SO₄ as sulfur;
- paste pH;
- AGP;
- ANP; and

- calculated ANP/AGP ratio.

ALS Chemex Labs, Inc., performed the following analyses on the solid samples.

The HCs were monitored for a total of 41 weeks with intermittent freezing of samples. All data reviewed were validated using the methods described above for the other field and laboratory data associated with the project. All data were deemed usable for supporting project objectives. MLI requested reanalysis for Ni on one sample set. Some samples required dilutions, and reporting limits were adjusted accordingly.

6.6 Recommendations and Conclusions

In the future, to avoid the identified difficulties that were associated with this project, the following recommendations are made.

- The mine wall sampling procedure should be reviewed with all personnel, and a simulated sample station should be established to determine and define the problems that may occur during sampling.
- Site-specific sample data sheets should be developed for this project to delineate mine wall station areas, measurements, pH, and other measured parameters. Logbooks should be organized numerically with descriptions of all changes that occurred between sampling events and should denote all critical measurements.
- Quality and safety requirements need to be reviewed and communicated thoroughly to all project personnel. The hazardous nature of working and sampling the highwall using the required mine wall sampling procedure needs to be understood by participants in the demonstration.
- Because the mine wall sampling procedure is not a standardized procedure with which the laboratory and other sampling personnel are familiar, all sampling procedures, including the mine wall sampling procedure, should be reviewed by laboratory and field personnel. Alternatively, applicable sections of the QAPP could be attached to the chain-of-custody in the future.
- The HC tests should be used for quantitative information regarding the performance of the technologies with respect to preventing the formation of AMD. However, these tests do not fully replicate field conditions.

Table 6-3. Summary of Flagged Data for Activity III, Project 26

Date of Collection	Sample ID	Analysis	Quality Criteria	Actual	Flag	Comment
9/19/02	MWA-509192002	Total Al	Analytical duplicate (≤20&% RPD)	21.9% RPD	J	The analytical duplicate was greater than 5 times the contract required detection limit and out of control for Al, Cu, and Fe. The associated samples should be flagged “J” as estimated.
	MWA-309192002					
	MWA-209192002	Total Cu		44.9%	J	
	MWB-109192002					
	MWB-209192002	Total Fe		70.8% RPD	J	
	MWB-309192002					
	MWB-509192002					
	MWC-209192002					
	MWC-309192002					
	MWC-409192002					
	MWD-409192002					
	MWE-109192002					
	MWE-209192002					
	MWE-309192002					
	MWE-409192002					
MWE-509192002						
9/19/02	MWA-509192002	Total Zn	Matrix spike (75-125% recovery)	65.1	J	The matrix spike was out of control for total and dissolved Zn. The associated samples should be flagged “J” as estimated.
	MWA-309192002					
	MWA-209192002					
	MWB-109192002	Dissolved Zn		68.6		
	MWB-209192002					
	MWB-309192002					
	MWB-509192002					
	MWC-209192002					
	MWC-309192002					
	MWC-409192002					
	MWD-409192002					
	MWE-109192002					
	MWE-209192002					
	MWE-309192002					
	MWE-409192002					
MWE-509192002						
Data Qualifier Definition: J - The concentrations are estimated.						

7. Conclusions

For the MWTP, Activity III, Project 26, *Prevention of AMD Generation from Open-Pit Highwalls* demonstration project, four treatment technologies were applied and tested in the field at the GSM. The primary objectives of this project were to determine the impact of the treated area for each technology on the total metal loading per unit area and pH of the rinsates compared to the rinsates from the untreated area. The objectives were not to compare the four passivation technologies against one another. Achievement of the objectives was not only evaluated using field mine wall sampling, but HC testing was performed on treated samples from the highwall also.

In summary, the data from the untreated GSM highwall for both field monitoring and HC laboratory testing show that the highwall would produce acid in a natural weathering and oxidizing environment. The same background data from the untreated GSM plot were used for comparison of all the treatment technologies to determine if the technologies were effective in decreasing potential for AMD.

For the reduction of acid generation, all test results, from both the field and the laboratory, indicate that the treatment technologies demonstrated at GSM (to some degree) controlled the acid generation potential of a mine highwall. Each of the technologies created an inert layer or coating on the sulfide material, preventing contact with atmospheric oxygen/water during the weathering of the sulfide highwall rock and thus preventing sulfuric acid generation and metals mobilization.

For the field mine wall sampling, EcoBond, UNR/MgO, and UNR/KP plots, the recorded pHs were as low as the pH of the background plot where the pH was less than 4, and the range of percent metals reduction ranged from 82% to a -211%. The pH recorded for the FARS technology was steady at 4 to 4.5 for the full demonstration, and the percent metals reduction ranged between 75% to 91%, compared to the background results. In the field, the FARS material also provided visible physical stabilization of the highwall. Mine wall movement did cause the highwall to become unstable, and it resulted in the loss of several sample ports, which could have potentially affected the

overall results. For future research on open-pit highwalls, it is recommended that a surplus of sample ports be established in case some ports are damaged.

However, when compared to the background plot for the HC testing, the EcoBond technology had a pH that was neutral; the EC was typical for systems exposed to air and indicated minimal metal mobility; Fe, SO₄, and acidity production was higher; and calculated ratios were substantially greater than regulatory guidelines. For the two UNR technologies, the pH was slightly greater than 6; EC was typical for systems exposed to air and indicated minimal metal mobility; Fe, SO₄, and acidity production was higher; and calculated ratios were substantially greater than regulatory guidelines. For the FARS technology, the pH ranged between 4 and 5, which is the pH of the acid catalyzed solution used to coat the surface of the material. The EC was typical of a system exposed to air, and some metals were mobilized. In addition, Fe, SO₄, and acidity production were higher than for the other three technologies but not close to background levels.

The mass data generated from the HC testing at MLI demonstrated that larger quantities of metals analyzed were mobilized from the untreated/background plot and the FARS treated sample than from the other three treated feeds. Essentially, no metals were mobilized from EcoBond, UNR/MgO, and UNR/KP treated feeds. The lack of metals mobility indicates that three treatment technologies prevented acid production. However, the dosages used to treat the samples were high and allowed for the sample surfaces to be fully coated and treated for an extended period of time.

- Upon completion of the demonstration, the following issues remain for possible future investigation. These issues include:

determining the effect of the airborne particulate and runoff on field sampling results;

determining the effect of allowing all HC samples that were saturated during the application to sit

until testing was initiated and also determining what effect was there on the samples that were allowed to sit during the time that HC testing was suspended; and

determining if the FARS technology performance was altered when the sample for testing had to be broken to fit into the HC sampling equipment, thus exposing untreated surfaces to the induced weathering processes

These issues still remain unresolved; however, overall, the technologies reduced the potential for acid production on the GSM highwall material, whether in the field or in the laboratory. After evaluating the data generated during the demonstra-

tion, these technologies that have the potential to passivate or stabilize open-pit highwalls, could limit the environmental impact from mining and processed ore at abandoned mines, active mines, and newly developed ore reserves.

Each technology inhibits AMD differently, dependent upon chemistry of the treatment formulation, sulfide content, morphology, pH of the waste material, weather conditions, and amount of water draining from the highwall. By reducing the potential for AMD generation from a mine highwall, reclamation costs for mining companies and regulatory agencies could be minimized. However, the cost for implementing these technologies may be prohibitively expensive, and a tradeoff could be made relative to capturing and treating AMD.

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