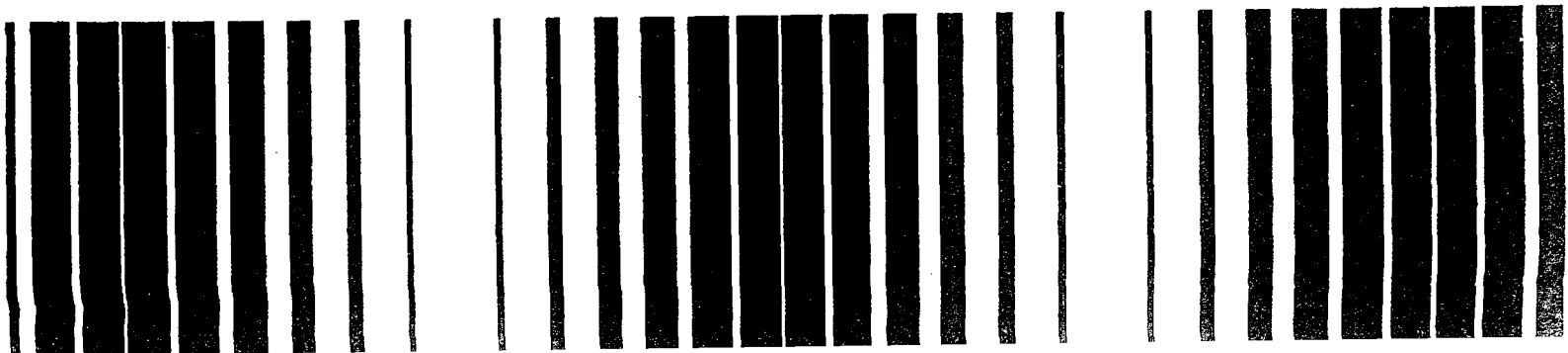




Seminar Publication

Managing Environmental Problems at Inactive and Abandoned Metals Mine Sites



Seminar Publication

Managing Environmental Problems at Inactive and Abandoned Metals Mine Sites

Center for Environmental Research Information
National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio

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Foreword

The U.S. Environmental Protection Agency (EPA) 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 as well as building the 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.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technologies and management approaches for reducing risks from threats to human health and the environment. NRMRL's research program focuses on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

For many years, mine waste at inactive and abandoned metals mine has been an issue of great interest to EPA. According to a 1985 Report to Congress, over 50 billion tons of mining wastes is estimated to exist in the United States. The Agency, through NRMRL, has provided technical support for the management of wastes from inactive and abandoned metals mines by conducting a series of seminars on the topic. The seminar series was developed based on input from federal, state, and local government organizations; mining, engineering, and remediation companies; and other interested parties. The goal of the seminars was to increase public awareness of environmental problems at inactive and abandoned metals mine and provide information on practical approaches to more effectively manage these problems.

This publication has been produced in support of NRMRL's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt
National Risk Management Research Laboratory

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Note: Papers presented at the seminars but not included in this publication due to extenuating circumstances include *Case Study: Sharon Steel/Midvale Tailings Superfund Site*, presented by William Cornell, U.S. Bureau of Mines, Rolla, MT; *Case Study: What We Learned About Liability at Penn Mine*, presented by Rick Humphreys, California State Water Resources Board, Sacramento, CA; and *History and Status of Congressional Initiatives Pertinent to Mining and Mine Waste*, presented by J. Curt Rich, Legislative Counsel, Senate Environment and Public Works Committee.

Chapter 1.

Introduction: Focusing on the Problem of Mining Wastes

Thomas V. Durkin and Jonathan G. Herrmann

Background

Mining waste, generated from active and inactive mining sites and from beneficiation activities, and its impact on human health and the environment are a continuing problem for government entities, private industry, and the general public. The nation's reported volume of mining waste is immense. A scoping study conducted by the Western Governors' Association Mine Waste Task Force (1) collected the following statistics on inactive and abandoned mines (IAMs) by state:

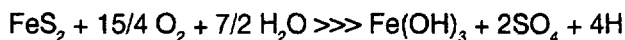
- Arizona—80,000 IAM sites covering 136,653 acres, polluting 200 miles of surface waterways.
- California—2,484 IAM sites, 1,685 mine openings, and 578 miles of polluted streams.
- Colorado—20,299 mine openings and 1,298 miles of affected streams.
- Idaho—27,543 acres affected by IAMs.
- Missouri—7,655 IAM sites covering 48,175 acres, with 109 miles of affected streams.
- Montana—20,000 IAM sites covering 153,800 acres, with 1,118 miles of stream damage.
- New Mexico—25,320 acres and 69 miles of streams affected by IAMs.
- Oklahoma—26,453 acres affected by IAMs.
- Utah—25,020 acres affected by IAMs, with 83 miles of polluted streams.

Of this total volume, approximately 85 percent is attributed to copper, iron ore, uranium, and phosphate mining and related activities. Approximately one-half of the waste generated is mining waste and one-third is tailings, with the balance consisting of dump/heap leaching wastes and mine water.

Because of the extent of these problems, the U.S. Environmental Protection Agency in conjunction with the U.S. Department of Energy organized a series of seminars to disseminate available information on approaches for addressing mine waste. This document presents papers written by the seminar presenters, for which this introductory paper provides a general context.

Definition and Chemistry of Acid Mine Drainage (AMD)

The types of mine waste problems are numerous, but the most difficult one to address is the acid mine drainage (AMD) that emanates from both surface and underground mine workings, waste and development rock, and tailings piles and ponds. AMD is defined as drainage that occurs as a result of sulfide oxidation in rock exposed to air and water. In the case of iron sulfide (pyrite/marcasite), the chemical reaction in the acid-generating process can be simplified to:



In the presence of oxygen and water, pyrite oxidizes to form iron hydroxide (commonly called "yellowboy"), sulfate, and hydrogen ions. The liberation of hydrogen ions causes acidity in water passing over the rock. Every mole of pyrite yields four moles of acidity.

AMD can be characterized by low pH and increased acidity, elevated heavy metals, sulfate, and total dissolved solids (TDS). The low pH water that results from acid generation is capable of solubilizing heavy metals contained within the waste rock. Most harmful to the environment is the high metals loading in the water emanating from the waste material. As AMD flows away from the acid-generating source and moves into the receiving environment where the pH is buffered, discoloration of the stream bed or the material over which the AMD is passing often is caused due to precipitation of solid metal hydroxides.

Stages in the Development of AMD

The development of AMD involves a complex combination of organic and sometimes inorganic processes and reactions. To produce severe acid drainage, where the pH of the system drops below 3, sulfide minerals must create an optimum microenvironment for rapid oxidation and must continue to oxidize for a sufficiently long time to exhaust all of the neutralization potential of the rock (2). The potential of sulfide rock to generate acid is strongly related to the amount of alkaline, often calcareous, material in the rock. For example, a rock containing 5 percent sulfide minerals may not generate acid due to an overabundance of calcite in the rock that is available for acid neutralization. Another rock, containing less than 2 percent sulfide minerals, might generate a considerable amount of acid if no neutralizing minerals are present within it.

When reactive sulfide rock initially is exposed to flowing water and oxygen, sulfide oxidation and acid generation begins. Any calcium-based carbonate in the rock immediately neutralizes this small amount of acidity and maintains neutral to alkaline conditions in water passing over the rock (3). As acid generation continues and the neutralizing agent is consumed or is rendered ineffective in further neutralization, the pH of the water decreases, which in turn enhances the conditions for further acid generation. As the rate of acid generation accelerates, the pH progressively decreases in a step-like manner. Each plateau of relatively steady pH represents the dissolution of a neutralizing mineral that becomes soluble at that pH (3). If the rate of acid generation remains high enough to remove all of the neutralization potential in the rock, the pH values will drop below 3 and AMD will become severe. These various stages can last for weeks, months, or centuries until the sulfide minerals completely oxidize and the rock becomes inert, or until special waste management and AMD control actions are taken.

Prediction of AMD

The prediction of AMD in particular is a rapidly evolving science. Predictive tests specifically designed for sulfidic coal mine wastes have been around for decades. Significant advances in the predictive techniques applied to hard rock metal mine waste samples have been made in the past 5 to 10 years. Recent studies have been conducted comparing various predictive tests for hard rock samples (4,5). Accurate predictive testing, proper waste rock characterization, and proper interpretation of the resulting data are all of paramount importance in developing successful sulfide waste rock management techniques. Conducting proper predictive tests prior to developing waste management plans is the preferred choice from an environmental as well as economic standpoint. Millions of dollars can be saved as a result of focusing on preventing AMD rather than reacting to problems it can cause.

Predictive analyses can range from simple comparisons to complex laboratory testing and computer modeling. A simple, but very useful, assessment might include comparing a proposed mining operation with geologically similar and/or nearby mines where acid generation is known to be a problem or not. Rock samples may undergo relatively inexpensive, short-term "static" predictive testing (e.g., acid/base accounting) in which the amount of acid-generating potential of the rock is weighed against the acid-neutralizing potential of the rock. Static tests are qualitative tests only. Rock types that undergo static tests that result in an indication for potential acid generation may undergo more expensive, long-term "kinetic" tests (e.g., humidity cells or column leach tests) in which actual weathering reactions are simulated in the laboratory. Kinetic tests are qualitative indicators of the rate and amount of acid that a given sample may generate.

Control of AMD

Much of the effort to control AMD in the past has been directed at treating the symptoms rather than controlling the problem at the source. In the early 1990s, significant research was undertaken to develop improved sulfide waste management techniques for hard rock mines. Control of acid generation can be achieved by removing one or more of the three essential components in the acid-generating process (i.e., sulfide, air, or water). Steps that can be taken to control AMD include:

- *Waste segregation and blending.* This would include thoroughly blending the acid-generating rock with enough rock of a net neutralizing potential that neutral pH levels within the waste system are maintained.
- *Base additives.* Alkaline materials such as limestone, lime, and soda ash can be added to the sulfide rock upon disposal to buffer acid-generating reactions.
- *Covers and caps.* Soil, clay, and synthetic covers can be placed over the acid-generating rock to minimize the infiltration of water and air into the system. Water covers at acid-generating tailing impoundments have been effective in controlling the problem.
- *Bactericides.* The introduction of certain chemicals that reduce the bacteria (*Thiobacillus ferrooxidans*) that catalyze the acid-generating reactions have been effective in controlling AMD.
- *Collection and treatment of contaminants.* In this case, AMD is collected and treated using active or passive treatment systems. Active treatment might include base additives to precipitate metals out of solution, remove the resulting sludge, and discharge the treated water. Passive treatment might include passing contaminated water through a constructed

wetland designed to remove contaminants. These control options are less attractive in the long term because they treat the symptoms of AMD rather than controlling the problem at the source.

Conclusion

AMD and the sources of its production are the legacy of over 100 years of mining in the western United States. AMD has been a problem in the eastern United States and throughout the world even longer. The presentations in this publication describe only a small fraction of the current thinking and ongoing research to address the issue of mining wastes in general, and AMD in particular, using comprehensive and cost-effective approaches. The problem of mining wastes is daunting. An all inclusive description of the types of environmental issues posed by mining wastes is beyond the scope of this document. Nonetheless, the case histories presented reflect common mine waste problems and provide insight to state-of-the-art management techniques. Although these techniques have been used to successfully address aspects of mine waste, they warrant further research and site application. For the country's best scientists and engineers, the challenge presented by mine wastes involves developing solutions to problems created in the past, while seeking ways to avoid these problems in the future.

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Chapter 2.

Understanding the Reasons for Environmental Problems From Inactive Mine Sites

Dirk Van Zyl

Background

Mining not only produced wealth, power, and fame for the United States it also attracted worldwide attention and investment to this underdeveloped nation, one that was sorely in need of a financial transfusion. Without mining—from coal to iron to gold—the United States could not have emerged as a world power by the turn of the century, nor could it have successfully launched its international career of the twentieth century. All this development did not take place without disturbance—environmental, personal, economic, political and social. Mining left behind gutted mountains, dredged-out streams, despoiled vegetation, open pits, polluted creeks, barren hillsides and meadows, a littered landscape, abandoned camps and burned-out miners and the entrepreneurs who came to mine the miners [1].

As pointed out by historian Duane Smith, mining played an important role in establishing America on its path to becoming a superpower. Unfortunately, along with the success of the mining industry came negative environmental impacts such as acid drainage from mine adits and waste rock piles. Indeed, old mining districts are dotted with eroded tailings and waste rock piles.

In the nineteenth century, mining was quite widespread in the United States, but was most concentrated around the Rocky Mountains in Colorado, the western parts of Montana, and California and Nevada. Mining operations in Missouri and Kansas were mostly related to lead and zinc. The major locations of hard rock mining activity during the nineteenth century are shown in Figure 1.

Ore Mineralization and Metal Extraction

The following broad comments can be made about the mineralization associated with hard rock mines:

- Gold and silver are found in oxidized zones near the ground surface, although they often are associated with sulfides at greater depths.

- Lead, zinc, and copper often are found in sulfide mineralization.
- Other metals can be associated with mineralization (e.g., arsenic, iron, mercury, cadmium).

Often natural mineralizations contain metals that can be economically exploited. These deposits also contain lower concentrations of metals, however, that are typically discarded as waste or exposed to water and oxygen following mining operations.

Historically, mine development occurred through prospecting for surface outcrops. Thus, initially miners exploited the ore bodies close to the surface or practiced vein-type mining. Lead zinc in Kansas and Missouri was mined through shallow shafts to a depth of up to 150 feet, and eventually dewatering became a problem. In mountainous terrain, dewatering was conducted through a series of adits and tunnels to allow gravity drainage of whole mining districts (e.g., the Yak Tunnel at Leadville, Colorado). The mining activities significantly increased the surface area of mineralized rock exposed to water and oxygen.

Miners performed metal extraction by various means. Physical processes such as grinding further increased the surface area of the minerals exposed to water and oxygen. Mercury was introduced for extraction of precious metals through amalgamation. Smelting also was conducted to extract metals such as copper from open stacks at mining camps (e.g., at Butte, Montana). This led to air pollution and extensive firewood consumption. Cyanidation as a process was introduced in the 1890s in the United States and quickly gained popularity (2). Flotation processes for the extraction of metal associated with sulfide minerals gained acceptance in the early twentieth century.

The overall effect of metal extraction processes was the increased exposure of minerals in the mine waste materials to water and oxygen. Geochemical interactions with the waste resulted in acid generation and the leaching of heavy metals to the surrounding environment. Smelt-

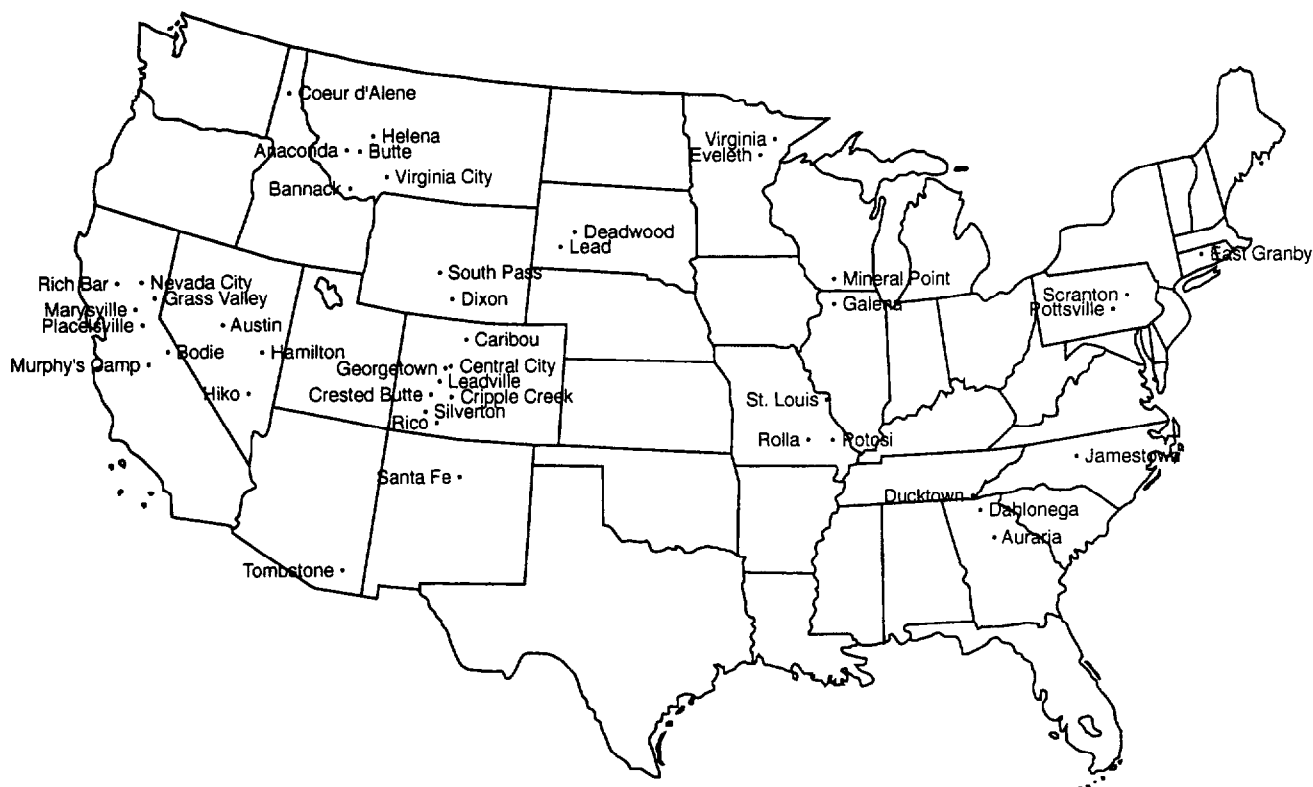


Figure 1. Sites of major hard rock mining activity in the United States during the nineteenth century.

ing resulted in the atmospheric dispersion of contaminants such as arsenic and lead.

The presence of mineralization made mining possible. Unfortunately, however, natural geochemical processes in undisturbed mineralized areas as well as in areas exploited for metal production can cause degradation of water quality. Although the major environmental consequence of mining is the increased surface area of minerals exposed to water and oxygen, the release of sediments is also of concern. Chemicals used in metal extraction, however, seldom have long-term impacts.

Water Quality

Effects on water quality associated with inactive mine sites are of particular concern. Selected constituents for three different catchment areas in Colorado are presented in Table 1. Alum Creek is a small catchment that drains into the Alamosa River downstream of Wightman Fork, which drains the Summitville area. Because mining has never been conducted in the Alum Creek drainage, the water quality shown is exclusively a result of leaching and runoff from natural mineralization.

Wightman Fork below Cropsy Creek is the exit point from the Summitville mine site. The 1981 data are a useful measure of the water quality as affected by past mining activity in the area. The 1991 data indicate some of the effects of continued mining at the site; to a significant degree, the higher concentrations of copper, iron, and zinc are due to discharge from the Reynolds Tunnel. The section of Silver Creek at the highway bridge is a catchment near Rico, Colorado. Typical ranges as well as mean values of constituents for this catchment appear in Table 1.

More extensive information on the geochemical behavior and water quality at certain basins in the Upper Alamosa River in the vicinity of Summitville is provided in two recent publications (3,4). The geochemical characteristics of the Alum Creek drainage appear to be different from those in the Cropsy Creek drainage because of exposure to a different alteration assembly (3). Researchers developed a conservative estimate of the maximum possible contributions of mining to the degradation of water quality in the Alamosa River above the confluence with Wightman Fork (4). According to the study, abandoned mines could be the source of about 11 percent of the iron, 18 percent of the aluminum, and 1 percent of the copper, manganese, and zinc; research-

Table 1. Water Quality Data Comparison for Selected Mineralized Areas in Colorado

Parameter (mean, max., min.)	Alum Creek at Mouth (Aug. 1991)	Wightman Fork Below Cropsy Creek (Oct. 1981)	Wightman Fork Below Cropsy Creek (Oct. 1991)	Silver Creek at Bridge Hwy 145 (Mar. 1966 to Dec. 1968)
pH	NA*	3.44	NA	7.9 8.4 7.4
Arsenic	5.7 9 3	2	NA	NA NA NA
Cadmium	7 10.2 4.9	5.4	62	NA NA NA
Copper	259 261 258	3,560	26,000	111 1,100 0
Iron	126,500 171,500 103,000	6,300	82,000	5,407 125,000 0
Lead	4.2 6.8 2	18.5	NA	655 6,350 0
Silver	<0.5	1.02	<0.2	NA
Zinc	652 843 543	770	6,300	855 2,000 100

* NA = not available.

ers attributed the remainder of these constituents to natural mineralization.

Considerations

The discussion and data presented above demonstrate that environmental problems from inactive mines are related to natural mineralization as well as mining activities that result in increased exposure of minerals to water and oxygen. Before the 1930s, for example, environmental effects of mining were poorly understood. Economic incentives were the driving force and not environmental protection. Our appreciation of the effects of mining on the environment has improved considerably since that time, and more significantly during the last 10 years. For instance, we now know that chemicals used for hydrometallurgical and flotation extraction typically do not present a long-term concern at inactive mining sites. Rather, natural mineralization and its exploitation are the source of concern.

Problems experienced at inactive mine sites have received increased attention because of changes in the environmental awareness and regulatory environment.

Also, we now know more about environmental processes from a multimedia perspective; that is, the interactions involving land, air, and water are better understood. Another development that has contributed significantly to the real or perceived problems at mining sites is our improved analytical capability. Because instruments are available to analyze to much lower concentrations, researchers can identify the presence of some constituents previously not detected.

Another factor has the potential to contribute to certain perceived or real concerns at mining sites: applying drinking water or aquatic standards to streams in mineralized areas without due regard for the likely baseline water quality of the stream prior to mining operations. Water quality can be restored only to what Nature gave us and not better. Thus, site-specific risk issues should be recognized, and evaluation of the level of risk should go beyond the broad application of conservative assumptions.

Conclusions

Natural mineralization is the greatest contributor to environmental problems at inactive mine sites. Man-made

materials such as cyanide and flotation chemicals have not played a significant role in contamination from these mine sites. Rather, mining increased the exposure of sulfides and other minerals to oxygen and water, which leads to acid rock drainage associated with mining at active and inactive sites. Thus, designing for closure is our only option from an environmental and economic view point.

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Chapter 3.

The Importance of Site Characterization for Remediation of Abandoned Mine Lands

A. MacG. Robertson

Requirements for Site Characterization

Mining is a disruptive activity involving physical disturbance of the earth's surface to gain access to the ore, removal and processing of the ore, and deposition of wastes generated by ore processing. Typically, mining operations leave behind large man-made structures (e.g., roads, mine and mill buildings, and processing facilities), the underground or open pit mine, and large deposits of mine rock excavated to expose the ore as well as tailings (i.e., the residue generated by ore processed to recover valuable minerals). These man-made structures and waste materials are often unstable or hazardous, or they become so over time as they weather and deteriorate when subjected to the elements. Indeed, they may disintegrate with time and may be vulnerable to vandalism and fire.

Mining also removes minerals from the deep anoxic environment, where they are chemically stable, and exposes them to the high oxygen atmosphere of the earth's surface and the leaching action of rainwater. Many of the newly exposed minerals can react with the gaseous and liquid components in their new environment to yield contaminants. These seep and flow—via ground- and surface-water pathways—into the adjacent environment, where they might be toxic to aquatic and terrestrial biota.

Remediation efforts at abandoned mine sites involve identifying sites and aspects of particular mining operations that have caused, or could result in, damage to the environment and loss of land-use values. Thus, the first step in the remediation process is to characterize the site in terms of:

- Premining conditions
- The nature of mine development and its present or potential environmental effect
- Contaminant control or reclamation measures that could be considered.

Many of the effects of mine development are time dependent. For example, the processes of erosion and the development of unstable ditch and dam conditions, as well as the chemical evolution that develops into acid mine drainage conditions, can take many years or tens of years to develop. At initiation of mining operations, anticipating the potential for such long-term degradation or predicting its course often is difficult. Such assessments depend on short-term laboratory tests using collected material and on the modeling of long-term effects using uncertain predictive models. Given the time that has elapsed since mining operations were undertaken at many abandoned sites, conditions of degradation and instability or chemical change and contaminant plume extension are often well developed. Thus, at abandoned mines, long-term site characterization usually can be determined directly from observation and characterization of current conditions. In such situations, extensive investigations and laboratory testing programs are not required to make a preliminary assessment.

Remediation objectives can be divided into three broad categories:

- *Physical stabilization.* Mine components must be safe and stable.
- *Chemical stabilization.* Materials must not decompose and yield soluble contaminants.
- *Land use and aesthetics.* The site must be useful and look good.

Technical Guides for Site Characterization

Because comprehensive guidance on the characterization of abandoned mine sites cannot reasonably be provided in this paper, the reader is referred to the following technical guidelines:

- *Rehabilitation of Mines: Guidelines for Proponents.* This document, issued by the Ontario Ministry of

Northern Development and Mines, provides an excellent framework for the characterization of abandoned or closed mines (1).

- *Draft Acid Rock Drainage Technical Guide*. This document, prepared for the British Columbia Acid Mine Drainage Task Force, provides a sound description of acid generation investigations, including testing and site characterization techniques for new mines (2).
- *Mine Rock Guidelines: Design and Control of Drainage Water Quality*. This document, issued by the Mines Pollution Control Branch of Saskatchewan Environment and Public Safety, describes site characterization techniques suitable for field reconnaissance and detailed investigation and characterization of mine rock wastes. Such wastes represent one of the most significant sources of environmental effects associated with abandoned mine sites (3).

The next section of this paper concentrates on a characterization methodology well suited to sites where acid drainage from mine rock waste is a particular concern. The final text section contains techniques of particular value for performing an initial investigation at sites with acid rock drainage (ARD).

Steps in the Characterization of Abandoned Mine Sites With Acid Rock Drainage

Mine site characterization can be divided into two stages:

- Initial, or reconnaissance-level, investigation and characterization
- Detailed investigation and characterization

For both of these phases, the activities required for investigation and characterization can be further divided into three steps as illustrated in Figure 1 and described in the list below.

1. The Planning Step:

- Define potential concerns for the site: What problems to consider?
- Select a methodology for site characterization: How to look at the site?
- Define the initial information requirements: Where to start?

2. The Investigation Step:

- Establish a set of techniques for initial reconnaissance: What can be seen from the site?

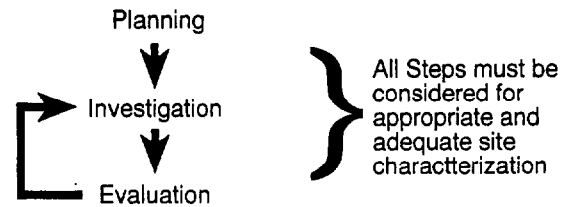


Figure 1. Site characterization steps.

- Evaluate existing information: Are data sufficient to define concerns?
- Define additional data requirements: Where do we go from here?

3. The Evaluation Step:

- "Quantify" potential issues of environmental liability: What are the real problems?
- Evaluate alternative control measures: How can these problems be solved?
- Conduct a cost/benefit evaluation: What is the best control/remediation measure for the cost?

All three steps must be considered **early** in the site characterization process. Only if the investigator has a sense of the potential environmental impacts associated with the site can a characterization plan be developed that adequately addresses concerns. Moreover, early identification of the "real problems" and potential remediation options ensures that site characterization provides sufficient information for designing the most advantageous remediation measures. Thus, the investigation and evaluation steps are performed iteratively, preferably by the investigator as site reconnaissance is in progress. The investigator must:

- Anticipate the concerns that may be associated with a site.
- Plan the investigation to explore for these concerns.
- Recognize new concerns as reconnaissance is in progress.
- Evaluate significance of concerns as they are identified.
- Consider the reclamation options that might be applicable to these concerns.
- Assess the requirements of such remediation.
- Perform any additional characterization necessary to provide the information for assessing the effectiveness of the remediation measures.

During the initial investigation and characterization, the investigator performs all the planning, investigation, and evaluation steps using low-cost techniques that can be applied in the field. A description of some of these techniques is the focus of this paper. The detailed level of site characterization that follows the reconnaissance phase can be planned to address subsequently the remaining data deficiencies. The effectiveness of the detailed-level investigation can be improved considerably by a complete initial site assessment. Moreover, additional characterization phases can be avoided.

Initial Investigations at Abandoned Mine Sites With Acid Rock Drainage

The objective of such reconnaissance is to assess:

- Signs of ARD
- Factors that control ARD
- Control/remediation measures
- Environmental effects (with and without control/remediation measures)
- Characterization requirements for the detailed-level investigation

The investigator should take the following to the site:

- Equipment for collecting water samples for subsequent laboratory analysis.
- pH paper or, preferably, a field pH meter as well as a conductivity meter for taking measurements of water pH and conductivity as an indicator of acidity and dissolved salt content.
- Demineralized water and a beaker in which paste pH and conductivity tests can be performed on tailings and rock waste samples.
- A 10% hydrogen chloride solution for testing for carbonates in rocks.
- A hand lens, rock hammer, and mineral identification book for examining mine rock and identifying minerals.
- Sample bags
- A camera for recording observations of color, texture, and physical conditions.

To assess the ARD conditions on a site, the investigator must have a basic understanding of the kinetics of acid generation and contaminant leaching. Acid generation occurs when sulfide containing rock is mined and brought to the surface where it is exposed to air and water. The sulfides react with the air and water to produce sulfuric

acid. If the resulting acidity is not neutralized by neutralizing minerals in the rock, then acidic conditions develop that leach metals from the rock. This results in the contaminated drainage referred to as ARD.

Figure 2 is a plot of the normalized rate of oxidation of sulfides for various pH values. In the absence of biologically catalyzed oxidation, oxidation rates are relatively slow for all pH conditions. Biological oxidation by *Thiobacillus ferrooxidans* occurs when the pH has dropped to below 4.5 and is at a maximum at a pH of about 3.5. Biological oxidation results in a dramatic (50 to 1,000 times) increase in the oxidation rate. Rocks exposed in the field typically are at neutral pH, which is controlled by the presence of alkali minerals such as calcite in the rock. The paste pH for such fresh rock is usually neutral with a low conductivity. Immediately after exposure, oxidation starts but at the slow chemical oxidation rate. Initially any acidity generated is neutralized by the alkali minerals in the rock, maintaining the neutral pH and controlling the rate of oxidation. During this phase, the pH of the rock remains neutral but sulfates are produced; thus, a paste of the rock will produce a neutral pH but a relatively high conductivity. If the quantity of sulfides is sufficient over time to generate enough acidity to consume all the available alkalinity, then acidic conditions begin to develop. The paste pH of the waste rock decreases and the conductivity becomes extremely high as the concentration of dissolved salts increases.

The decrease in pH that can occur over time is illustrated in Figure 3. Each step in the downward curve represents the pH value at which a particular mineral in the waste rock buffers the paste pH. As each buffering mineral type is consumed, the pH drops and the oxidation rate might increase. The time required for acidic conditions to develop depends on the amount and nature of the sulfides and the alkali minerals present in the waste rock. This process may take from months to many tens of years. Because large variations in mineral assemblages occur in the waste rock, the rates and time of onset for acid generation can vary considerably. Thus, acid generation initiates in spots where conditions are particularly favorable. At these locations color changes, which occur as the minerals oxidize and are neutralized, are often readily apparent. The selective sampling of such "trigger" spots results in paste pH and conductivity values indicative of the oxidation and acid-generation processes. Thus, by performing field paste pH and conductivity tests an investigator can make an early assessment of potential acid-generating conditions long before the contaminants generated in the process have had a chance to migrate to the seeps issuing from the waste dumps or adjacent streams.

Once acidic conditions have developed locally, then the acidic solutions can be leached by infiltrating waters and carried along a seepage pathway. As the acidic solutions migrate along this pathway, they encounter neu-

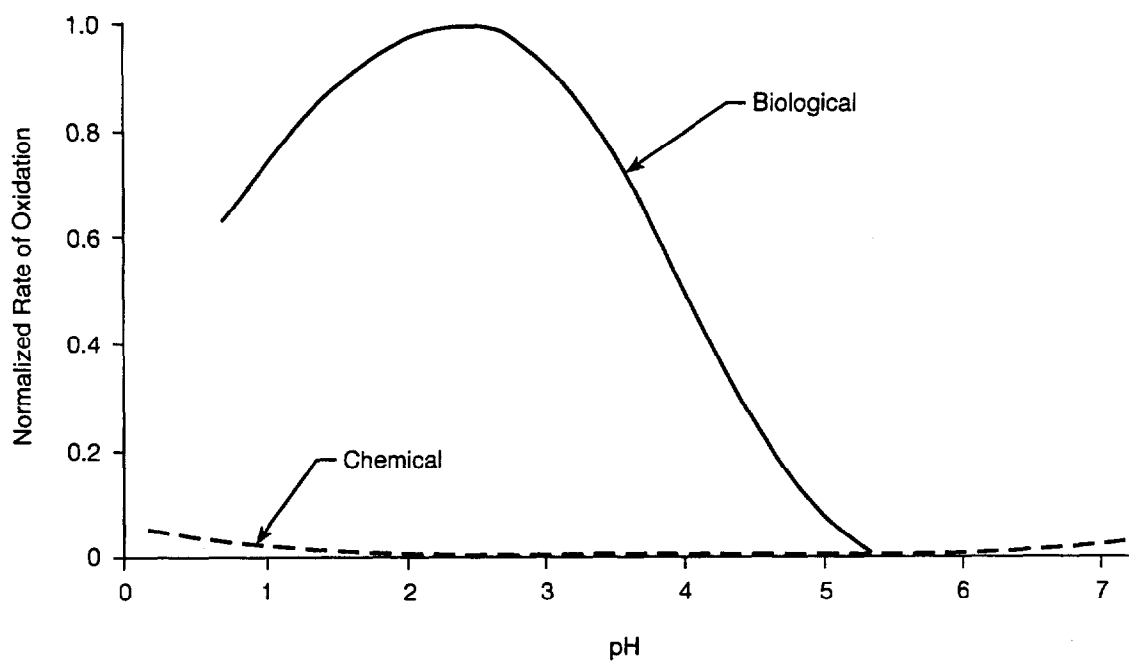


Figure 2. Kinetics of acid generation.

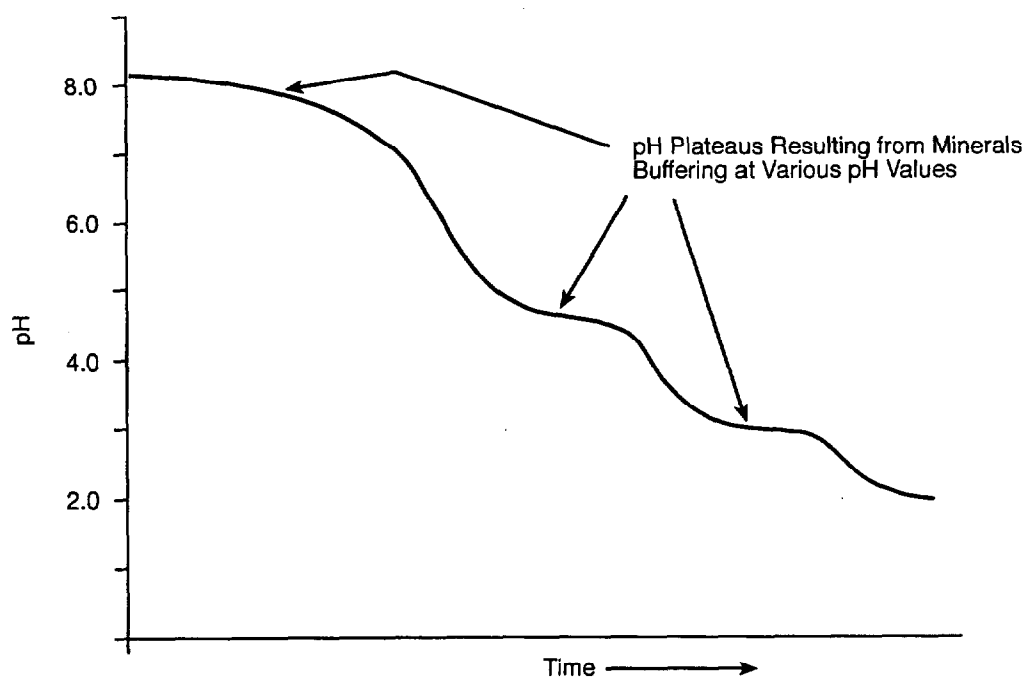


Figure 3. pH control during acid generation.

tralizing minerals and the acid solution is neutralized with the resultant deposition of salts and metal hydroxides. These deposits have many characteristic colors; they range from red ferric hydroxide to white aluminum hydroxide and blue and green copper carbonates. As acidity continues to migrate down a seepage pathway, the available alkalinity in the pathway is consumed and the acid front migrates farther from the source. At a particular point along a seepage pathway, a progressive change occurs over time as the pH of the passing seepage water decreases. This pH decrease is accompanied by increases in metals and other contaminant concentrations.

The change in metals concentrations that can occur at a point in a seepage pathway downstream of the acid-generating source is illustrated in Figure 4. The time needed for increased metal concentrations to be apparent in downstream wells and monitoring points can be extremely long (tens and hundreds of years). Thus, the monitoring of downstream effects often is not a reliable early indicator of potential acid-generation conditions. For this reason, the site investigator must assess carefully the acid-generating conditions of the potential source materials, rather than concentrate on trying to measure the downstream environmental impacts.

Where the investigator should look:

- As close as possible to the potential acid-generating sources; perform paste pH and conductivity tests on the materials themselves.
- Surface pools on the wastes
- Seeps at the toe of the wastes
- Decants and surface runoff
- Ground water and monitoring wells.

When the investigator should look:

- Spring and fall when the flushing by infiltration is normally greatest
- In mid-summer when staining may be most apparent.
- At first snowfall when hot spots can be readily observed.

What the investigator should watch for:

- Field observations
 - Visible sulfides
 - Red, orange, yellow, white, blue stainings or precipitates
 - Dead vegetation

- Melting snow or steaming vents on wastes
- Dead fish and other biota
- Water quality
 - Low pH in seeps, ground water, decants
 - Elevated or rising conductivity, sulfate and/or metals
 - Increasing acidity or decreasing alkalinity
- Geochemistry
 - Low paste pH of mine wastes
 - High conductivity in field extractions

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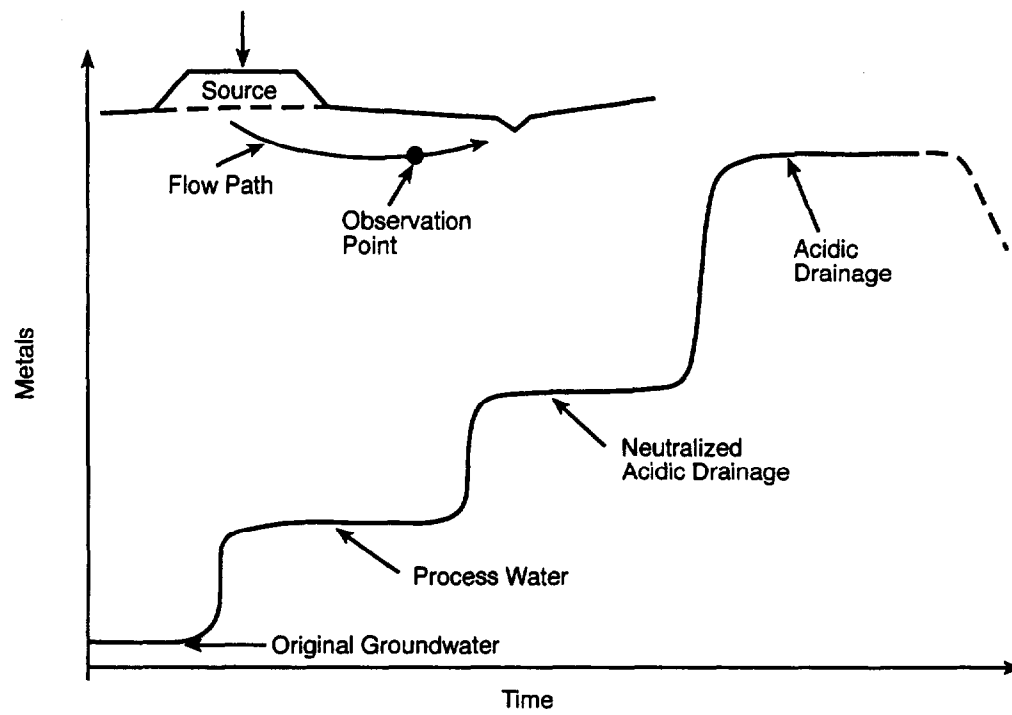


Figure 4. Kinetics of contaminant front migration.

Chapter 4.

U.S. Bureau of Mines Remediation Research*: New Uses for Proven Tools

William B. Schmidt

Introduction

The U.S. Bureau of Mines (USBM) has been actively involved in mine waste research for 3 decades, with particular emphasis for the past 8 years in the hard rock area. Historically, USBM's research in the environmental area has focused on coal-related issues. From 1965 to 1982 this emphasis was consistent with USBM's involvement in coal-related health and safety issues and later with the implementation of the Surface Mining Control and Reclamation Act of 1977. The emphasis shifted to hard rock issues as a result of the increasing public and industry concern about associated environmental issues, as well as consolidation of USBM's metallurgy and mining research efforts and USBM's general rethinking of its mission.

Consolidation of USBM's metallurgical and mining areas was beneficial, particularly in regard to hard rock environmental issues. As a result of changes, extractive metallurgists and process engineering specialists were brought together with hydrologists, geologists, geophysicists, and other mining related practitioners to address the multidimensional problems typical of mine wastes.

Current remediation research at USBM focuses on the following areas:

- Mine drainage technology
 - Acid drainage from coal mines
 - Acid drainage from metal and nonmetal mines
- Solid mine waste and subsidence
- Hazardous waste treatment technologies
 - Characterization
 - Treatment
- Abandoned mine land (AML) remediation

Two programs are related to the most critical problems at present in the mine waste area—liquid and solid wastes. One program is related to the extension of the USBM's mining skills to the larger world of contaminated wastes, and the other is related to the problems of reclaiming abandoned coal mine lands, a subset of the mine waste problem. This latter program is specifically mandated by Congress and subject to legislative requirements.

The allocation of USBM funds between the four principal research areas in fiscal year 1995 is shown in Figure 1. Funding for these programs in fiscal year 1996 is expected to increase by about 50 percent.

Mine Drainage Research

USBM's research program for liquid mine waste (i.e., mine drainage) focuses on the following areas:

- Prediction
 - Fundamental sulfide reactions
 - Geochemical models (correlated with static and kinetic testing and field test results)
 - Host rock and waste rock dumps
- Mitigation/control
 - Seals, grouts, and caps
 - Passivation
- Treatment (contaminant removal)
 - Chemical
 - Biological

USBM mine drainage research is carried out in partnership with the U.S. Forest Service (FS). Several years

* NOTE: Since these seminars, the U.S. Bureau of Mines has been abolished.

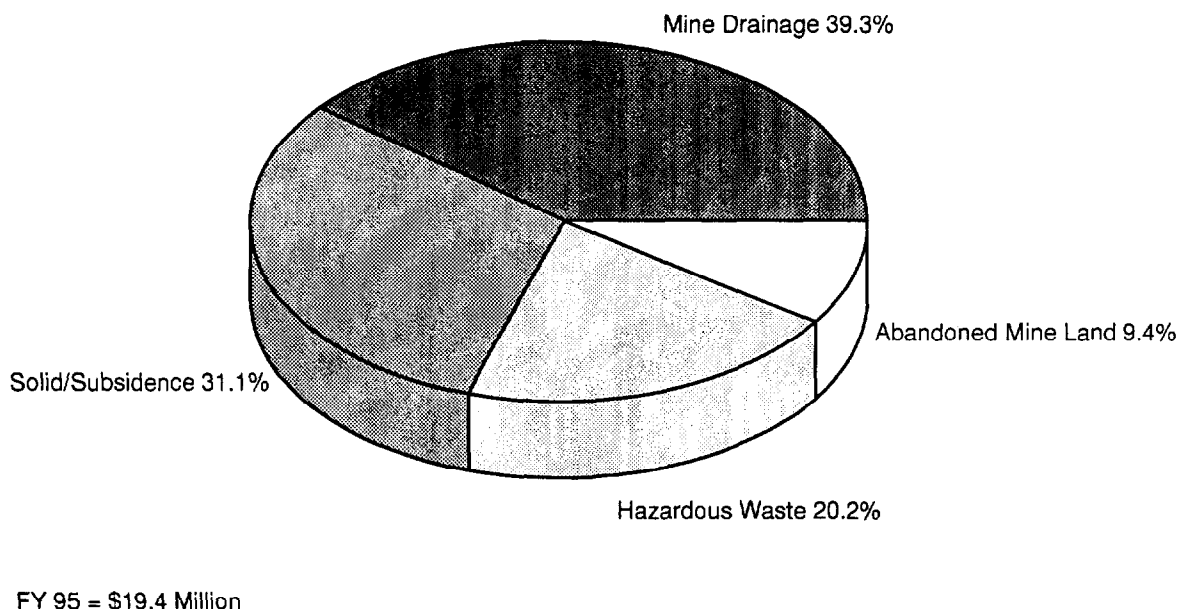


Figure 1. USBM funding distribution for remediation research in fiscal year 1995.

ago FS officials proposed this cooperative effort to USBM to solve a most intractable environmental problem—acid rock drainage (ARD).

Research concerning prediction of mine drainage problems concentrates on the host rock and waste dumps. Field work draws heavily on the efforts of researchers in Canada's Mine Environment Neutralization Drainage (MEND) program and other activities in the ARD area worldwide, including groups working on a major contributor to ARD—mine tailings. Although the research effort focuses on the development and testing of better tools for predicting ARD problems, considerable emphasis also is placed on determining the generation, migration, and ultimate fate of mining-related contaminants in nature.

Mitigation/control is important for situations where potential ARD problems could not have been identified beforehand. If ARD cannot be predicted, the best approach is to apply tools and techniques that interrupt the ARD process or stop the flow of contaminants. The types of tools being developed or investigated range from passivation of reactive mineral surfaces to the use of grouts and seals.

The development of treatment technology represents the "holy grail" of much of the current research on mine waste. In this area, a dichotomy exists between regulators and mine operators. Regulators are faced with the problem of contaminated discharges from an adit or other mine opening and are looking for a black box that can be attached to the end of a pipe to produce gold-book quality water. Mine operators, as well as land manag-

ers, envision perpetual treatment, liability, and expenditure of scarce resources as the inevitable consequence of this approach. Short of these broad goals is the objective of developing low cost/low maintenance treatment systems for remote sites.

The need for treatment is inevitable as is the need for techniques that are both cheaper and pose less of a compromise than those offered by the current options. In some cases, perpetual treatment will be the least costly and most effective option. Nonetheless, many opportunities for useful research exist. For example, "lime" treatment (i.e., pH adjustment accompanied by precipitation of acid mobilized metals) is the technology of choice for many applications. Even this technology offers opportunities for further improvement, such as development of denser flocs and approaches for removing metals that would change a nonregulated sludge into a regulated waste. In addition, researchers should address the many "niche" needs for technologies to deal with special situations and problem contaminants. Also, biotreatment appears to offer great potential for improved treatment systems if researchers can engineer ways to use the biologic phenomena that they are beginning to understand.

Recent changes in clean water compliance requirements likely will shift attention to an area that has thus far received little attention from the technology community—nonpoint source controls. Instead of the black box at the end of the pipe (the visible discharge flowing from the picturesque old mine) the nonvisible flows through disturbed host rock, old tailings, and waste piles that are contaminating streams and rivers will need to be ad-

dressed. USBM's research approach should prove beneficial in this area, but a lot of new lessons will be learned.

Solid Waste Research

The solid waste area of USBM's program deals with a fairly broad range of issues, as listed below:

- Reprocessing/process modification
 - Pyrite removal
 - Heavy metal removal
- Pyrometallurgical treatment (high temp)
 - Vitrification
 - Metal extraction
- Waste disposal
 - Fly ash (i.e., only fly ash from coal covered by this program)
 - Dump stability
- Subsidence effects
 - Prediction
 - Prevention

A more accurate description of this topic might be nonliquid, nongaseous environmental problems. Much of this work (e.g., on fly ash disposal, dump stability, subsidence-related research, and blasting vibration studies) is intended to provide regulatory agencies, the mining industry, and other interested parties with unbiased information upon which to base sound decisions. A component of this work, however, relates to the issue of hard rock mining wastes.

One of the subjects that has been of interest to many in the field has to do with the practicality of separation of the more reactive components of mine waste. This would allow for the trouble-free disposal of the 90 percent of waste that will not present an environmental problem and the special treatment of the much smaller, problem components. USBM's work using state-of-the-art mineral beneficiation technology would suggest that this approach to waste remediation has different applicability to freshly processed wastes than it does to aged wastes on abandoned sites.

Use of the Technology

In many ways the technology of the mining/mineral processing industry, the focus of USBM, is well developed

for the remediation of various contaminated wastes. The technology is "proven"—a strong technical underpinning exists for these technologies. In addition, the equipment used is robust and relatively simple. The industry is given to building plants around the replication of a series of "unit operations," each of which is well understood.

On the other hand, as USBM researchers discovered, applying these technologies to nonmineral production problems requires some rethinking of very basic considerations in regard to the minerals industry. As a general statement, mineral production operations are very sensitive to the cost of reagents and supplies. Because the plants are designed to run for a long time (e.g., 30 years), capital costs diminish in importance. The situation with regard to a 3-year Superfund cleanup is almost exactly the opposite: Reagent costs are almost trivial and the cost of a plant is significant. This presented two lines of thought to USBM researchers. The first is that reagents that they tended not to consider in regard to the screening process because of their cost (e.g., organic acids instead of mineral acids) needed to be assessed in light of changed circumstances. The second is that the current process of treating each site as a unique problem also needed to be rethought by those in charge of cleanup. If the same plant could be reused 3, 4, or 5 times on similar wastes, the cost per yard of treated material would fall dramatically as the capital costs were spread over a larger base. Treatment (i.e., permanent removal of the contaminants) became much more competitive with, or cheaper than, other approaches, such as stabilization or removal and disposal. Unfortunately, implementation of this strategy is beyond the control of USBM.

Recovery of Valuable Metals

Another issue is the potential for making money from the treatment of wastes, particularly mine wastes, by recovering valuable metal. In some instances, part of the cost of remediation of mine wastes might be returned from the metal recovered. Those instances will be few, but far more numerous than instances of covering the cost of the remediation as well as making a profit.

Most of the mineral sites are mine sites from which the ore, the valuable metal concentrations, have been removed. The cost of extracting additional value from processed material generally exceeds the value of the product. In addition, the material left at processing sites has been altered by natural processes (e.g., oxidation) and would require additional treatment to restore it to a species that has value in the marketplace. Similar limitations apply to liquid wastes. Any contaminated stream might contain some valuable metals, but the concentrations would be such that the kinetics of the reactions needed to recover them would be generally unfavorable. For example, a tremendous quantity of gold is in the

oceans in aggregate; however, the concentration of gold in any given cubic meter of seawater is minuscule.

Abandoned Mine Land

Another element of USBM's environmental research program is the Abandoned Mine Land program. This work primarily concerns areas east of the Mississippi River. The program was established specifically to help reduce the cost of reclaiming lands that were mined and abandoned before the passage of the Surface Mining Control and Reclamation Act in 1977. The focus includes the

control of coal-mine acid drainage, coal subsidence, and the extinguishing of fires in abandoned mines and coal dumps. Some of the relevant technology (e.g., sealing for mine shafts) can be applied to the remediation of physical hazards from metal mine openings. Most of the research enhances the USBM's technical base for addressing hard rock issues rather than being directly applicable.

USBM has been very active in seeking partnerships with the users of mine technology. USBM encourages additional opportunities to work with others to advance the cause of hard rock environmental remediation.

Chapter 5.

The Technology and Operation of Passive Mine Drainage Treatment Systems

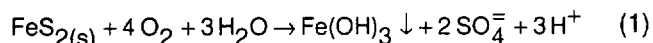
Ronald R. Hewitt Cohen

Introduction¹

Mining activity has increased since the late 1800s as a result of technological improvements and economic advantages in blasting, materials handling, and an increase in the size of equipment, combined with the constantly increasing demand for minerals. The mining industry's efforts to meet demand and minimize U.S. dependence on foreign mineral supplies has meant an increase in disturbed lands and adverse environmental effects. Mining conducted prior to 1900 has also left us with a legacy of waste rock, mine tailings, and drainage tunnels from which metal-laden waters contaminate receiving waters.

Treatment of mine effluent using a passive mine drainage treatment system (PMDTS) is addressed in this paper. Please note that the Colorado School of Mines PMDTS can be used to treat wastewaters from galvanizing and cadmium, chromium, and nickel plating as well as from lead-acid battery recycling industries.

Production of acid water is common to mining situations where pyrite and other metal sulfides become exposed to atmospheric conditions. Upon exposure to the atmosphere, sufficient oxygen and water are present to initiate the oxidation of pyrite. The overall reaction is:



Notice the necessity for air and water (although the process can occur in a dry environment). Few other natural weathering reactions produce this amount of acidity.

At pH 3.5 or less, bacteria such as *Thiobacillus ferrooxidans* accelerate the rate of conversion of Fe^{++} to

Fe^{3+} . Such bacteria may accelerate reactions by orders of magnitude (2). Numerous studies have documented the damage acid water causes for surface and groundwater systems. Sources of acid coal mine drainage pollution in Appalachian active and inactive mines number 66,500 (3). This mine drainage results in approximately 10,500 miles of streams with water quality below desirable levels.

Metals mining can result in a diffuse source of pollution from multiple piles of waste rock and tailings. Each mine portal, or opening, has mounds of rocks from the mine workings. Some of the material is waste rock from the mine and some is the result of crushing and sorting rock to obtain the ore. In the Rocky Mountain region, it is not unusual to see hundreds of small mines in an area of a few square miles, each with mine tailings piles. Once in piles, the waste material is exposed to the atmosphere and water such that the remaining sulfide ores can be oxidized. In addition, the broken and crushed rock offers a large surface area for the chemical and biological reactions. Emerick (personal comm.)² estimates that thousands of kilometers of waterways are contaminated by residuals of metal mining in Colorado alone.

Water contaminated with acid mine drainage may not be suitable for drinking, livestock watering, support of wildlife, irrigation, or industrial use. Effects can be associated with cadmium, copper, lead, arsenic, and zinc as well as antimony, arsenic, beryllium, chromium, nickel, silver, thallium, uranium, radium (from uranium mine tailings and phosphate mines), and selenium.

Metal Wastes Pollution Control

Pollution control in the U.S. mining and metals industry is a major factor in any mining operation. This was not always the case. Public demand for action resulted in mining legislation to prevent damage to mined lands.

¹ Much of this paper is based on information from research and development studies performed in the laboratory, from the Big Tunnel Pilot system, and from the Eagle Mine in Minturn, CO (research supported by Paramount Resources, through Dames and Moore, Inc.) by Colorado School of Mines personnel. The documentation can be located primarily in Masters and Doctorate thesis of graduate students at the Colorado School of Mines. In particular, the paper makes significant use of results from studies by Toshisuke Ozawa, Mark Willow, Mary Lanphear, Julia Reynolds, Margaret Staub, JoAnn Euler, Peter Lemke, Steven Machemer, and Judy Bolis

² Personal communication with John C. Emerick, Colorado School of Mines, Division of Environmental Science and Engineering, Golden, CO (1989).

Today federal legislation is in place, and nearly every state has enacted statutes and regulations concerning mining and mined land reclamation. To conform to these regulations, the mining industry has developed and continues to develop pollution control measures and treatments. Nearly \$1 million is spent each day on acid mine drainage prevention and abatement by mining companies throughout the United States (4).

Removal of metals can be facilitated by neutralization using a hydroxide precipitate-caustic soda treatment. Often, chemical neutralization is accomplished with slaked lime or calcium carbonate added directly to the water (5). Also, an in-line aeration and neutralization system (ILS) has been developed that incorporates the chemical treatment processes into a functionally closed system in which the treatment reactions can be more closely monitored and accelerated. This system makes possible the reduction of the chemical reagent costs and reaction processing times (6). Electroprecipitation processes accomplish similar results by the precipitation of metal hydroxides or by metal ion adsorption (7). All of these processes, both chemical and physical, are severely limited, however, in that they cannot be used to treat the sometimes excessive sulfate concentrations associated with most acid-mine drainage; also, these processes impart a high degree of hardness to the water and produce waste sludge that requires additional treatment and/or disposal (8). These methods also can require large capital operations and maintenance costs. Precipitation operations must be perpetual, and the resulting high volumes of sludge must be disposed of in increasingly space-limited hazardous waste repositories.

Passive Mine Drainage Treatment Systems

Treatment of acid mine drainage using artificial and natural wetlands is a promising new approach. The focus of these PMDTSs (9) is to apply biogeochemical water treatment mechanisms at or near the source of the mine drainage to concentrate and immobilize metals and raise pH. Prototype PMDTSs have been constructed in Colorado, Pennsylvania, and West Virginia. Eger and Lapakko (10) estimated that PMDTSs required less than one-half the capital costs and one-twentieth the maintenance costs of conventional plants.

Past PMDTS technologies were based on constructing shallow ponds or cells that resembled natural wetlands. These systems were filled with peat or another organic substrate. Cattails, sedges, and rushes were then transplanted from natural wetlands. Approximately 400 constructed wetland treatment systems have been built in the United States (11).

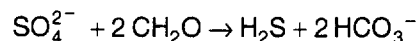
PMDTS Evolution and Limitations

Klusman and Machemer (12) listed the major metals removal processes in a PMDTS system as follows:

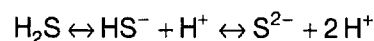
- Adsorption and complexation of metals by organic substrates
- Microbial sulfate reduction followed by precipitation of metals as sulfides
- Precipitation of ferric and manganese oxides
- Adsorption of metals by ferric hydroxides
- Metal uptake by plants
- Filtration of suspended and colloidal materials

The following discussion focuses on the evidence for metal removal and a pH increase in the PMDTS by the mechanisms listed above. The evidence is used in combination with data from hydraulic studies to suggest design configurations and parameters.

Reynolds and coworkers (13) and Machemer (14) examined the chemical and biological processes in wetland treatment systems (PMDTSs) receiving acid mine drainage and found that the rate of sulfate reduction to sulfide was the most crucial parameter involved. This conclusion has been corroborated by additional research on the utilization of natural and artificial wetlands for acid mine drainage treatment (15,16,17,18,19). The activity of the sulfate-reducing bacteria in these systems controls the efficiency of metal decontamination (15,12). During respiratory processes, the sulfate-reducing bacteria oxidize simple organic compounds (represented by the chemical formula CH_2O), resulting in the formation of hydrogen sulfide and bicarbonate ions at the circum-neutral pHs of "optimal" sulfate reduction (19):



The electron donors for this reaction can include molecular hydrogen (H_2) and organic compounds such as acetate and lactate. The formation of bicarbonate indicates the ability of the sulfate-reducing bacteria to control the pH of their particular microenvironment (16,17). The form of the sulfide from the bacterially mediated sulfate reduction is dependent on the pH of the reaction and is represented by the equilibrium:



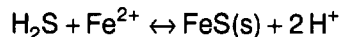
Both HS^- , which occurs at neutral pH, and S^{2-} , which occurs at high pH, are soluble in water, while H_2S , the predominant form at low pH, is not soluble and tends to evolve from solution, even at neutral pH where it is at equilibrium with HS^- .

The bicarbonate ion formed during sulfate reduction will equilibrate between CO_2 , HCO_3^- , and CO_3^{2-} . The predominant form at the "optimal" pH range for dissimilar sulfate reduction, however, will be the bicarbonate ion. This rise in pH will facilitate the hydrolysis and precipita-

tion of some contaminant metals from acidic waters as insoluble hydroxides and oxides (1,21):



The hydrogen sulfide created during the reduction reaction also will react with many metal species, forming insoluble metal sulfide precipitates:



These processes all contribute to the removal of contaminant metals from wastewaters through the action of sulfate-reducing bacteria.

Other processes that may contribute to metal removal within these systems include the precipitation of ferric hydroxides and manganese carbonates, the subsequent adsorption of metals by the ferric hydroxide, adsorption to the organic substrate, and the physical removal of colloidal particles through filtration by the substrate matrix.

To thrive, sulfate-reducing bacteria require a strict anaerobic environment (they are obligate anaerobes) with a pH in the range of 5 to 8 (21). When pH and/or redox conditions are not optimum, the rate of microbial sulfate reduction declines. This in turn reduces metal removal capacity. The rapid influx of acidic, aerobic waters appears to drive the pH of the treatment system down and redox up, thus inhibiting bacterial sulfate-reducing processes. The metal removal efficiency and loading capacity of the treatment system then becomes a function of not only size and hydraulic conductivity, but of the acidity and oxygen content of the influent water (15).

Results, Evidence, and Implications

The Role of Vascular Plants in the PMDTS

Many studies in the late 1980s either focused on plants or assumed plant uptake of metals was an important process in metal removal (22,23,24). Girts and Kleinmann (11) suggested that metal removal was mediated by plants and bacteria. Such was the emphasis on plant removal processes that Guntenspergen and associates (23) evaluated 1,000 plant species. Considerable emphasis was placed on cattail species, a plant found in most wetlands that is particularly resistant to poisoning by heavy metals and low pH (24,25,26). At the Big Five Tunnel Pilot system in Idaho Springs, Colorado, cattails not only dominated the PMDTS, but almost completely outcompeted the other plants and formed very high biomass densities. Evidence indicates, however, that plants account for as little as 1 to 5 percent of metal accumulation. Evidence for uptake of metals into the root, stem, and leaves of plants suggests no net uptake of metals over the period of the experiments (25,27,28,29). A possible, but not statistically supportable, increase in

plant tissue metals occurs for some metals, but that is probably within the range of analytical and sampling error. As much evidence exists indicating decreasing metal concentrations in the plants. In addition, one 3 by 3 by 1 meter unit at the Idaho Springs site was covered with hay and a black, opaque liner. It proved to be the most successful design for removing metals.

Although plants may not accumulate metals, they may promote metal removal by generating microzones of oxidizing or reducing conditions in the organic substrate. Microzones around the root mass may be more aerobic due to oxygen excretion (25), inducing precipitation of manganese iron as Fe(III). The process of manganese and iron oxide formation may be a removal mechanism for the metals, but it occurs in only 2 percent of the volume of the system. The remaining 98 percent of the system is anaerobic. Thus, plants are not the dominant removal mechanism for metals.

Adsorption and Complexation Processes in Metal Removal

Adsorption is a process in which a cation like Fe^{2+} is bound to the solid phase that contains a residual negative charge on its surface (usually in the form of a hydroxide ion). Complexation is the result of humic materials terminating in phenolic and carboxylic groups that dissociate under particular pH conditions. Kerndorf and Schnitzer (30) found that the strength of sorption to humic materials varied with metal species as follows:



The adsorption process also varies with pH.

For natural and constructed wetland systems, metal removal due to adsorption takes place until sorption sites are saturated. Thus, the system will have a fixed life-cycle, perhaps as short as a month (14,15). When sulfate-reducing bacteria activity was terminated by poisons specific to their systems, Willow (15) reported that all metals were removed by the organic substrate for approximately 20 days, then manganese, zinc, copper, and iron started breaking through to the effluent (Figure 1). Cadmium, manganese, and zinc containing inflow was fed to organic substrate that had no sulfate-reducing bacteria activity. All metals were adsorbed to the substrate for the equivalent of 20 days. The most weakly sorbed metal, manganese, was displaced from the sorption sites first and demonstrates breakthrough starting at 55 volumes. The next most weakly sorbed metal, zinc, begins breakthrough at 75 volumes (15).

The interpretation of the data is that competition occurs for the sorption sites, particularly after the sites are saturated. Iron and copper, which bind to the particles more strongly than zinc and manganese, cause desorption of the zinc and manganese. Therefore, in 20 to 30 days,

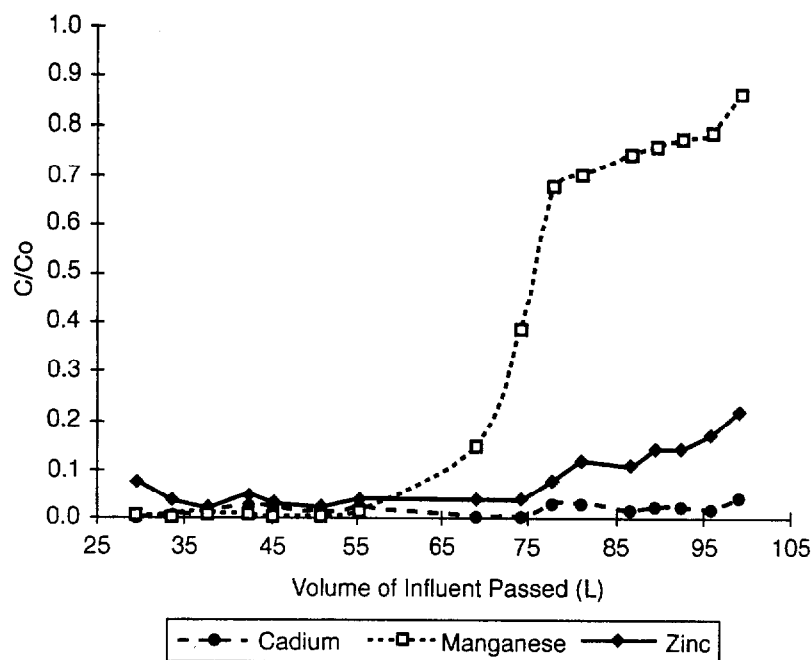


Figure 1. Breakthrough of manganese, followed by zinc, from wetland system to the effluent after saturation of sorption sites (15).

the sorption sites were saturated. Thus, sorption processes are not the removal mechanism of choice if the PMDTS is to have a multiyear life-cycle.

Sulfate-Reducing Bacteria

Sulfate-reducing bacteria (SRB) are obligate anaerobes that decompose simple organic compounds using sulfate as the terminal electron acceptor. The result is the production of sulfide that may be given off as H_2S gas or react with metals to form metal sulfides. Much of the following comes from a review by Staub (17). As discussed in the Introduction, SRB reduce sulfate to sulfide, followed by precipitation of metals as metal sulfides. FeS is one of a family of compounds called acid volatile sulfides (AVS). These compounds will generate H_2S with the addition of acid. Reynolds and investigators (13) reported that the dominant forms of sulfur resulting from SRB activity in the PMDTS are H_2S , dissolved S^{2-} , and solid AVS. Reynolds and coworkers also noted that H_2S is present in small quantities when influent metal loadings are high, resulting in AVS being the major form (over 90 percent). Herlihy and Mills (31) also reported that most of the sulfide readily reacts with metal ions to precipitate them as metal sulfides.

Hedin and associates (32) have suggested that a good estimate for rates of sulfate reduction is 300 nmole S-produced per cubic centimeter per day. Reynolds and investigators (13) reported typical levels to be 600 to 1200

nmole/ cm^3 /day using both radiolabeled tracers and measurements of rates of production of AVS (Table 1).

These numbers permit the calculation of theoretical treatment capacities of the PMDTS if one assumes that most removal of metals can be accounted for by sulfate reduction and the metals are removed on a one-to-one molar basis as AVS. Reynolds and coworkers (13) reported that sulfate-reducing activity could account for all of the removal of metals in the Big Five Tunnel PMDTS. In addition, work at the U.S. Bureau of Mines and Colorado School of Mines demonstrated that as metals were removed, pH increased and alkalinity increased (33,34). This is not unexpected because bicarbonate is produced and the loss of H_2S gas represents a loss of hydrogen ions.

Updegraff (personal comm.)³ and Reynolds and coworkers (13) reported experiments examining the effects of substrates and other variables of SRB activity. They used many different substrates, including spent mushroom compost, peat, corn wastes, rice waste, decomposed wood chips, and composted cow manure. Results from the Big Five Tunnel PMDTS showed that peat-based systems were ineffective, even when limestone was added (35). The wood chips and cow manure gave the highest activity rates, with other materials often yielding

³ Personal communication with David Updegraff, Colorado School of Mines, Chemistry and Geochemistry Department (in transitional retirement) (1992).

Table 1. Results of Isotopic and Acid Volatile Sulfide Analyses of the Rate of Sulfate Reduction in Samples Taken From a Pilot-Scale System(13)

Rates of Sulfate Reduction (nanomoles of S^{2-} per cm^3 of substrate per day)

Isotopic Method ^{35}S			
Location Sample Taken in Reactor	Date	Rate	% Standard Deviation (number of samples)
Surface	10/90	600	10.9 (4)
Bottom	11/90	440	10.4 (3)
Surface	11/90	750	8.6 (6)
Control	11/90	12.2	29 (3)
AVS Method			
Surface	11/90	670	35 (6)

near-zero activity. Decomposed wood chips and composted cow manure also had the highest buffering capacity and pHs of the tested substrates. When pH-raising additives and alkalinity were included in the poor substrates, activities of SRB increased substantially. Reynolds and coworkers (13) also found that water extracts of hay could increase sulfate reduction 2.5 to 7 times. SRB cannot utilize complex organics, however; they require simple organics such as acetate and lactate. Indeed, additions of these nutrients enhanced SRB activity (13). A consortium of heterotrophic bacteria probably exists in the substrate that decomposes complex organics into forms available to the SRB. That possibility is being studied in the laboratory at the Colorado School of Mines.

Lemke (36) found that biofilms clog the pores of substrates used in horizontal flow units, regardless of the size or amount of amendments. Cohen and Staub (16) used composted cow manure and hay in a 4:1 by volume ratio. The substrate used by Cohen and Staub was able to efficiently (98 to 100 percent metal removal) treat between 4 and 8 times the mine drainage flow rates of previous systems used in the Rocky Mountain region. The advantages of using cow manure and hay can be seen in the section on sulfate reduction. The manure pH was 8 to 9 and it had high buffering capacity. The hay has been demonstrated to enhance SRB activity by 250 to 700 percent. The composted manure can neutralize the pH of the mine drainage. The organic matter in the manure encourages decomposition and generation of low redox potentials and serves as an SRB nutrient source. Thus, ideal conditions are presented to the SRB until they can modify their own microenvironments.

Structural and Hydraulic Considerations

The Big Five Tunnel system in Idaho Springs was constructed in a horizontal flow pattern similar to natural wetlands and other constructed wetland-like systems. Lemke showed that hydraulic conductivity of the substrate decreased two to three orders of magnitude in a few weeks (36). As a result, very small quantities of wastewater passed through in contact with the substrate and most of the water flowed untreated over the surface of the system. The system was reconfigured to force the water through the substrate (35). Lemke (36) showed that upflow systems retained their hydraulic conductivity and guaranteed wastewater contact with substrate. A cell of the Big Five Tunnel PMDTS was divided into an upflow cell and a downflow cell. The upflow cell substrate remained saturated throughout the experiments and treated mine water efficiently. The downflow cell worked well, but flows that were too low followed channels through the substrate and a large percentage of the substrate remained dry and unutilized. The upflow configuration seems to fulfill the requirement of steady hydraulic conductivity and water substrate contact. A schematic of an upflow reactor is shown in Figure 2.

Five-hundred-gallon upflow reactors were constructed in one area of the Eagle Mine at Minturn, Colorado, and filled with composted livestock manure. The influent distribution pipe, made of perforated irrigation tubing, was protected against clogging by the particulates in the substrate. In the 500-gallon pilot system, the influent pipe was covered with pea gravel and landscape fabric, which in turn was covered with a water-permeable geomembrane (Figure 3). The gravel disperses the inflow and the geomembrane separates the influent chamber from the substrate. Larger systems may require the construction of an influent plenum that is covered with a geomembrane.

Results of the Pilot-Scale Experiments

Research at the Colorado School of Mines has demonstrated that SRB activity is approximately 600 nanomoles of sulfide produced per cubic centimeter of substrate per day. Calculations based on the metal-loading rates at the Eagle Mine and the 37 cubic feet of substrate of the PMDT indicate that the system should theoretically reach its limit of metal removal at a flow of between 200 and 400 mL/min. Maximum removal rates of 97 to 100 percent have occurred for all metals except for manganese at the 200 mL/min and 400 mL/min flow rate (Figure 4).

A dramatic decrease in metal removal efficiency seemingly occurred for iron, zinc, lead, copper, and cadmium on two dates noted on the graphs. On or before August 27, an inflow valve to the system inadvertently was turned up to very high flows, flooding the system at levels significantly beyond its treatment design limits. Prior to October 28, a backup of untreated water into the system

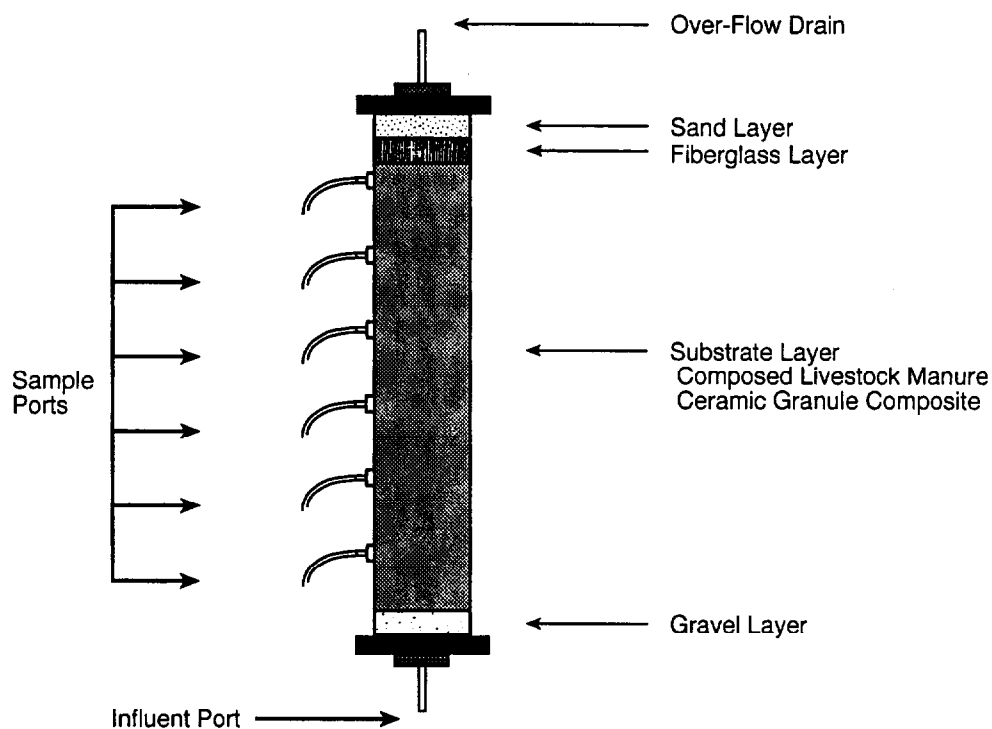


Figure 2. Construction of 1.5 meter, 15 centimeter diameter experimental reactor. Gravel layer separates substrate from distribution tubing. All sampling ports extend the entire diameter of the unit with perforated tubing covered with permeable geomembrane.

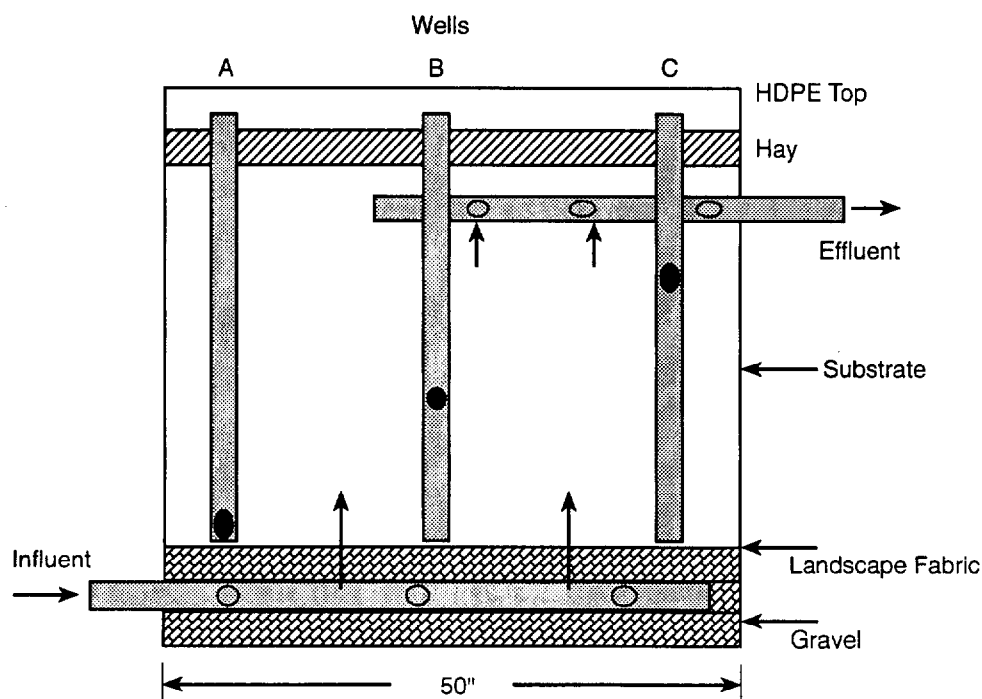


Figure 3. Construction of pilot-scale reactor (total reactor volume is 500 gallons).

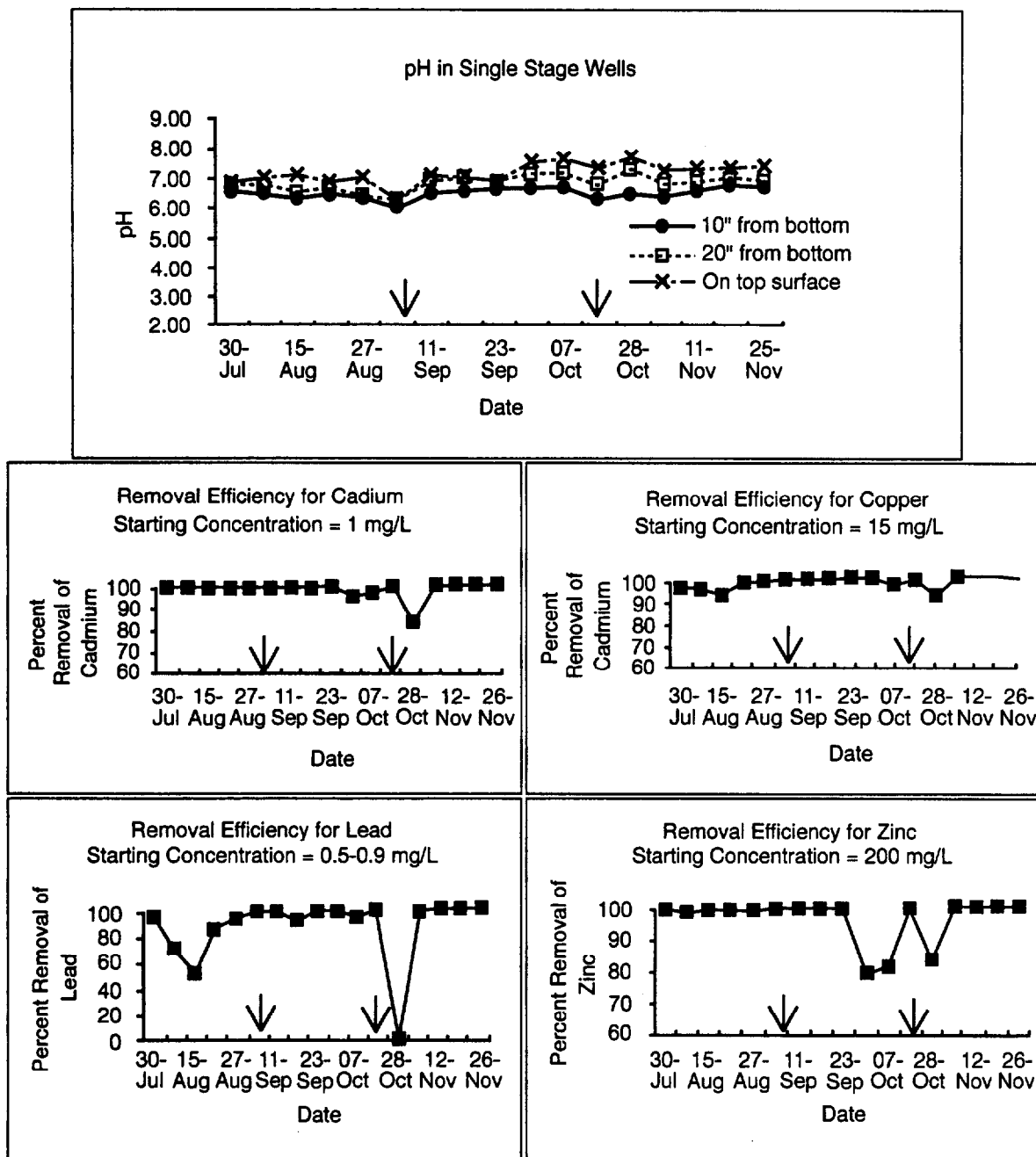


Figure 4. Removal efficiency for iron, zinc, lead, copper, cadmium, and manganese in the Eagle Mine Pilot PMDTS. Arrows show where flow was doubled. Regions of low treatment efficiency were due to backup of untreated water into the treated water area or sudden, inadvertent surges of flow caused by mine personnel.

occurred. The drain to which overflowing, untreated water is discharged was clogged with metal hydroxides. This water backed up and mixed with the treated water near the sampling point. Evidence that this backup was not a failure of the system's treatment capability was demonstrated in that by the following week treatment efficiencies for all metals except manganese were again near 100 percent. Flows were doubled from 50 to 100 mL/min on September 3 and from 100 to 200 mL/min on October 15. Near the end of the study, flows were doubled to 400 mL/min. The times of flow adjustment are shown as arrows in Figure 4.

Further Improvements

Until PMDTS optimization research and development reduced hydraulic detention times required for 99 percent or better metal removal rates to 40 hours or less (16), PMDTSs were constrained in their volume/discharge handling capacity. Older PMDTSs could treat metal waste streams effectively (99 percent or greater removal) for hydraulic detention times of 250 to 300 hours, or remove 40 to 70 percent of metals at shorter hydraulic detention times.

To have high sulfate-reducing activity, and therefore a system with high metal removal capacity, the sulfate-reducing bacteria require a strict anaerobic environment (they are obligate anaerobes) with a pH in the range of 5 to 8 (22). When pH and/or redox conditions are not optimum, the rate of microbial sulfate reduction declines. The rapid influx of acidic, aerobic waters appears to reduce the pH of the treatment system and increase redox, thus inhibiting bacterial sulfate reduction. The metal removal efficiency and loading capacity of the treatment system then becomes a function not only of size and hydraulic conductivity, but of the acidity and oxygen content of the influent water. One of the limiting factors appears to be the pH of the influent water (15).

A second possible limiting factor in the PMDTS at higher inflow rates is the introduction of dissolved oxygen to the system by the acid mine drainage (AMD). An increased loading rate of oxygen would reduce the capacity of sulfate-reducing bacteria, which require anaerobic conditions, to produce hydrogen sulfide. With a greater influx of dissolved oxygen, one may assume that redox would increase, sulfate reduction would decrease, and metals treatment capacity would decrease. If the dissolved oxygen content of the influent mine drainage could be reduced prior to entering the treatment system, the anaerobic conditions could be maintained for a greater volume of the treatment substrate, thus allowing for an increased influent treatment capacity.

Experiments at the Colorado School of Mines have shown that pH is more critical to reactor efficiency than dissolved oxygen. The metal-loading rate capacity of a

wet-substrate bioreactor can be enhanced and hydraulic detention times reduced to as low as 16 hours by modifying the pH of the influent to near neutral (15). The neutral pH permits enhanced activity of SRBs, the production of sulfide, and the removal of metals as metal sulfide precipitates. The dissolved oxygen was completely removed in the first few centimeters upon entering the reactors, while the pH required a greater proportion of the substrate to reach suitable levels for SRB activity. As the pH of the influent increased, the rate of sulfate reduction increased, raising the metal removal capacity of the system.

Treatment of Oxyanions such as Arsenate and Chromate

Not all metals appear as positively charged cations. Some appear as negatively charged oxyanions with metals such as arsenic, selenium, and chromium bound to oxygen to yield arsenate, selenate, selenite, chromate, and chromite. Can an anaerobic bioreactor dominated by SRBs remove metal oxyanions? A pilot-scale, anaerobic PMDTS dominated by sulfate-reducing bacteria was utilized to investigate the removal rates as well as removal processes of arsenic and chromium in a wastewater and/or acid mine drainage. A computer modeling code, MINTEQA2 (37), modified from MINTEQA2, was utilized for the inverse modeling of the bioreactor. Ninety to over 99 percent of the arsenic and 86 to 94 percent of the chromium were removed (20). Cadmium, copper, iron, lead, and zinc also were removed from the feedwater. Several mechanisms could account for arsenic and chromium removal. We believe that the primary mechanism is microbial sulfate reduction, resulting in production of high concentrations of hydrogen sulfide and bicarbonate ion. Experimental evidence and inverse modeling with MINTEQA2 confirmed that most (90 to 95 percent) of the removal of arsenic and chromium occurred in the first quarter volume of the bioreactor. Additional removal of target metals could still occur in the remaining volume of the bioreactor. The investigation also supported the contention that removal was the result of the reduction of Cr(VI) to Cr(III) by hydrogen sulfide, followed by precipitation of chromium hydroxide $[\text{Cr}(\text{OH})_3]_{(s)}$, and reduction of As(V) to As(III), followed by precipitation of arsenic sulfides (As_2S_3 or AsS). The use of a PMDTS was effective for wastewater and acid mine drainage with elevated concentrations of arsenic and chromium.

Summary, Conclusions, and Design and Construction Recommendations

The final design and construction decisions will be based on the flow rate to be treated, the loading rates of metals, and the space available for the bioreactor. The decision whether to use vegetation should be based solely on aesthetic and erosion considerations, not on a belief

that vegetation is a major contributor to metal removal or system longevity. Once operating, one can expect an effective life of 4 to 6 years from a single load of substrate, based on experience at the Big Five Tunnel. At the end of the system's life, the concentrated AVS must be disposed of as a Resource Conservation and Recovery Act (RCRA) waste or recovered from the organic substrate. Future work is required to determine if recovery can be sufficiently efficient to justify recycling the metal values from the laden sludge.

Mass Loading Rates of Metals

Metal concentrations must be converted from mass/volume (mg/L) to moles/L. Then:

$$\text{moles/d} = Q \times c,$$

where

Q = discharge in volume/time (L/d), and

c = concentration, mass/volume (mg/L).

For example, at the Eagle Mine, the mass loadings for the major metals was 1.49 moles metals/d for 100 mL/min and 2.97 moles metals/d for 200 mL/min. Once metal-loading rates are known, the total volume of substrate required must be determined using estimated SRB activity. At the Eagle Mine, the substrate volume was 2.46×10^6 cm³. The estimated sulfide production rate based on our own study results and literature values range from 300 to 1,200 Nm S⁻/cm³/d. Therefore moles of S⁻ produced/d = V (volume of substrate) \times SRB activity rate (mass/volume/d), and for this system the sulfide produced should be 0.74 to 2.95 moles S⁻/d. Waters with lower metals concentrations than the Eagle Mine water, such as the effluent at the Big Five Tunnel (i.e., an order of magnitude lower concentrations), could either be treated with a smaller system or with higher flow rates.

Alternatively, and perhaps even better, assume an empty bed hydraulic residence time of 20 to 40 hours. Forty hours would be used if the feedwaters were below pH 5 and 20 hours if the feedwaters were near neutral pH.

Configuration to Minimize Hydraulic Problems and Maximize SRB Activity

The upflow configuration has been shown to pose the least hydraulic problems of systems studied. Construction is more complicated than for horizontal flow systems, but hydraulic conductivity or surface flow problems are fewer. The water is forced into contact with the substrate. Downflow units are possible but require careful control of flow rates. If flow is too high, water pools on

the surface. If flow is too low, water moves through channels, leaving most of the substrate dry and unused.

Distribution pipes in the upflow configuration require protection against contact with the substrate. Two possible solutions are:

- Distribution pipes can be buried in pea gravel (or similar material), then covered with a geomembrane or landscape fabric.
- A plenum can be built to house the distribution system. The plenum is covered with landscape fabric or a geomembrane. The substrate then is placed upon the geomembrane.

If a system is to be passive, the driving force for the mine water is hydraulic head. Recent work suggests that 3 meters of head will drive water through the system for the long term, although less head may suffice. Systems have been built with valve control of flow rates. Globe and ball valves rapidly clog with hydroxide precipitates and need frequent maintenance. Butterfly and gate valves seem to clog less frequently but need periodic (weekly) adjustments and cleaning. The higher the flow maintained through the system, the less frequent are the requirements to remedy clogging and flow rate adjustment. The Eagle Mine system uses a constant head tank to control flow to the reactors.

The reactor tanks can be made of high-density polyethylene (HDPE) or similar plastic, or the reactor can be made of a wood or concrete support structure covered by an HDPE liner. The Big Five Tunnel system uses a concrete base and a Hypalon liner. If tailings ponds or tailings dams are available, they can be lined and fitted as a PMDTS. The Eagle Mine research also suggests that units can be run in series and will act as a single larger unit. The possibility exists of constructing units to run in parallel. The result would be a group of smaller, easier-to-access units.

Because maintenance is a consideration, one should configure plumbing to be as accessible as possible. Ports could be designed to access distribution pipes for cleaning and unclogging. Pipes should be oversized to reduce clogging by sediments of frozen water. All delivery and effluent systems should be buried or insulated to minimize frozen pipes.

Substrates

The preceding sections suggest that composted cow manure, mixed with hay, is a good substrate. This substrate supplies acid neutralizing capacity to bring pH into the ideal range for SRB and organic nutrients for growth of the complex microbiological consortium that develops in PMDTS.

The hay also can act as a bulking agent, helping to maintain hydraulic conductivity. We have found that porous ceramics used as a bulking agent for enhanced drainage on golf courses and athletic fields, when mixed in a ratio of 9 units of substrate to 1 unit of bulking agent (7.5:2.5 is even better for hydraulic conductivity), is considerably better than hay for long-term permeability. In the Colorado School of Mines studies, we used Turface and Profile. This is not to say that it is the best or only substrate for this purpose. Decomposed wood chips act in a similar fashion. Additions of simple organic compounds, such as lactate, are known to enhance SRB activity. They can be added to the solid organic substrate by a feed mechanism. In fact, the future may bring active, batch units filled with liquid nutrient media to which mine drainage is added for the requisite contact period and AVS precipitated in a clarifier. Other substrates, such as peat and "mushroom compost," have been shown in both the laboratory and field to be inferior to composted cow manure. They lack the buffering capacity or nutrient composition to efficiently enhance SRB activity. Substrate amendments, such as potting soil, dilute the nutrient and buffering capacity of the manure and do not appreciably enhance hydraulic conductivity.

Problems are associated with any organic substrate, be it manure or wood chips, because a dissolved organic carbon (DOC) component is leached from the system. Also, nitrogenous materials such as nitrate or ammonia might occur in the effluent. A plant-based polishing treatment step might be required to bring the effluent to standards.

Ultimately, an efficient, long-lasting, low-sludge-generation, inexpensive, low-maintenance system can be constructed to treat metal-laden and acidic (or neutral) wastewaters.

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Chapter 6.

Cyanide Biotreatment and Metal Biomineralization in Spent Ore and Process Solutions

Leslie C. Thompson

Introduction

Cyanide and heavy metals are by-products of gold and silver production and are the focus of regulatory, legislative, and public scrutiny concerned with reforming mining laws and operations. Thus, the development of economical and effective treatment processes for mine waste remediation is a critical issue facing the mining industry. Bioremediation processes for cyanide detoxification and metal immobilization or remineralization are emerging as both cost-effective and efficient treatment technologies.

Metals in leachate solutions originating from mining operations or acid mine drainage are one of the major environmental problems facing the mining industry today. Sulfide and oxidized ores exposed during mining operations have the potential to produce leachate solutions that contain high concentrations of dissolved metals. Metal leachate solutions can affect the quality of plant and animal health in surface water used for agriculture, recreation, and human consumption. The problem posed by these leachate solutions arises in historical and inactive mining districts as well as current mining operations where containment of metal solutions in leach heaps or waste rock can require perpetual monitoring and permanent containment.

Pintail Systems has developed biological detoxification processes for the decomposition of cyanide in spent ore and process solutions and applied them at several gold mines. This paper includes summaries of case studies for three of these mines. In each case, the primary goal was to biologically detoxify cyanide to meet closure requirements at the end of the mine's operation. Secondary treatment goals included enhancing precious metal production during detoxification and removing or remineralizing soluble heavy metals.

Technology Description

Cyanide Biotreatment

Cyanide compounds are formed and transformed in nature in a global mineral cycle. Cyanide is naturally present in the biosphere in simple and complexed forms, and numerous industrial processes use or produce cyanides. In recent years, a variety of simple bacteria have been identified that can use cyanide as a nutrient for cell-building reactions (1). Although cyanide is extremely toxic, even in small doses, to many terrestrial life forms, these primitive bacteria are able to take cyanide compounds into the cell and use the carbon and nitrogen from the cyanide as the basic building blocks for production of amino acids and proteins in the cell. Using bacteria for biodegradation of cyanide wastes from electroplating operations was proposed as early as 1956 (2). Mining industries in both the Soviet Union (3,4) and the United States (5) have developed microbial treatment schemes for cyanidation wastewaters.

Cyanide and cyanide compounds were important components in the chemical evolution that occurred in the earth's oceans and atmosphere before life formed (6). This chemical evolution in the prebiotic earth likely was necessary for the appearance of the first protolife and primitive life forms. The development of early life forms suggests that these organisms would have been able to live and flourish in the presence of cyanide. Primitive bacteria could have used cyanide compounds as a source of carbon or nitrogen for cell-building reactions (7). Recent research has demonstrated that various amino acids, purines, and pyrimidines can be formed from hydrogen cyanide precursors (8). Additional tracer studies using radiolabeled cyanide have confirmed that the purines adenine and guanine and the pyrimidines

cytosine and thymine can be synthesized in bacteria cells from cyanide raw materials (9).

Prokaryotic bacteria are defined as the simplest single units of life. They do not have a membranebound nucleus, contain only one chromosome, and do not have any cell organelles. These simple bacteria exhibit a great metabolic diversity and are ubiquitous in both normal and extreme environments.

The reaction sequence in bacteria for cyanide oxidation is summarized in the following equations:

1. $2\text{Fe}(\text{CN})_6^{4-} + 29\text{H}_2\text{O} + 6.5\text{O}_2 \rightarrow 12\text{CO}_3^{2-} + 12\text{NH}_3 + 2\text{Fe}(\text{OH})_3(\text{s}) + 16\text{H}^+$
2. $\text{M}_x\text{CN}_y + 2\text{H}_2\text{O} + 0.5\text{O}_2 \rightarrow \text{M/bacteria} + \text{HCO}_3 + \text{NH}_3$
3. $\text{NH}_3 \rightarrow \text{NH}_2\text{OH} \rightarrow \text{HNO?} \rightarrow \text{NO}_2 \rightarrow \text{NO}_3$
4. $\text{NO}_3 \rightarrow \text{NO}_2 \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2$

Biological remediation of cyanide mine waste is accomplished by introducing cyanide-metabolizing bacteria to a waste source or stimulating indigenous bacteria by adding nutrients. The bacteria chosen for field cyanide treatment of spent ore at various mines are isolated from the spent ore heap and process solutions. Some of the species that are known to oxidize cyanide include species of the genera *Actinomyces*, *Alcaligenes*, *Arthrobacter*, *Bacillus*, *Micrococcus*, *Neisseria*, *Paracoccus*, *Pseudomonas*, and *Thiobacillus* (10).

The biological cyanide detoxification process consists of isolating native cyanide-oxidizing species from cyanide-leached spent ore. For successful cyanide biotreatment in spent ore solids and process solutions, the natural detoxification ability of the microorganisms must be augmented and the augmented bacteria and nutrients must be applied to spent ore in process solutions. Each mine has site specific and waste-specific chemistry that requires that biotreatment processes be individually engineered for the particular waste treatment. Every field biotreatment design consists of laboratory, pilot, and field test programs. For each field design, process development includes the following elements:

- Isolate native bacteria from mine site waste environments.
- Test native bacteria for natural waste treatment capacity.
- Augment natural detoxification processes by:
 - Eliminating nonworking portions of the back ground population.

- Putting the detoxification population under stress in waste infusion and chemically defined media.
- Preserving the detoxification population.
- Define nutrient requirements for lab, pilot, and field bacteria production.
- Test the detoxification potential of augmented bacteria in column, batch, or continuous treatments.
- Design field treatment process:
 - Field bacteria production nutrient requirements
 - Staged bacteria culture production design
 - Bacteria application to process solution design
 - Environmental safety review
 - Operator training program design
- Mobilize for field treatment operation.
- Grow treatment bacteria at site in staged culture system.
- Apply bacteria to spent ore and process solutions.
- Monitor treatment.

Biological processes for cyanide detoxification in mine waste have many advantages over conventional chemical treatment options for spent ore detoxification. These include:

- Low comparative treatment cost
- Shorter treatment time
- In situ treatment
- Complete detoxification
 - Ends long-term liability
 - Eliminates perpetual monitoring
 - Allows for natural revegetation
- Natural and nontoxic nutrients, by-products, and process end products

Metal Biomineralization

In addition to detoxification of cyanide and thiocyanate compounds, biological processes can be adapted to catalyze natural biomineralization reactions that immobilize soluble and leachable metals in the heap. Biomineralization is described as a surface process associated with microorganism cell walls where the

remineralization occurs. The biogeochemical activities initiated by microorganisms in ores, soils, surface, and ground-water environments can dominate the formation and transformation of those mineral environments. Soluble metals leaching from spent ore heaps and waste rock dumps presents a long-term environmental problem. Biological processes are the only technology that has demonstrated in situ remineralization and immobilization of leachable metals. Reactive minerals are transformed naturally to new mineral species that may dissolve to produce acidic leachate solutions containing soluble metals. Geochemical cycles forming metal leachate solutions can be accelerated as a result of mining activities.

Numerous species of bacteria, fungi, and yeasts are capable of accumulating many times their weight in soluble metals. Both living and dead biomass are effective in removing soluble metals from waste streams containing gold, silver, chromium, cadmium, copper, lead, zinc, cobalt, and others. Soluble metals also can be immobilized in soils by natural or engineered biomineralization reactions. Several commercial processes using biological reactions are being applied on an industrial scale for metal remediation. Bacteria found in natural and extreme environments have developed a wide variety of metabolic functions to adapt to these environments. These natural microbial functions contribute to global mineral cycling that continuously forms, transforms, and degrades minerals and metals in the environment.

Two basic mechanisms are involved in metal uptake by bacteria:

- Accumulation by surface binding to the bacterial cell wall or extracellular materials.
- Uptake into the cell for use in metabolic processes as necessary nutrients.

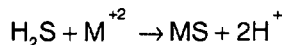
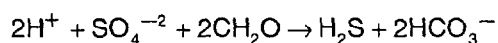
Surface reactions are accepted as the processes responsible for the majority of the remineralization reactions removing metals from solutions. Intracellular uptake of metals to meet the nutritional needs of the cell has a minor role in overall metal removal. Several cell surface reactions contribute to biomineralization:

- Complexation with organic compounds produced by the cell.
- Precipitation and ion exchange.
- Chelation by cell membrane components (e.g., pigments, polymers, cellulosic ligands, chitin).
- Remineralization from complex interaction with extracellular by-products of cell metabolism.

In addition to direct biological metal accumulation and remineralization reactions, microorganisms may catalyze other chemical and physical processes on micro- and macro-environmental scales that contribute to remineralization reactions. Examples of these reactions include:

- Production of hydrogen sulfide by sulfate-reducing bacteria that precipitates insoluble metal sulfides from solution.
- Reduction of available oxygen in the environment, thereby limiting biooxidation and acid rock generation reactions.

The reactions for sulfate reduction and metal sulfide precipitation are:



During biomineralization, a complex series of reactions are initiated by microorganisms. In the mine case studies, microorganisms were added to heap-leached ore and solutions. The metal remineralization process is catalyzed by biological processes alone and by biological processes initiating physical and chemical processes that cause an alteration of the microenvironment. During the course of the column and field treatment tests, a series of observations were made on the changing surfaces of spent ore. These observations are the basis of the following hypothesis for formation of biominerals:

- Bacteria added to the ore columns attach to the ore surfaces forming a "bioslime" layer.
- Soluble metals bind to cell walls and extracellular products excreted by the microorganisms (e.g., exopolymers, pigments, waste organics).
- Metal hydroxides, oxides, and carbonates are formed in the primary bioslime layer as amorphous mineral precursors. Curing, or maturation, of the amorphous slimes suggests that a molecular rearrangement of the hydroxy-metals to more stable forms occurs.
- Stabilization of the amorphous precipitates forms a remineralization nucleation crystal template for further mineralization to occur. The microenvironment alteration and bacteria metabolism continue to catalyze the remineralization by ongoing formation of organometallic compounds and precipitates as well as by transformation of metal oxidation states. The biomineralization appears to follow a sequential and "layered" development on many of the surfaces. Some of the possible minerals formed include calcite, gypsum, bornite, pyrite, and covellite.

Mine Site Biotreatment Case Studies

Hecla Yellow Pine Mine

The Yellow Pine Mine near Yellow Pine, Idaho, was the first full-scale demonstration of *in situ* biotreatment processes for cyanide detoxification in a spent ore heap. Located east of McCall, Idaho, the site elevation is approximately 6,500 feet (Figure 1). Approximately 1.3 million tons of agglomerated oxide ore were processed in a single-use leach pad stacked in lifts to a total depth of about 114 feet. The biotreatment process was begun at the end of March 1992 and was completed in September 1992.

The goals of the heap detoxification process were to:

- Reduce weak acid dissociable (WAD) cyanide from 47 to 0.2 mg/L in heap leachate solutions.

- Treat spent ore and process solutions to remove the cyanide point source.
- Complete ore and process solution treatment in one operating season.
- Enhance gold production during detoxification operations (secondary goal).

The site was a challenge for biotreatment processes due to low solution temperatures and extreme cold weather conditions throughout the operating season. Laboratory and pilot tests were designed to produce an augmented biotreatment engineered for site-specific conditions. A final test program was designed using native, augmented bacteria grown in a three-stage culturing system at the mine site. Bacteria and nutrients were transferred to the barren pond and applied to the spent ore heap in a drip irrigation system. The decrease in WAD cyanide was measured in preg pond solutions.

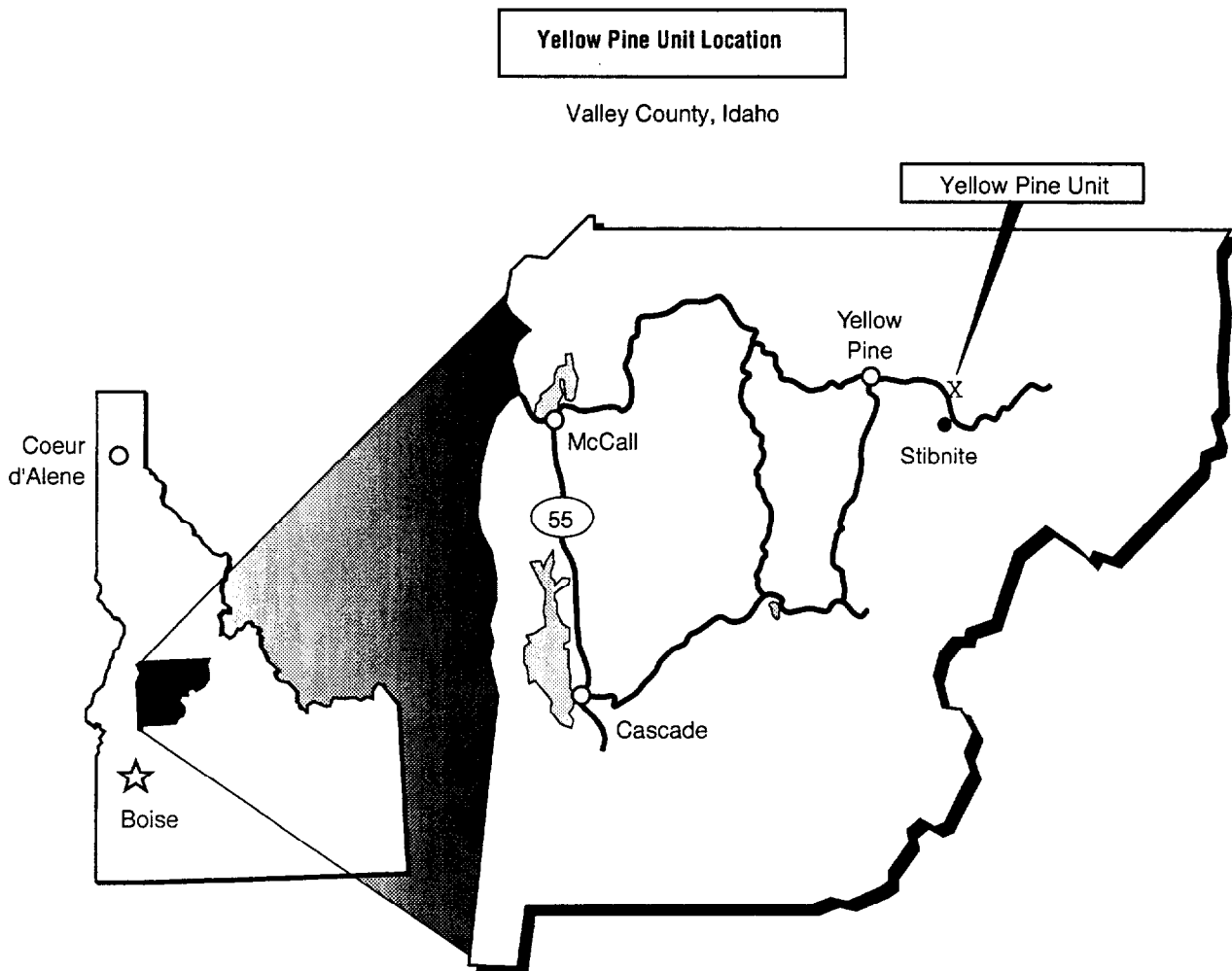


Figure 1. Site location map for Yellow Pine Mine.

The treatment results demonstrated complete cyanide detoxification in spent ore and process solutions after a 5-month treatment program. Less than 0.4 tons of treatment solution per ton of ore were applied during the 180-day process. Treatment time estimates for conventional chemical treatments (peroxide and sulfur dioxide/air) suggested two to four operating seasons for complete detoxification.

A secondary benefit of the biotreatment process was an enhanced gold production above predicted recoveries for water rinse operations. Biological solutions catalyze several biooxidation and biomineralization reactions that contribute to enhanced gold recovery. Biologically catalyzed processes include:

- Partial biooxidation of trace sulfides
- Biooxidation of gangue minerals, making gold more available for recovery
- Surfactant processes improving wettability of ore

Hecla Mining Company received the 1992 Industrial Pollution Award for the state of Idaho awarded by the Northwest Pollution Control Association for application of innovative and effective biotreatment processes. Additional awards include recognition from the U.S. Forest Service and the state of Idaho's Governor's Award.

A comparison of laboratory and field data is provided in Figure 2.

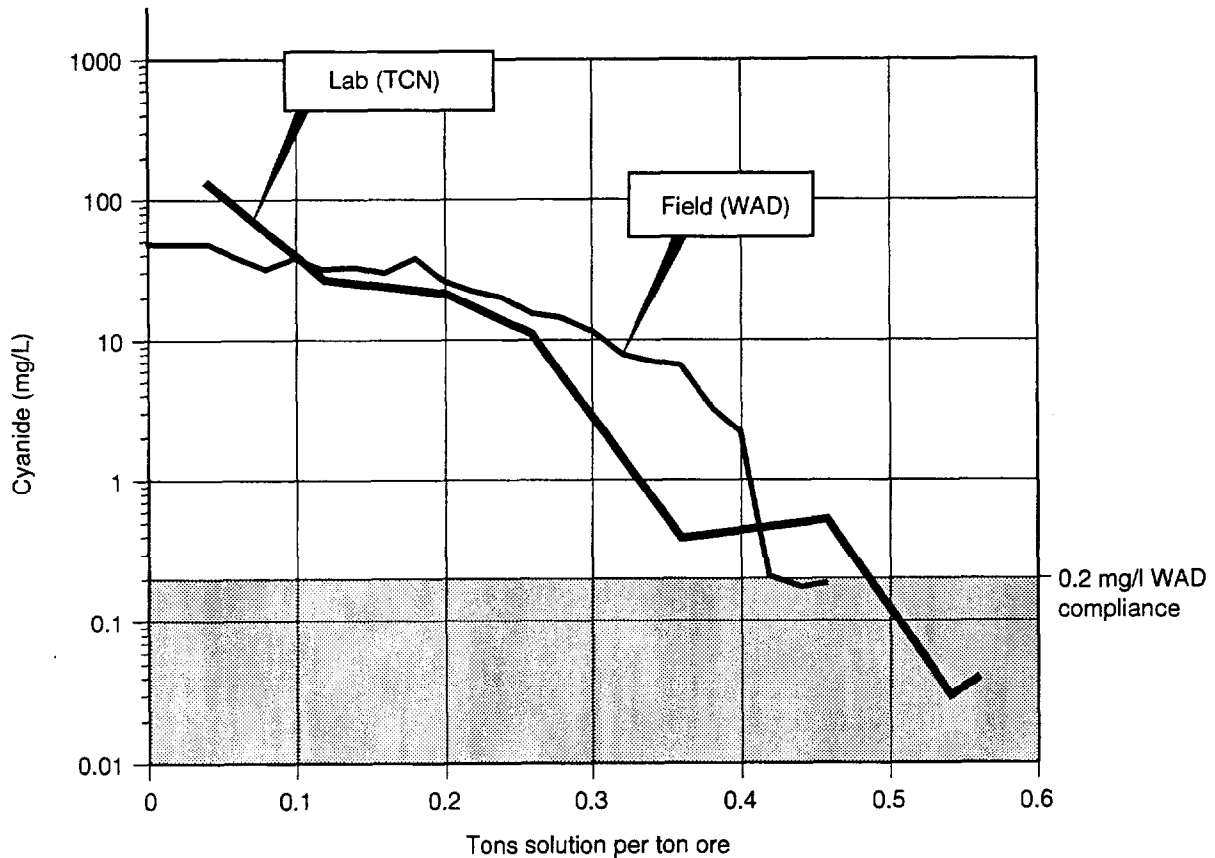


Figure 2. Comparison of laboratory and field data for Yellow Pine Mine cyanide biotreatment.

Cyprus Copperstone Mine

The Cyprus Copperstone Mine is located near Parker, Arizona (Figure 3). At this mine, 1.2 million tons of ore in a single leach pad were biologically treated between July and October 1993. The goal was to reduce WAD and total cyanide (TCN) from 30 to less than 0.2 mg/L in heap leachate solutions. A secondary treatment goal was to monitor soluble copper in process solutions. The biotreatment process was designed to be completed in less than 5 months. The treatment processes were projected to be faster at Copperstone due to high solution temperatures.

Development of a biotreatment process was similar to Yellow Pine's, including a laboratory and pilot testing phase to isolate and augment treatment bacteria. The treatment process was designed from pilot test data. Treatment bacteria and nutrients were transported to the mine site and were grown in a three-stage culturing system. The decrease in WAD cyanide was measured in preg pond solutions.

The treatment was complete after 70 days or application of less than 0.3 tons of solution per ton of ore. The rapid treatment was due to the high temperatures (80 to 90 degrees Fahrenheit) in all process solutions during the course of treatment. Both WAD and total cyanides were reduced to less than 0.2 mg/L.

Data from cyanide detoxification and solution copper are shown in Figures 4, 5, and 6.

Summitville Mine Focused Feasibility Studies

Introduction

Results of laboratory and pilot demonstrations of cyanide detoxification and metal biomineralization of the Summitville heap leach pad (HLP) spent ore and heap leach solution (HLS) are presented in this portion of the paper. The tests were run with support from EPA Region 8 and the Superfund Innovative Technology Evaluation (SITE) program and provided data for the *Report of Investigation/Focused Feasibility Study*. The *HLP Focused Feasibility Study Report for the Summitville Mine Site* was issued August 1994 by Morrison Knudsen Corporation to the EPA Region 8 office (under ARCS Contract number 68-W9-0025).

The Summitville Mine was the site of mining operations that began in 1873 with the discovery and development of gold placer and lode deposits in the mine district. Located about 25 miles south of Del Norte, Colorado, in the San Juan Mountains, the mine site is at an altitude of approximately 11,500 feet (Figure 7). The site was actively mined for gold, silver, and copper between 1873 and 1947. The mine was inactive from 1947 to 1986,

when the Summitville Consolidated Mining Corporation, Inc. (SCMCI), a wholly-owned subsidiary of Galactic Resources, Ltd., started an open pit mine and heap leach operation at the site.

SCMCI ran a large-tonnage open-pit and cyanide-heap-leach operation from 1986 to 1992. Gold ore (approximately 10 million tons) was mined, crushed, and stacked on a lined leach pad. This leach pad was unique because it was a lined bowl with containment dikes that ponded leach solutions in the ore heap, as compared with more standard, well-drained percolation-type leach.

Heap leach operators experienced problems with water balance and unplanned solution discharges from the start of the mine life. Solution containment complications and ineffective water treatment contributed to environmental problems. Despite the production of 249,000 troy ounces of gold during the mine operation, SCMCI was unable to meet remedial requirements and notified the state of Colorado of its intention to file a Chapter VII bankruptcy in December 1992. The EPA Region 8 Emergency Response Branch took over site operations on December 16, 1992, to prevent a catastrophic release of hazardous substances to the environment. The Summitville Mine site was added to the National Priority List in June 1994.

Multiple sources of contamination at the site exist due to past and recent SCMCI mining operations. Emergency response operations at the site have prevented releases of severely contaminated solution. Studies are under way to define a permanent solution to detoxification or neutralization of the various mine waste units. Demonstration activities of an innovative bioremediation technology for treatment of cyanide and soluble leachable metals in the heap and heap solutions are addressed in this paper.

Heap Leach Remediation Evaluation

The heap leach pad is a bowl-shaped structure located within the Cropsy Creek drainage. A French drain structure underneath the heap comprises a network of gravel trenches and perforated pipe designed to intercept ground water and leakage from the heap. The heap consists of approximately 10 million tons of cyanide-leached ore and 90 to 150 million gallons of process solution. EPA Region 8 commissioned a focused feasibility study (FFS) and report of investigation (RI) to evaluate remedial options for the heap leach pad (HLP). The RI/FFS was completed by Morrison Knudsen Corporation and submitted to EPA Region 8 on August 19, 1994. A cross section of the heap is portrayed in Figure 8.

A request for proposal (RFP) was issued by Environmental Chemical Corporation (ECC) in October 1993 at the request of EPA Region 8, the U.S. Department of the Interior, and the U.S. Bureau of Reclamation. The RFP requested interested companies to provide information

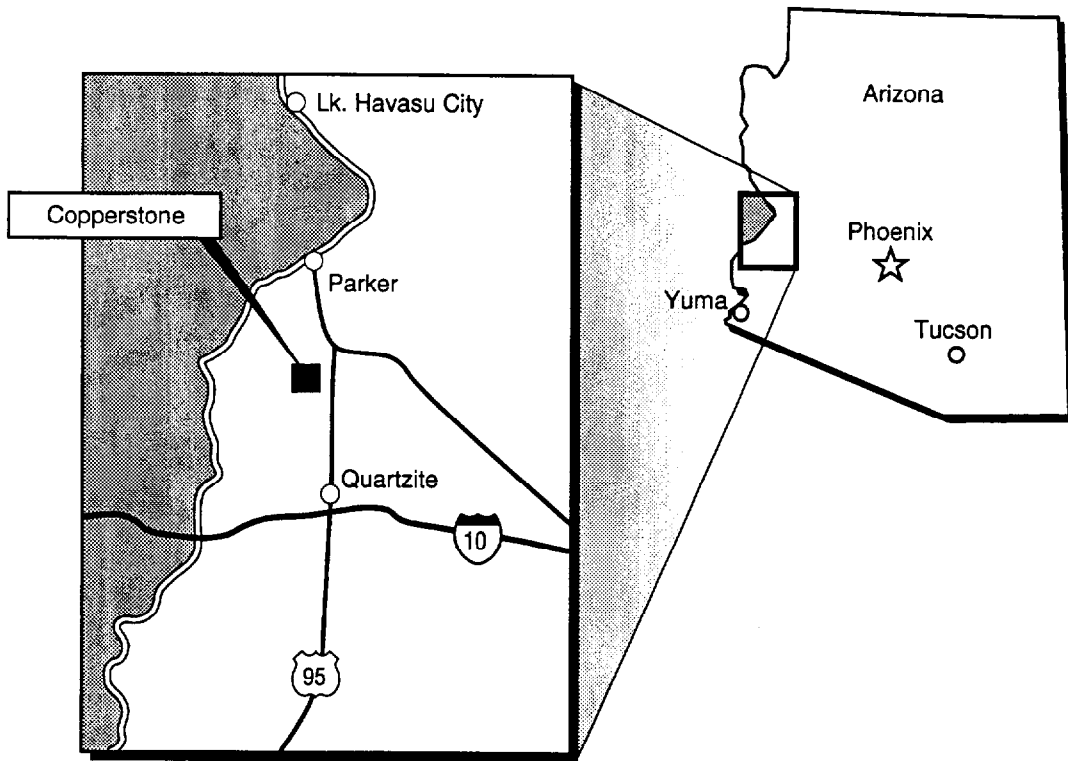


Figure 3. Site location map for Copperstone Mine.

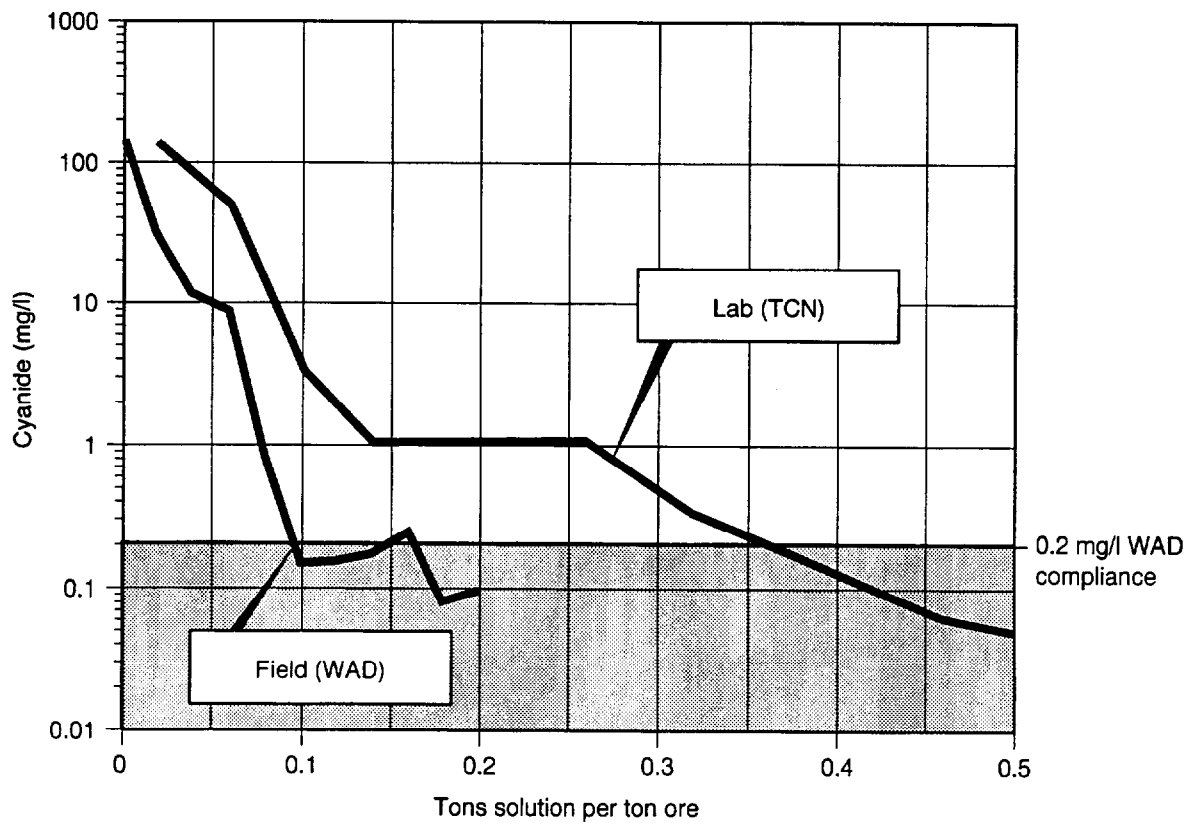


Figure 4. Comparison of laboratory and field data for Copperstone Mine biodegradation.

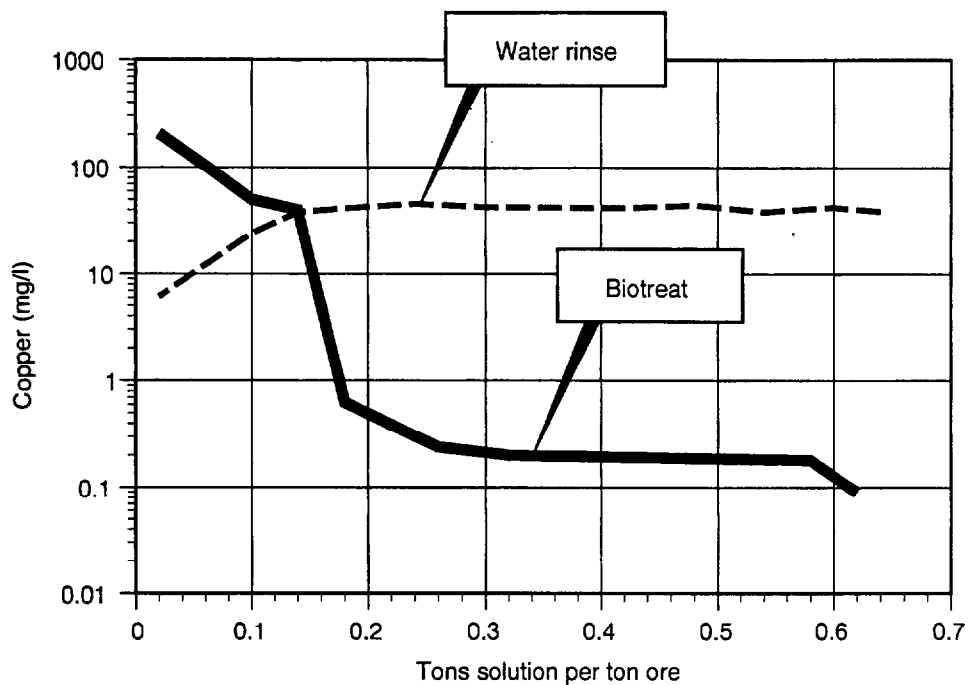


Figure 5. Comparison of column test data for copper in leachate solution at Copperstone Mine.

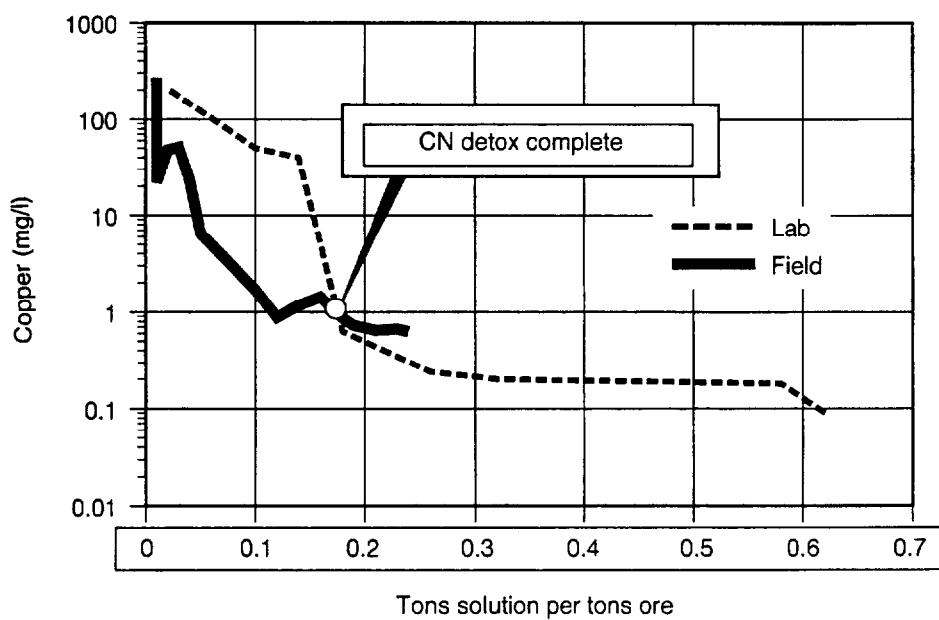


Figure 6. Comparison of laboratory and field data for copper in leachate solution at Copperstone Mine.

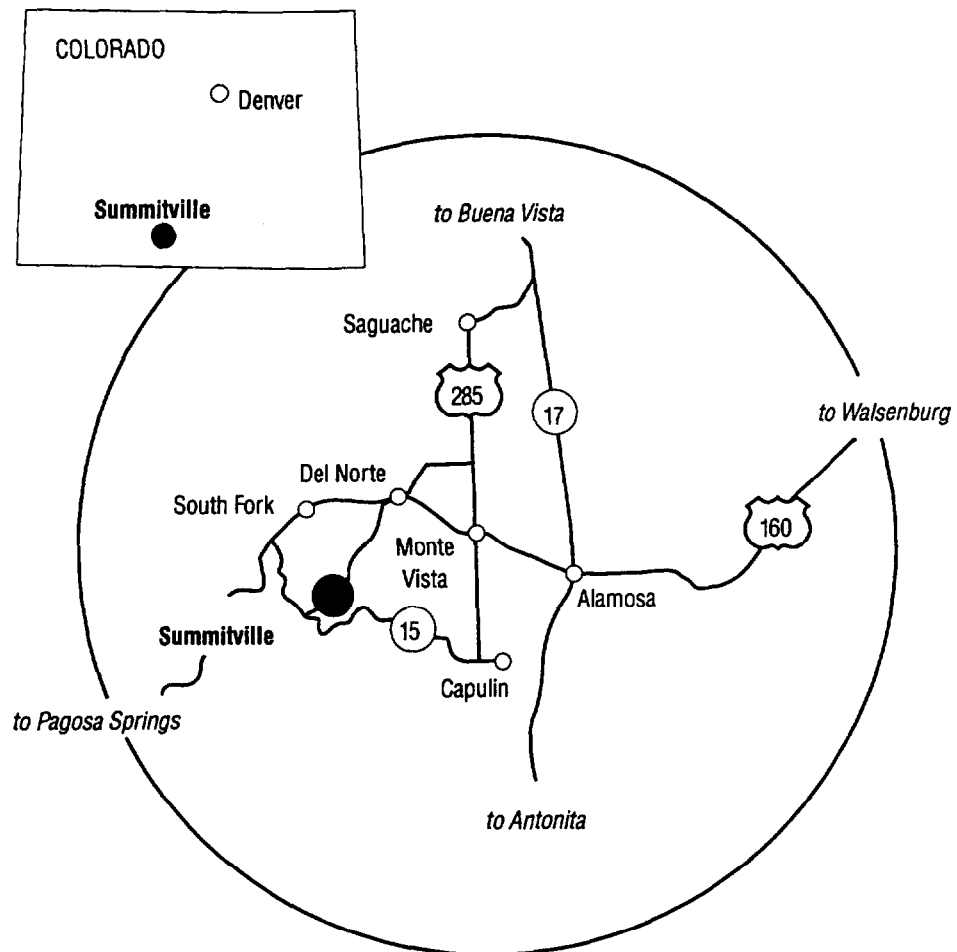


Figure 7. Site location map for Summitville Mine.

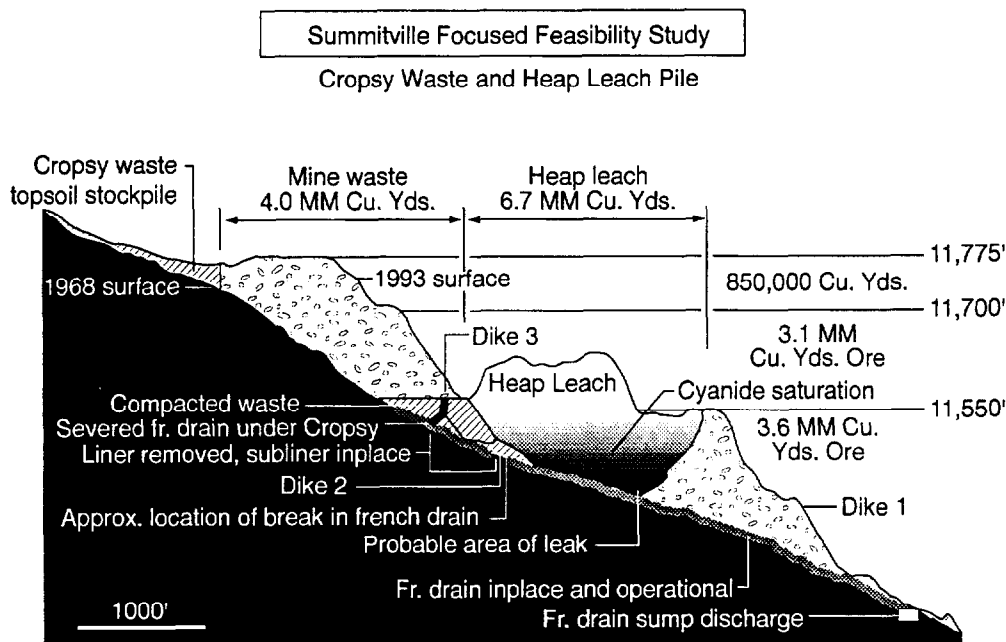


Figure 8. Cross section of the heap leach pile at Summitville Mine.

on their ability to implement innovative treatment technologies to improve treatment efficiency and reduce the cost of treatment of the heap-leach-pad spent ore and leachate solutions. Dames & Moore and Pintail Systems, Inc. (PSI) jointly submitted a proposal suggesting application of biotreatment processes for the spent ore and process solutions in the HLP. The proposal was accepted for feasibility demonstration under the SITE program with additional funding from EPA Region 8.

The primary objectives of the Dames & Moore/PSI proposal were to:

- Demonstrate the feasibility of spent ore and process solution cyanide biotreatment.
- Develop site-specific biotreatment processes for spent ore and process solution cyanide detoxification.
- Provide treatment data for use in the RI/FFS and record of decision (ROD) for the spent ore and entrained solutions operable units at the Summitville Mine.
- Immobilize potentially leachable metals including zinc, copper, manganese, iron, and arsenic within the heap to improve water quality.
- Define the potential for enhancing precious metal recovery (gold and silver) as a result of spent ore cyanide biotreatment.

- Compare innovative biological treatment to conventional peroxide treatment for cyanide detoxification. Develop data to evaluate potential replacement of peroxide treatment.

Tests and demonstrations outlined in the proposal were conducted in PSI's Aurora, Colorado, lab and pilot plant and at the mine site. Spent ore treatability testing included waste characterization, bacteria isolation and bioaugmentation, parallel column treatment tests, data evaluation, and reporting.

Demonstration of copper remineralization as insoluble mineral species was a primary goal of this focused feasibility study.

Laboratory Work Plan

1. Samples of spent ore were collected from the Summitville HLP in July 1994 by SAIC under contract to the EPA Risk Reduction and Engineering Laboratory and the SITE program. The sample collection program provided HLP spent ore material for the column test program and for isolation of indigenous microorganisms from the HLP.
2. Samples of the Summitville HLS were collected concurrently with the HLP sampling program. Approximately 60 gallons of HLS were provided for use in the column demonstration program.

3. Spent ore from the HLP sampling program was graded in the laboratory and was loaded into a total of six 6-inch x 10-foot polyvinyl chloride (PVC) test columns. The column tests were designed to evaluate biological detoxification of spent ore and biomineralization of soluble metals in spent ore leachate solutions. Each column represented different zones or ore types within the HLP. The column setup included:

Column #1: Sulfide zone ore, percolation leach biotreatment.

Column #2: Oxidized ore, 25 to 90 ft depth, percolation leach biotreatment.

Column #3: Oxidized ore, 90 to 130 ft depth (saturated zone), saturated with HLP solution, percolation biotreatment.

Column #4: Oxidized ore, 0 to 90 foot depth, rinsed zone (1993 peroxide rinse program), percolation leach biotreatment.

Column #5: Oxidized ore, 0 to 25 foot depth, percolation leach biotreatment.

Column #6: Control column, oxidized ore, 90 to 130 ft depth (saturated zone), saturated with HLP solution, percolation leach with peroxide-treated HLP solution.

4. Test columns #1 to 5 were treated with bacteria solutions developed in a laboratory test program for cyanide detoxification and metal biomineralization. Column #6 served as a control column and was treated with HLP solution in which WAD cyanide had been detoxified with hydrogen peroxide.

5. Test results from the column treatment program demonstrated that:

- Biological treatment of spent ore resulted in oxidation of WAD cyanide in ore and leachate solutions to less than 0.2 mg/L with application of less than 0.6 tons of treatment solution per ton of ore. The control column treatment WAD cyanide did not reach the 0.2 mg/L compliance level with application of more than 1.6 tons of solution per ton of ore.
- Biological treatment of spent ore demonstrated that total cyanide in column leachate solutions was reduced to less than 1 mg/L with application of between 0.3 and 0.65 tons of solution per ton of ore. Total cyanide in the control test column was only reduced to 40 to 50 mg/L in column leachate solutions with application of 1.5 tons of solution per ton of ore.

- Soluble and leachable copper and cobalt were reduced in column leachate solutions to 0.1 to 0.2 mg/L in the biotreatment test columns in the same test period. Soluble copper in the control test column was reduced to 1 to 2 mg/L with application of 1.5 tons of solution per ton of ore.

- Metallic biofilms were evaluated using scanning electron microscopy (SEM), which confirmed that biological processes were responsible for remineralization of soluble copper and iron into crystalline mineral species.

6. The FFS program demonstrated that biological treatment is an effective process for:

- Biomineralization of soluble and leachable metals in spent ore and heap leachate solutions.
- Biodetoxification of cyanide in spent ore and heap leachate solutions.

The data collected from the pilot column ore treatment program are presented in Figures 9 and 10 and summarized in Table 1. Treatment compliance for successful cyanide detoxification was 0.2 mg/L WAD cyanide measured in column leachate solutions. The control peroxide rinse column of saturated zone ore did not achieve compliance with a WAD cyanide standard. All other column treatments reached compliance levels. Total and WAD cyanide were plotted against the tons of solution applied per ton of ore.

Amounts of treatment solution applied per ton of ore for each column to reach compliance are listed in Table 1. The amount of biotreatment solution required for complete cyanide detoxification is projected to be 25 to 30 percent of the amount of solution required by conventional chemical rinse detoxification treatments.

Biomineralization Observations—SEM Investigation of Biomineralized Metallic Films

During application of spent ore cyanide biodetoxification processes at other mines, PSI has observed a substantial reduction in many of the leachable metals in biotreatment solutions. These field observations of soluble metal reduction led PSI to propose that metal biomineralization should be a possible secondary treatment concurrent with spent ore detoxification in the FFS for the Summitville Mine.

Thus, a secondary treatment goal in the FFS was to reduce the amount of leachable or soluble metals in the spent ore and entrained heap leachate solution. This test was designed to quantify reduction of metals in column leachate solution and to identify any remineralized products in the column tests. Copper in column leachate so-

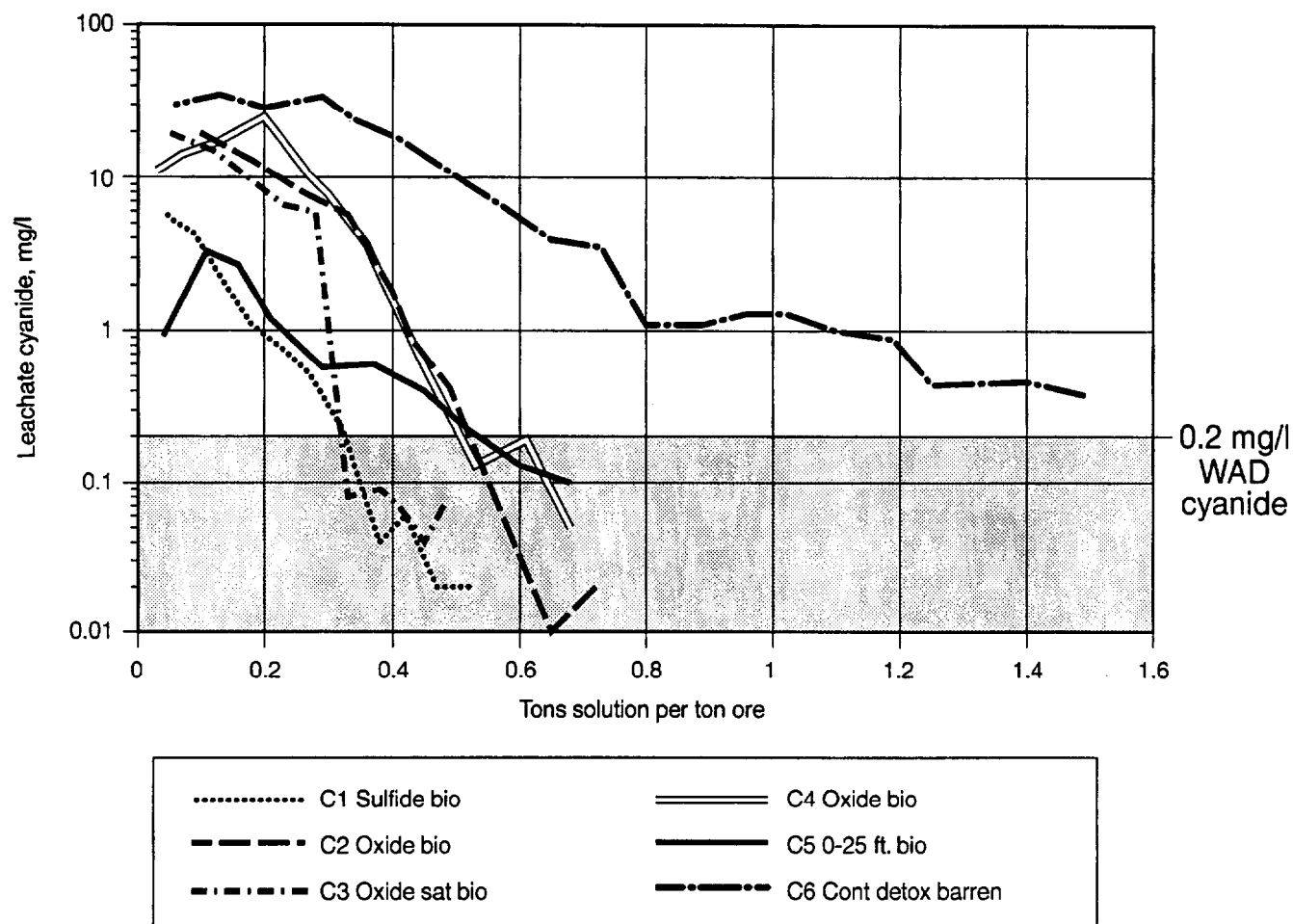


Figure 9. Leachate WAD cyanide versus tons of solution per ton of ore resulting from treatment program at Summitville Mine.

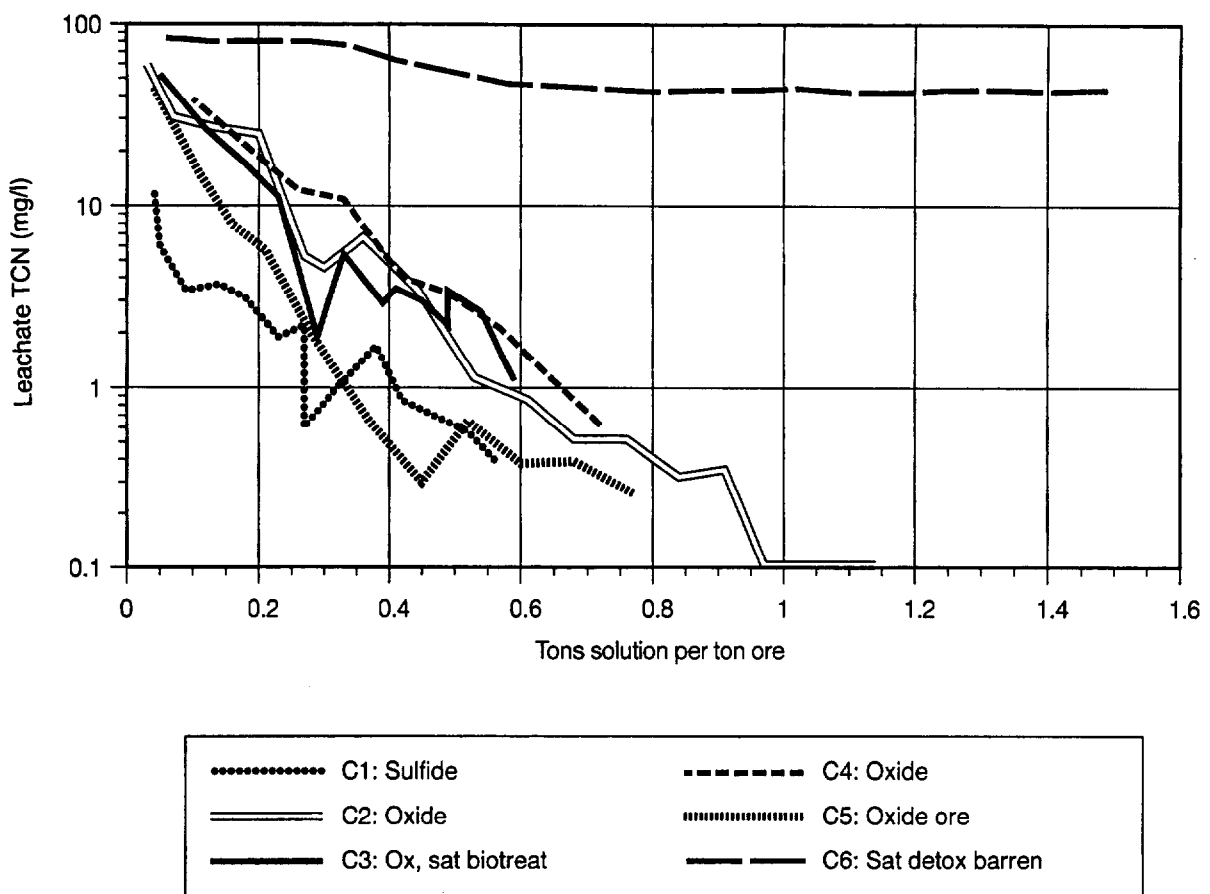


Figure 10. Leachate TCN versus tons of solution per ton of ore resulting from treatment program at Summitville Mine.

Table 1. Ore Effluent Solution Quality

Column #	Weak Acid Dissociable Cyanide (mg/L)	Treatment Solution per Ton of Ore
1	0.2	0.32
2	0.1	0.56
3	0.1	0.28
4	0.1	0.53
5	0.1	0.60
6	0.4	1.49

lutions is shown in Figure 11 for Columns #3 and #6. Column #3 was the biotreatment test column run as a saturation zone sample. Column #6 was a control rinse using a barren solution detoxified with hydrogen peroxide in a saturation rinse.

In the FFS for Summitville Mine, spent ore from the HLP was loaded into PVC test columns (6 in. x 10 ft) and was leached with bacteria/nutrient solutions. Two treatment designs were studied: a standard percolation leach (aerobic), and a saturated leach design in which the ore was saturated with the heap leach solution to which bacteria and nutrients were applied in a continuous biotreatment leach.

The bacteria for all column treatment tests were isolated from the spent ore at depth through the HLP in the saturated and unsaturated zones. Bacteria isolated from the heap material were tested for cyanide oxidation capacity and were submitted to a bioaugmentation program to

improve reaction kinetics and metals tolerance. The final treatment population consisted of several distinct species, including aerobic heterotrophs, facultative anaerobes, and sulfate-reducing bacteria.

The remineralization of soluble metals was observed through a decrease in copper and cobalt in column leachate solutions and the formation of observable mineral products on ore surfaces in the columns. Several of the tests were run in clear PVC columns to facilitate observation of mineral formation. The column ore contents were photographed before, during, and after the biotreatment process, which ranged from 10 to 20 days for each test column. Ores were collected from each column after the treatment was complete and were submitted for scanning electron microscopy (SEM) and transmission electron microscopy (TEM) study at two laboratories—the U.S. Geological Survey (USGS) SEM Laboratory in Denver, Colorado, and the City College of New York (CCNY) SEM laboratory.

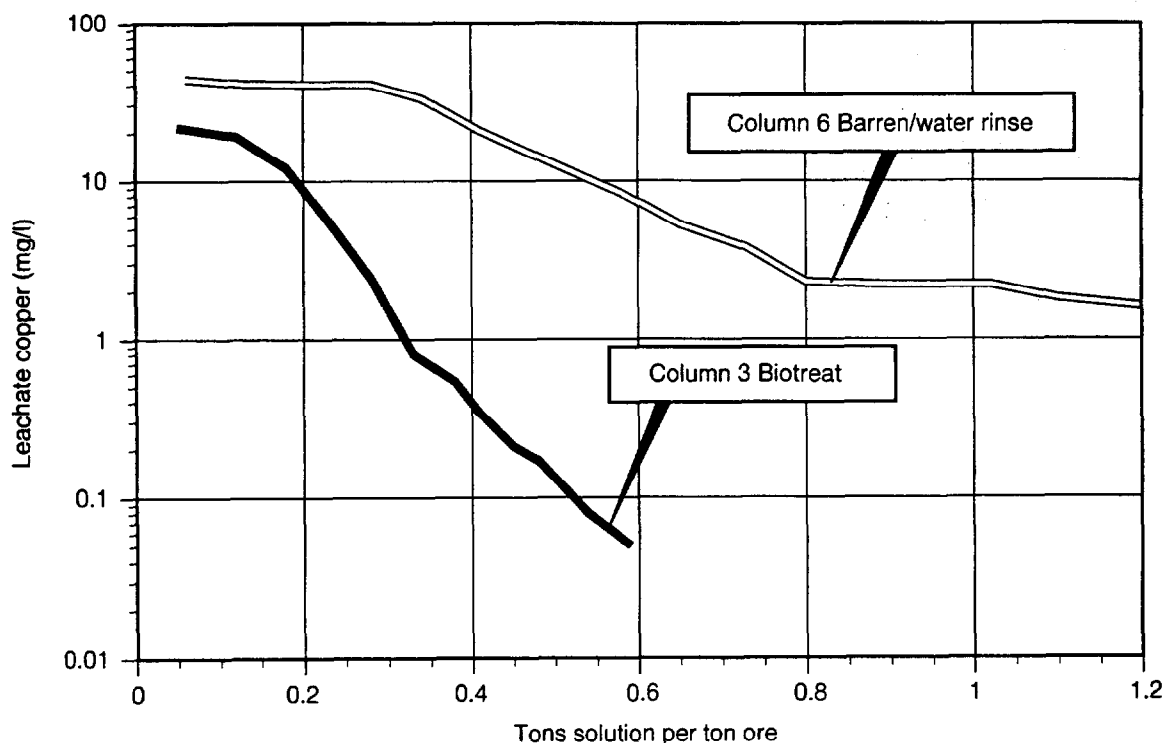


Figure 11. Comparison of column test data for copper in leachate solution at Summitville Mine.

The first SEM work suggested that calcite spherules, bladed gypsum, and layered bornite mineralization occurred as shown in Figures 12a, 12b, 13a, 13b, 14a, 14b, and 14c with companion energy dispersive x-ray spectroscopy scans for remineralized products from test Columns #2 and #5. Column #5 was biotreatment of oxidized ore collected from an unrinsed, unsaturated zone in the HLP between 0 to 25 foot depths. Column #2, spent oxide ore, was collected from an unrinsed, unsaturated zone of the HLP collected between 25 and 90 foot depths.

The stabilization of microorganisms in soils has been linked to local microenvironmental factors such as clay speciation and the availability of appropriate colloidal surfaces (11,12,13). Microorganisms in macroscale systems establish population profiles in the near-surface environment dependent on mineralogical/organic variations and the availability of oxygen in the environment. In the case of the column treatment tests, the microenvironment was forced by the addition of bacteria and dissolved nutrients.

The microorganisms injected during the column experiments may be indifferent to such environmental controls, given the relatively short life of the experiments, and one might expect that microbial populations are uniformly distributed in the test column. In these column tests, however, SEM investigation revealed that the metallic-appearing coatings on run products are not uniform in composition. Rather, they vary in a complex fashion from point to point within a test column and also from one column to the next. This variability may indicate that the microorganisms are in fact not identically distributed in columns or react differently at different times and places over the course of an experiment. Thus, surface films of remineralized product may provide important information concerning the interplay between biological populations and the ambient fluids in bioremediation tests.

To illustrate the variability of the surface film formation of biominerals, observations of material in test Column #5 and test Column #2 are compared. In both test columns the metal-bearing biomineral sheets coat an aggregate of kaolinite + halloysite + jarosite + alunite. A preliminary TEM study indicates that the individual substrate minerals are compositionally similar and exist in about the same proportions in both test columns. The sheets examined to date tend not to develop on quartz particles as frequently as clay aggregates.

Biomineralization Test Observations— Column #5

The generally three-part metal-enriched sheets of biominerals tend to be amorphous at the base (TEM work in progress) and grade upward into breccia-like admix-

tures of both variably crystallized and fully crystallized minerals ending in outermost layers that are predominantly monomineralic and thin. Outer layers tend to be either Cu, Cu-Fe, or Fe-enriched over lower horizons and are markedly thinner, down to 20 Angstroms for copper.

The middle layer(s) is punctuated by seemingly chaotic populations of crystals (primarily sulfides and metals), with metal fragments easily recognized by their high reflectivity in backscatter images. The Cu-Fe-S sequence of the upper layers tends to be stratified upward in a sort of reverse "supergene enrichment" series, reflecting an apparent evolution of increasingly neutral pH and reducing conditions as the tests proceed. The progression appears to be made more cryptic by the entrapment of both falling and tumbling particles, in addition to those produced by in situ nucleation and growth.

While many embedded crystals of the middle layer(s) follow the inverted supergene sequence (typically precursors to possible chalcopyrite overlain by more covellitic phases), exceptions are numerous. A flake of tin is shown in Figure 15a. The SEM image (right section of Figure 15a) shows that the tin flake is embedded with the copper sulfide materials and is not an artifact. The backscatter image (right portion Figure 15a) casts the tin flake as a bright object against a background of copper sulfides, demonstrating that the tin (see Figure 15b) has a greater atomic number than the average for the copper sulfide substrate. This suggests tin over cassiterite (SnO). An energy dispersive spectrum (EDS) trace (Figure 16a) also is given for a middle-layer Fe-Cu particle located in the vicinity of the tin particle.

Whereas the stratigraphic relationship between height and copper and sulfur speciation is still unclear, copper and copper sulfide apparently are the probable dominant final crystallization products in microcavities. The intricate patterns formed by copper ribbons (Figure 16b) and copper sulfide ribbons (not illustrated) indicate relatively high structural integrity and high atomic number. Note that much of the background film of Figure 16b is also copper and that the background Cu-films are exceptionally thin, comprising a layer of less than approximately 20 Angstroms. Given that the underlying material is Cu-Fe-S-Si-Al-bearing and the final stage is monomineralic and strongly reduced, evidence is abundant for precipitation mechanisms that either shift with ambient experimental factors over time or are themselves variable, causing different metal populations to precipitate at different times.

The geochemical observations are consistent with several models for fluid-crystal evolution:

- *Oxidation-state variability.* A constant process (supersaturation response) whereby fluids in the microenvironment become more reductive over time.

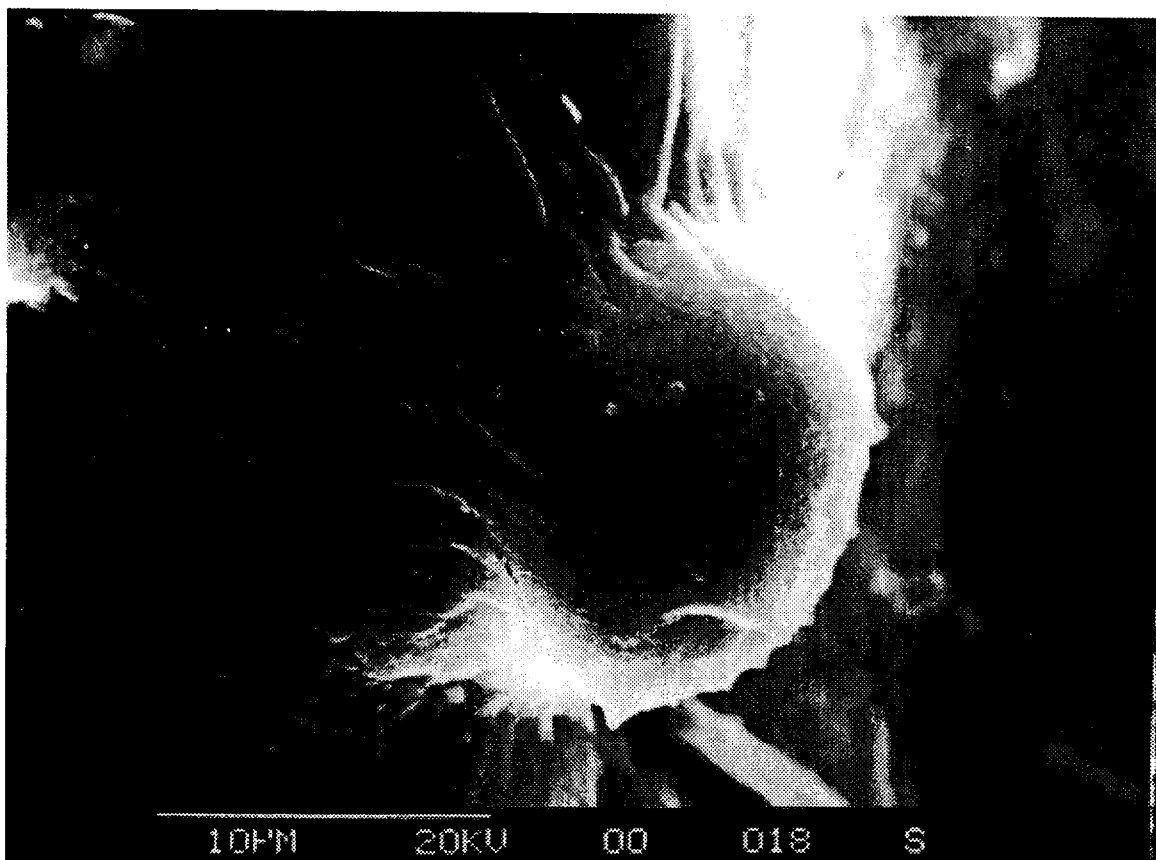


Figure 12a. Summitville Mine: Possible calcite spherule.

Calcite Spherules

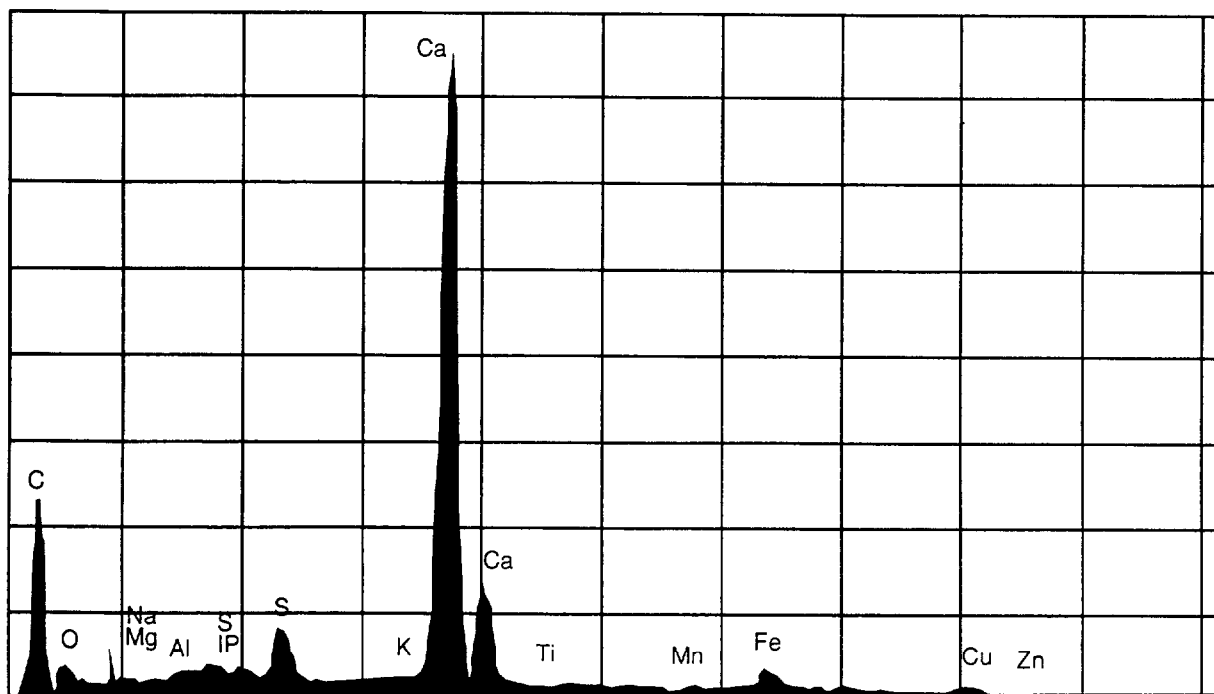


Figure 12b. Summitville Mine: EDS spectrum for calcite spherule.

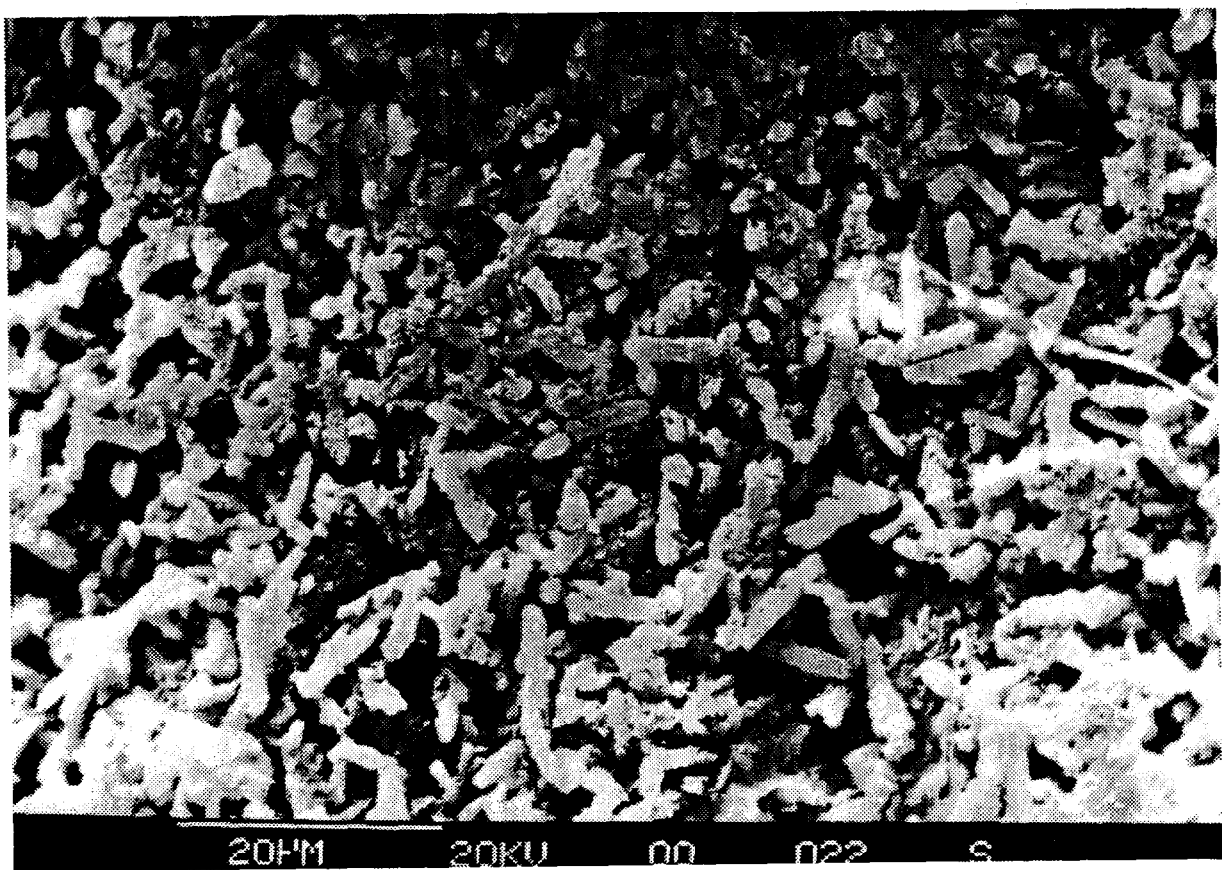


Figure 13a. Summitville Mine: Calcium-rich blades.

Ca-Rich Blades

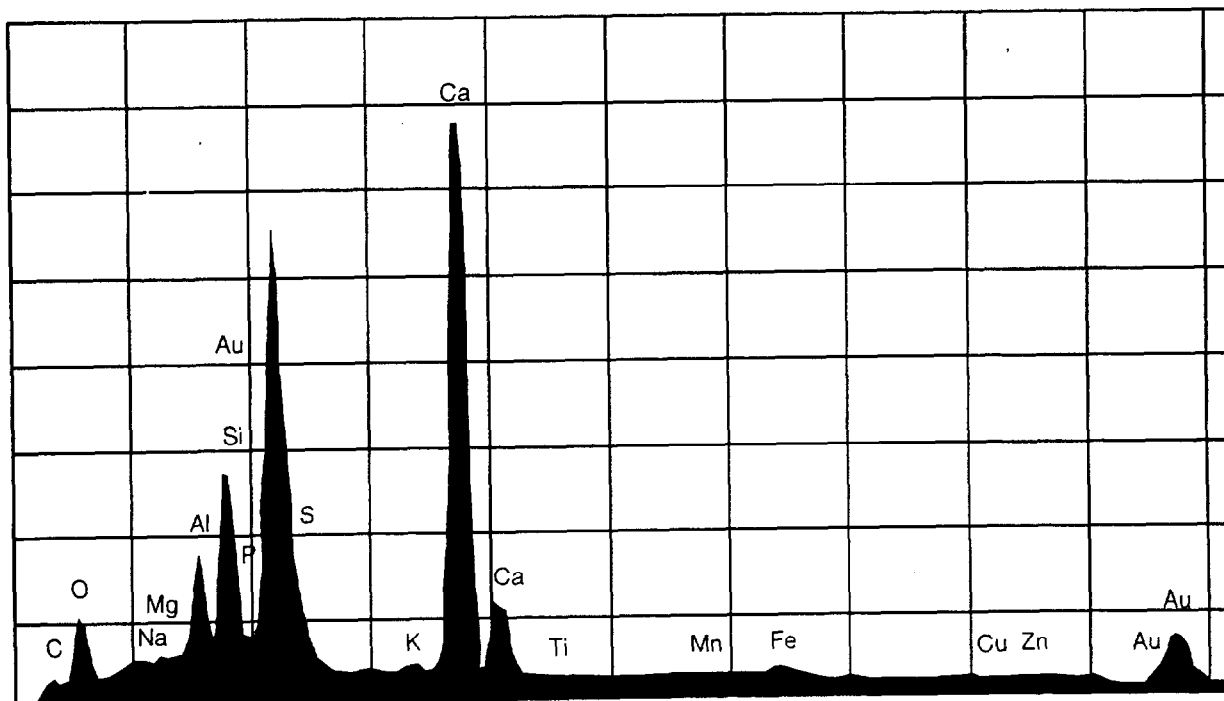


Figure 13b. Summitville Mine: EDS spectrum of calcium-rich blades

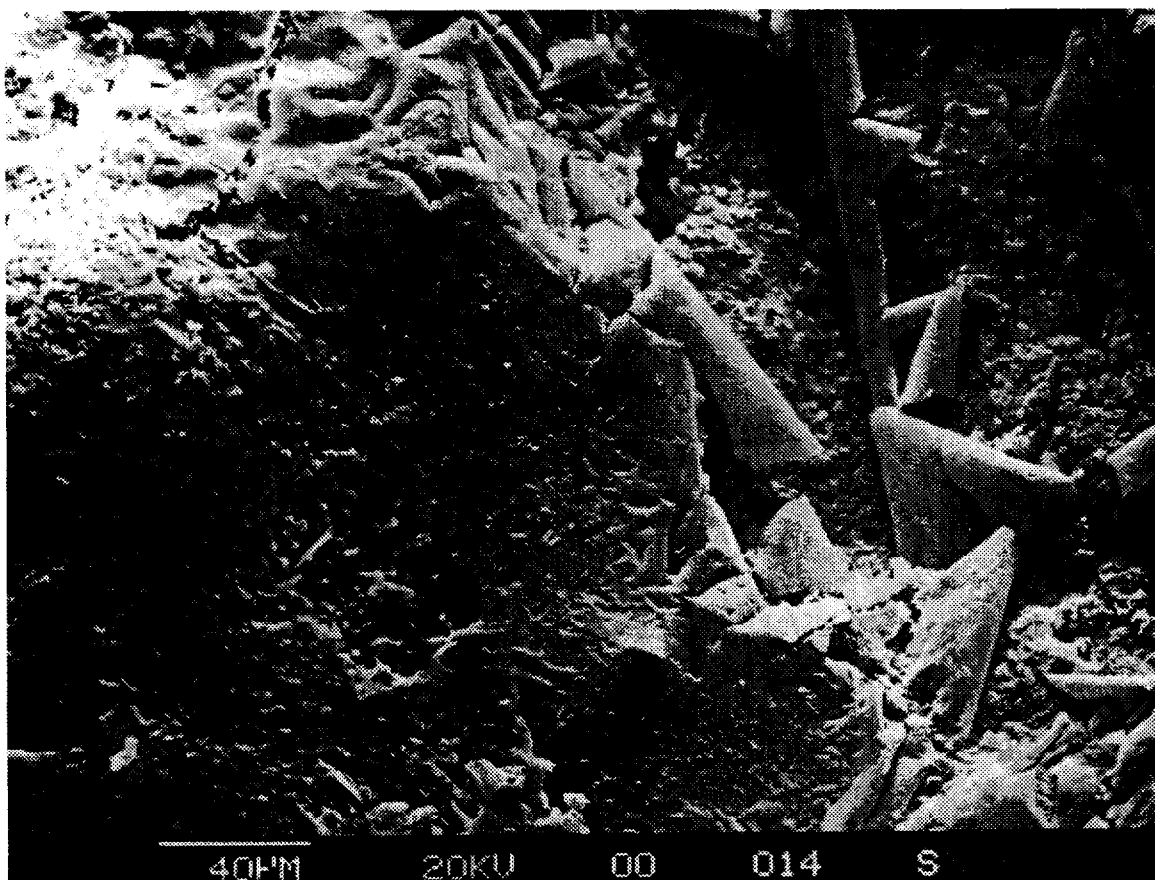


Figure 14a. Summitville Mine: Biofilm layering over ground mass.

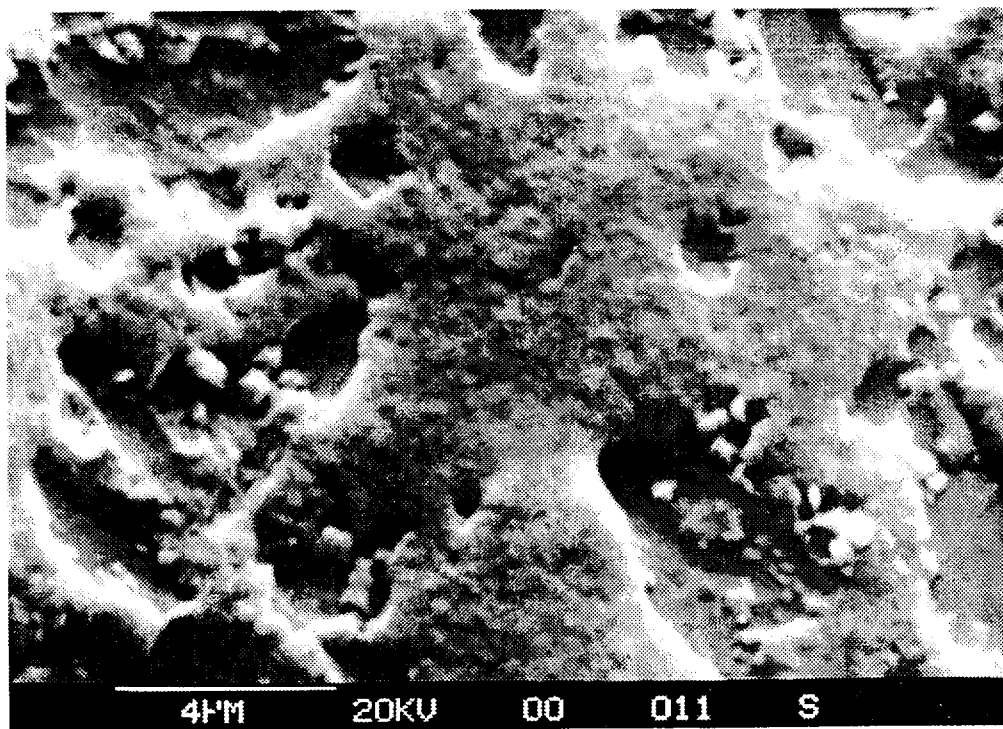


Figure 14b. Summitville Mine: Possible two-layer bornite mineralization

"Bornite" Coating - Top Layer

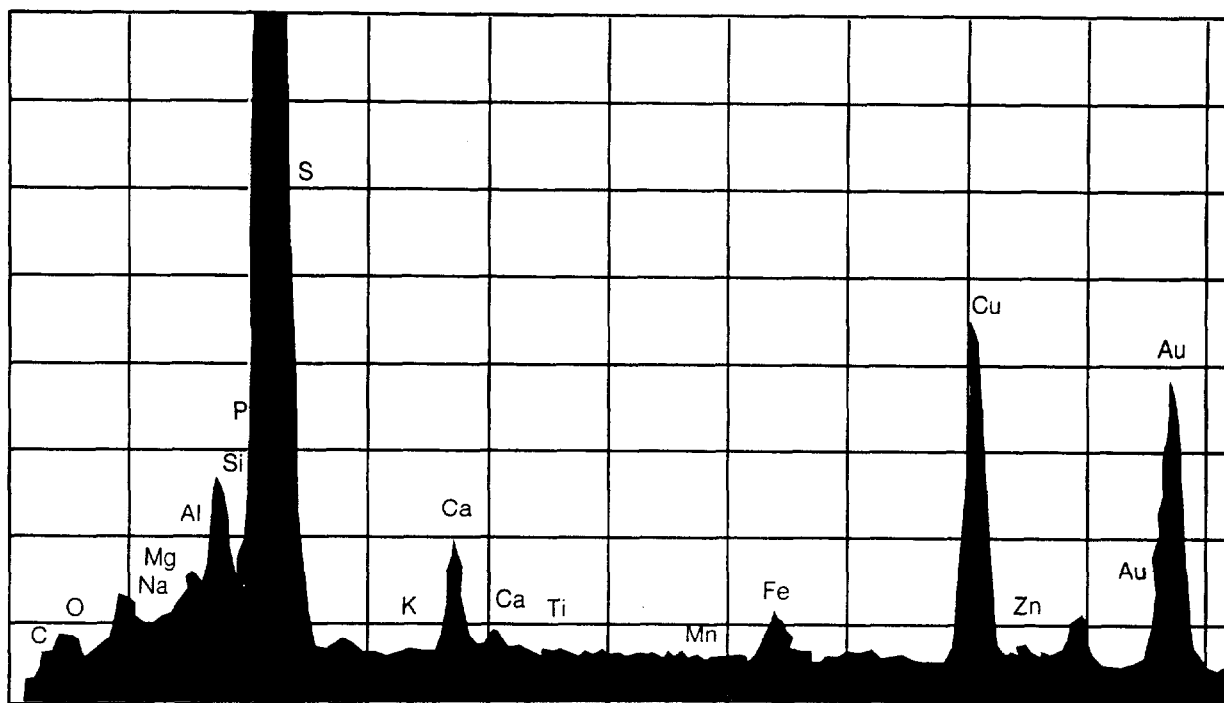


Figure 14c. Summitville Mine: "Bornite" coating (top layer).

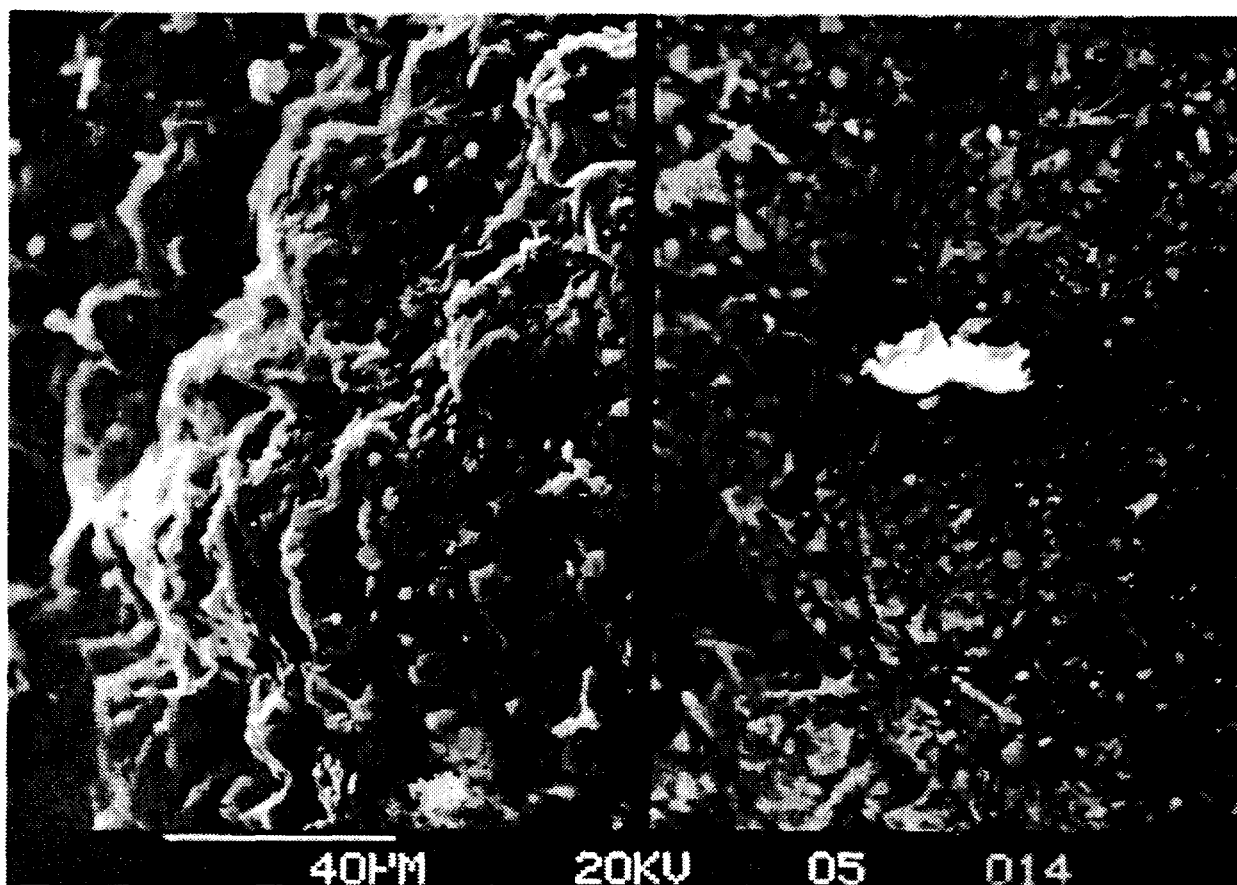


Figure 15a. Summitville Mine: Tin flake imbedded with copper sulfide materials.

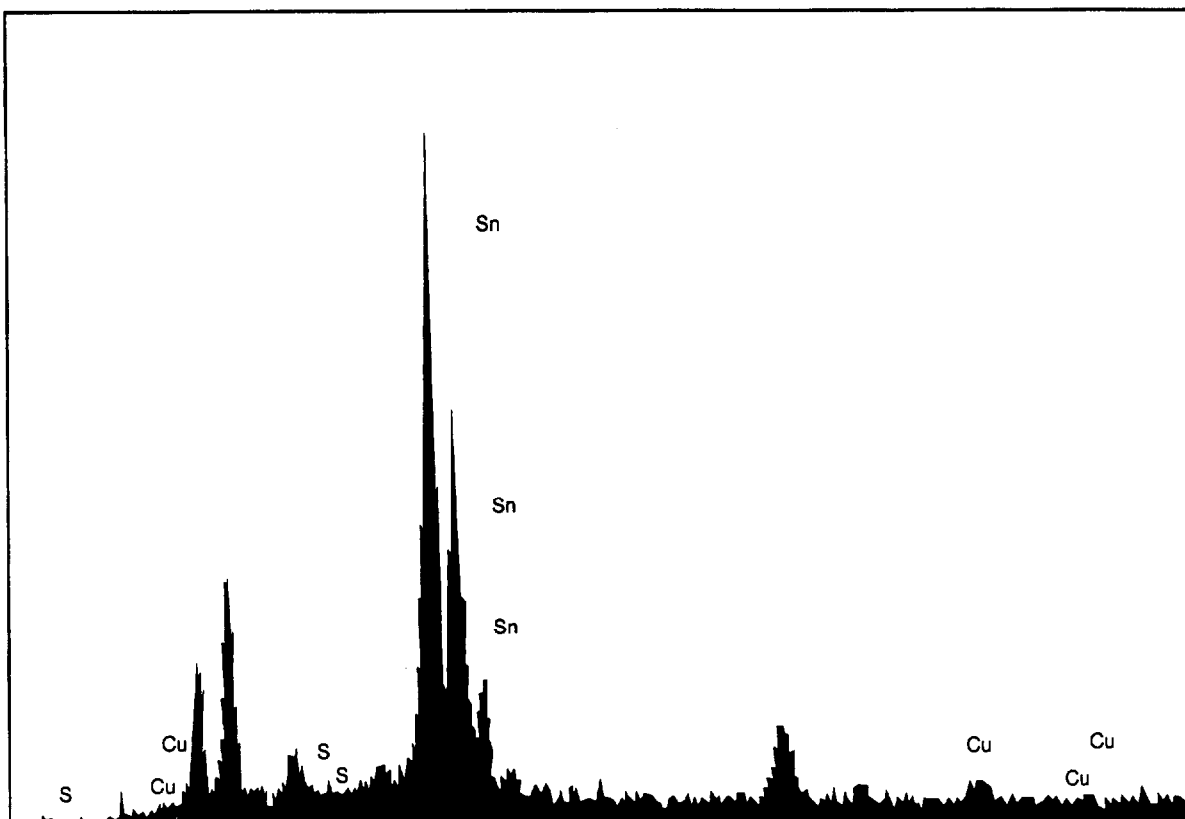


Figure 15b. Summitville Mine: EDS spectrum for tin flake imbedded with copper sulfide materials.

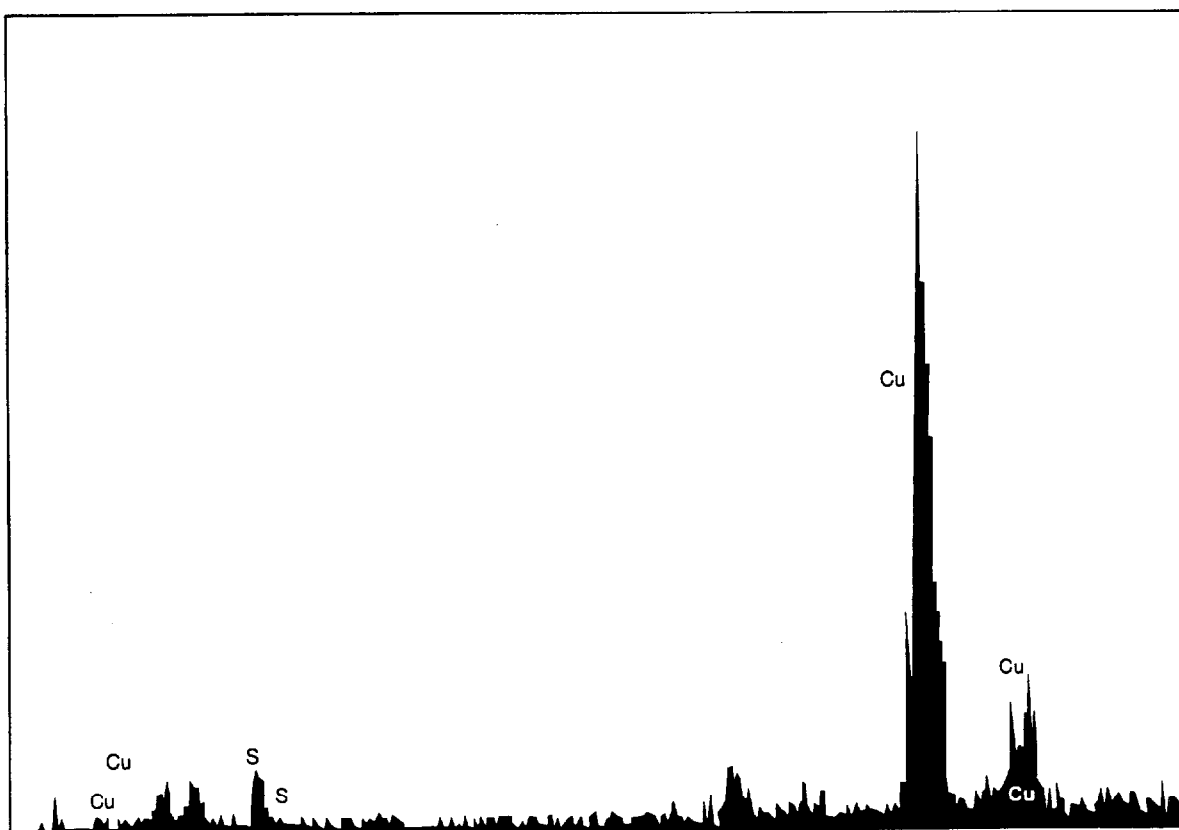


Figure 16a. Summitville Mine: EDS spectrum of iron-copper particle.

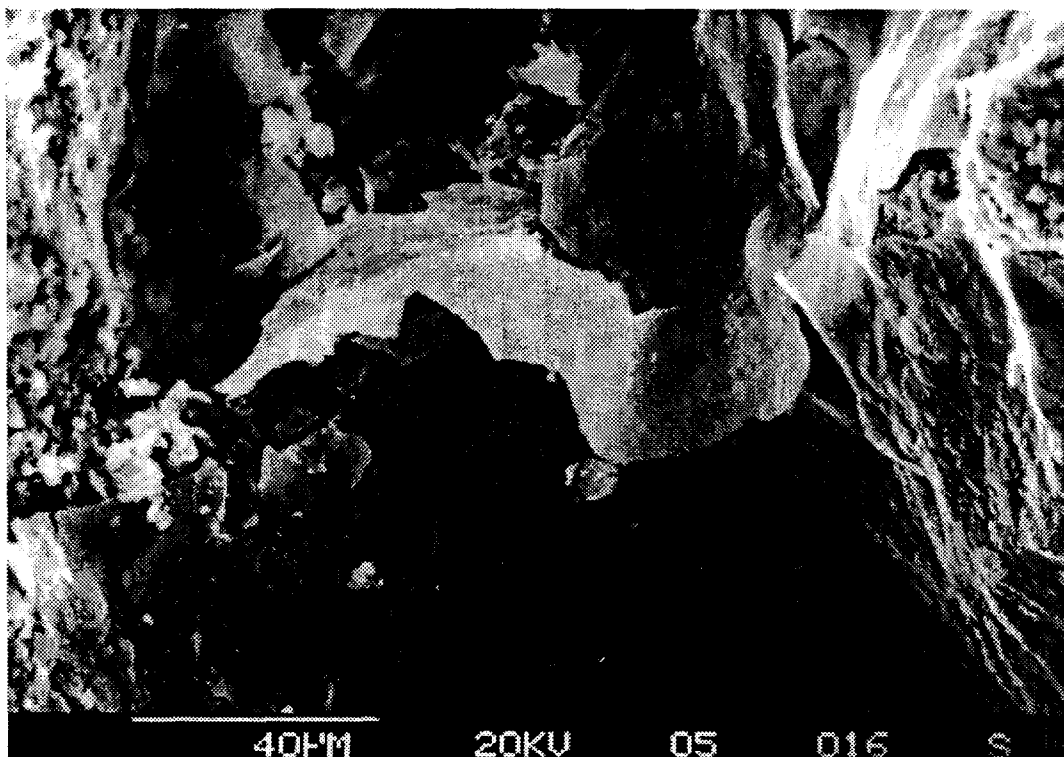


Figure 16b. Summitville Mine: Iron-copper particle.

- **Ligand depletion.** A constant process whereby sulfur and other agents are progressively removed by bacterial action.
- **Bacterial catalysis.** A variable process accounting for the plating out of a variable metal film dependent on evolutionary changes taking place in the bacterial colony.

Thus, numerous models for film production are possible, several of which may be simultaneously active during the nucleation and growth of films.

Biomining Test Observations— Column #2

Although the bulk material composition of matter recovered from Columns #2 and #5 are similar, if not identical, bacterial treatment has resulted in the production of radically different films, at least locally in the column experiments. In Column #2, films have evolved that differ substantially in bulk composition and mineralogy from those in test Column #5. Although the textures are comparable, the deposits tend to be thicker and more hummocky, and the uppermost stratum is thicker and more frosting-like, as shown in Figures 17a and 17b. The bulk compositional shift, as before, is in the direction of reduced-chemistry phases and mineralogic simplicity. This is apparent in the greater brightness of the surface of

the film and the correlative energy-dispersive determinations (as shown in Figures 17a and 17b). Here, both the innermost and outermost layers are iron enriched and copper depleted.

This constitutes a marked departure from the overall Cu-Fe-S films forming in samples from the near surface (Column #5). Therefore, to assign the control to depth of sampling is tempting; however, because no major differences in substrate character are discernible (based on TEM work to be reported elsewhere), the fundamental local cause probably rests with the microbiological species rather than mineralogy.

Conclusions—Cyanide Bioremediation

Cyanide detoxification in spent ore is a function of solution application efficiency and bacterial use of cyanide. The ore biotreatment in this test gave similar results and required a detoxification time comparable to prior PSI experiments. The treatment bacteria adapted well to the spent ore environment and effected a rapid detoxification of cyanide in spent ore and ore solutions. The Summitville ore is a suitable candidate for a field biotreatment.

The biological treatment column achieved a greater than 99 percent removal of WAD cyanide with application less than an average of 0.5 tons of solution per ton of ore.

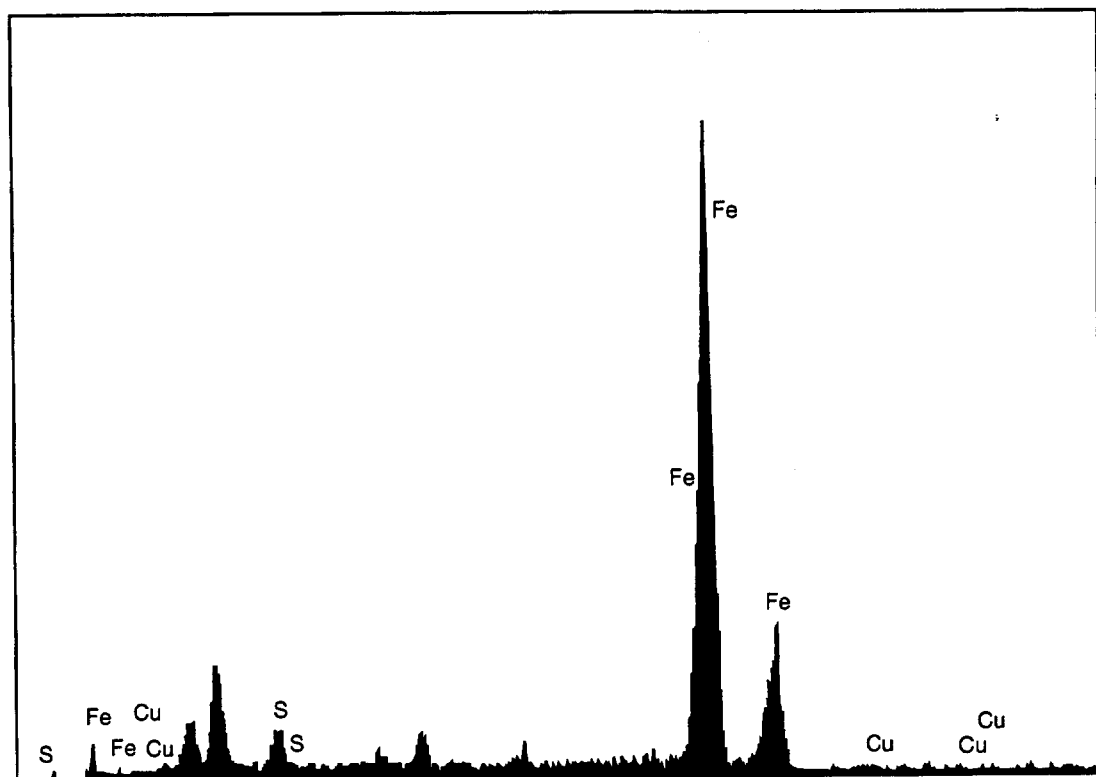


Figure 17a. Summitville Mine EDS trace #1.

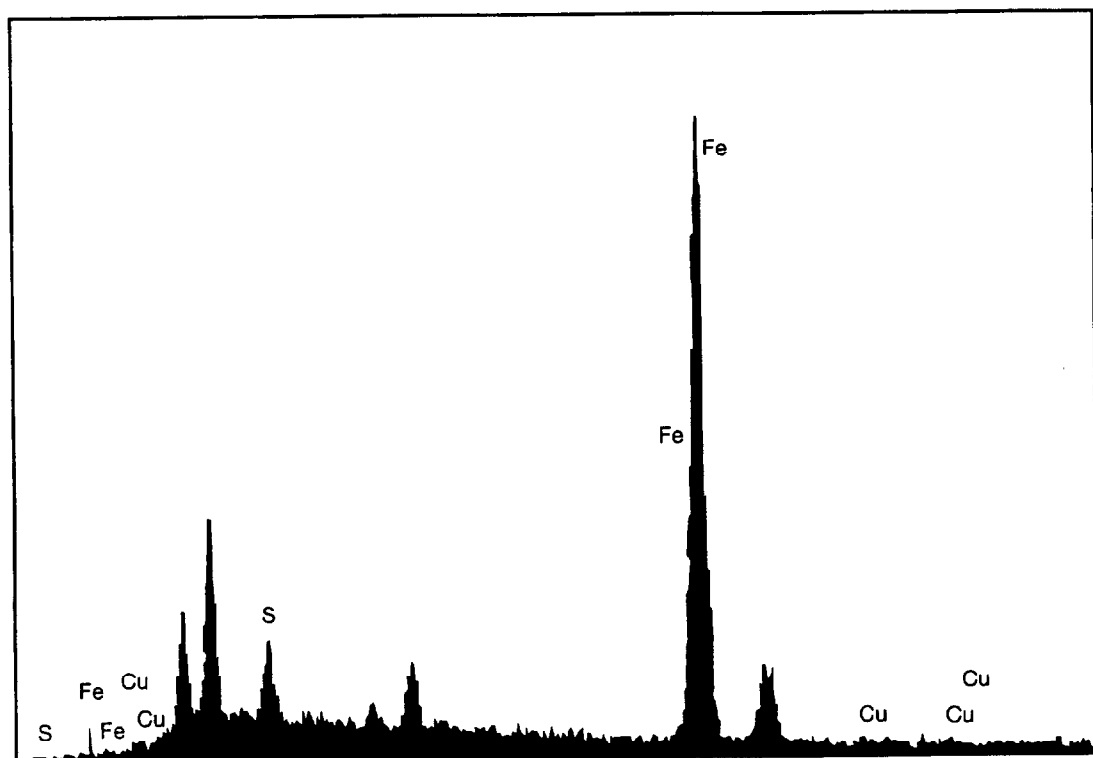


Figure 17b. Summitville Mine EDS trace #2.

Total cyanide in column leachate solutions at the end of the test was less than 0.5 mg/L, indicating that bacterial action in the treatment solution will metabolize strong metal-cyanide compounds. A field treatment of a leach pad cell or other division of spent ore could be planned for a treatment program using less than 0.5 tons of solution per ton of ore.

Biotreatment in this study achieved a greater reduction in total cyanide in a shorter application than competitive treatments can achieve. In situ biotreatment is the most efficient heap cyanide detoxification method as compared with peroxide rinse treatments. The data generated in this study indicate that the biotreatment processes have the potential to operate as an effective field treatment. Biological treatments are projected to be cost and time competitive with chemical rinse treatments.

The objectives of the pilot column tests were met in this biotreatment demonstration:

- Existing strains of cyanide-oxidizing bacteria were adapted to grow in the ore environment and to use cyanide as a carbon and/or nitrogen source.
- The adapted bacteria grew best in a chemically defined nutrient media of food-grade reagents.
- Flask and column tests of the adapted, augmented treatment population verified that bacteria would grow and metabolize soluble cyanide in the Summitville spent ore.
- Cyanide was detoxified in biotreatment tests in spent ore and column leachate solutions with application of less than an average of 0.5 tons of solutions per ton of ore. Cyanide levels did not reach a 0.2 mg/L discharge criteria with the peroxide kill, saturated, barren rinse test column with application of more than 1.5 tons of treatment solution per ton of ore.
- Total cyanide and thiocyanate also were treated to low levels in the column treatability studies. Conventional chemical remediation methods for cyanide detoxification do not treat the strongly complexed metal cyanides, including ferrocyanide, ferricyanide, gold cyanide, cobalt cyanide, or thiocyanates.

Biom mineralization Test Conclusions

The microscale studies conducted by Professor Jeff Steiner at CCNY and Dr. Gene Whitney at the USGS clearly define several distinct microscale films that evolve on generally the same substrate (agglomerations of kaolinite, halloysite, jarosite, and alunite) within the confines of highly similar experimental systems. The relative proportions of copper- versus iron-enriched film areas have yet to be determined accurately. In studies at CCNY, however, the suggestion clearly arises that the

microbial populations have acted locally to produce different film chemistry and endpoints in metal film deposition. The controlling factors are as yet unrecognized, but the suggested possible controls include local production of reducing atmospheres; changing ligand concentration due to bacterial consumption; and varying tendencies to catalyze precipitation reactions linked to changes occurring in bacterial populations. These various localized phenomena appear not to affect the overall release (macroscale release) of dissolved chemicals in the recovered leachate in any pronounced fashion. The variability brought out by this study, however, encourages the general concept that a wide range of metal-fixing films is produced by bioremediation that can be engineered to isolate and seal metals in ore waste.

This treatment concept should have application for both in situ treatment of ore and waste rock heaps and for surface passivation of exposed minerals in pit walls. Although biominerals would be subject to natural weathering cycles, the end effect on the environment would be gradual and of relatively low impact.

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Chapter 7.

Acid Mine Drainage: Reclamation at the Richmond Hill and Gilt Edge Mines, South Dakota

Thomas V. Durkin

Introduction

Acid mine drainage (AMD) is defined as contaminated mine drainage that occurs as a result of weathering reactions between sulfide-bearing rocks, air, and water that can lead to problems in the receiving environment. AMD is characterized by low pH, increased acidity, elevated heavy metals, sulfate, and dissolved solids in the drainage emanating from the sulfide rock source. Various physical, chemical, and biological controls can be used to prevent, minimize, and treat AMD. The best environmental controls, and the least expensive in the long run, are waste management practices that focus on "prevention" rather than "treatment." Two cases are illustrative.

In 1992, the South Dakota Department of Environment and Natural Resources (DENR) identified environmental problems associated with reactive sulfide rocks at a valley-fill waste depository at LAC Minerals' Richmond Hill gold mine in the northern Black Hills. This led to a shutdown of the mine, a significant increase in the reclamation surety bond from \$1.2 million to \$10.7 million, a settlement of \$489,000 for permit and water quality standard violations, and the development of an AMD reclamation plan. This plan is in the process of being finalized, and preliminary results are impressive.

Numerous abandoned mine reclamation projects have been conducted by active mine operators in the Black Hills on a voluntary basis. These efforts have resulted in a net improvement to the environment while lowering the environmental liability posed by the abandoned mine sites. One of the more notable reclamation projects was conducted by Brohm Mining Corporation, which operates an active heap leach mine.

Case histories for these two mine waste remediation sites are presented in this paper.

Richmond Hill Mine

Physical Setting and Ownership

LAC Minerals operates the approximately 400-acre Richmond Hill Mine located in the northern Black Hills, four miles northwest of Lead, South Dakota. This surface gold mine, which is operated using conventional heap leach technology, was permitted by the state of South Dakota in 1988. At that time, the mine was owned and operated by St. Joe American, Inc. Successors included St. Joe Gold Corporation, St. Joe Richmond Hill, Inc., Bond Gold Richmond Hill, Inc., Bond Gold Corporation, and Richmond Hill, Inc., a subsidiary of LAC Minerals (USA), Inc.

The mine facilities are located at an elevation between 5,500 and 6,000 feet above sea level in an area of relatively rugged terrain. Annual and daily temperature variations can be extreme. Annual precipitation averages about 28 inches per year. The pit/waste facility is drained by Spruce Gulch, an intermittent tributary to perennial Squaw Creek, which flows into perennial Spearfish Creek. The process facility is drained by Rubicon Gulch, an intermittent tributary of Spearfish Creek. Ground water is confined to two systems: In the shallow, alluvium system, flow is predominantly controlled by topography; in the deep, bedrock system, hydraulics are more complicated and flow is structurally controlled (1).

The mine pit and valley-fill waste rock depository are connected to the processing facility (e.g., crusher, leach pads) by a 1.5-mile haul road. The nearest area to the ore body that was sufficiently flat to construct the leach pads was 1.5 miles away. South Dakota requires a double liner system for leach pads and ponds, complete with leak detection, collection, and recovery systems (2).

Geology

The ore body is associated with a Tertiary breccia pipe that intruded into Precambrian amphibolites, forming a near vertical contact. Sulfide and oxide components of the breccia exist. Oxidation of the Richmond Hill ore deposit resulted in a well-developed hematitic-jarositic cap up to 260 feet thick. The oxidized cap closely follows the extent of the breccia pipe. Primary sulfide mineralization occurs below the oxide cap and consists of 70 to 80 percent feldspars, showing variable argillic alteration, and 10 to 20 percent pyrite and marcasite. Minor quartz, micas, carbonates, barite, rutile, apatite, zircon, and monazite account for the rest of the rocks. Traces of chalcopyrite, bornite, sphalerite, galena, and arsenopyrite are found in the major sulfide species. The protolith of this rock was determined to be the Precambrian amphibolites, with the sulfide mineralization replacing the original mafic minerals. Unaltered amphibolites contain little to no sulfides (3).

Discovery and Description of the AMD Problem

From the time operations began in 1988 until 1992, the mine was operated without any significant environmental problems. In 1988, several general conditions were written into the state mine permit that addressed AMD prevention as follow-up to preliminary indications that a small amount of sulfide rock might be encountered during mining. The mine operators encountered a significantly larger amount of sulfide rock, however, than they originally anticipated.

During a routine inspection in January 1992, the Department of Environment and Natural Resources (DENR) identified a 200,000-ton stockpile of sulfide ore on top of the Spruce Gulch waste rock depository as well as sulfide waste in the dump. Uncrushed sulfide ore had been stockpiled on the waste dump to allow it to oxidize and become more amenable to leaching, with the intent to later crush and leach it. This prompted a series of additional inspections and communications with mine personnel to field-document the potential for AMD from the sulfide ore and waste rock.

Richmond Hill's Spruce Gulch, valley-fill waste dump is located in the upper reaches of an intermittent drainage to perennial Squaw Creek, which is classified as a fishery. The Spruce Gulch dump contained about 3.5 million tons of waste rock. During the 1992 mid-winter inspections, no flow was exhibited at the toe of the dump, but pH measurements of melting snow taken at the base of the sulfide ore stockpile on top of the dump were between 4.5 and 5. A very apparent odor of oxidizing sulfides was noted. As a result of spring runoff in April 1992, flow appeared at the toe of the dump; pH was 3.1 and heavy metals, sulfate, and total dissolved solids (TDS)

were elevated. Preliminary field observations indicated that AMD was a potential long-term problem, and an intensive environmental and economic assessment was undertaken.

Contamination of surface runoff at the toe of the dump (located above the treatment system described below under Short-Term Mitigation Actions) continued from the discovery of the AMD problem in 1992 until this writing in mid-1995. Field pH levels on the order of 2.6 to 3.6 are typical; sulfate levels commonly range between about 700 and 3,400 mg/L, and TDS between about 800 and 5,700 mg/L. Isolated spikes above these levels have occurred on occasion. Elevated heavy metals include aluminum, copper, iron, manganese, and others. The short-term treatment systems described below are effective in removing most of the contamination from the water.

The chemical reactions involved with acid generation are exothermic. The predominant problematic sulfide mineral is marcasite. Marcasite in the Richmond Hill rock is extremely fine grained, exhibits a high surface area, and oxidizes rapidly. During the late summer and early fall of 1992, fumaroles (areas of escaping steam) were noted along the crest of the waste dump and in areas on top of the dump where backhoes had disturbed the crust that formed from compaction due to heavy equipment traffic. The rate of acid generation was manifested in the temperatures recorded at the fumaroles. A temperature probe inserted just below the surface of one of the fumaroles recorded a temperature of 180 degrees Fahrenheit (4).

Temperatures of AMD water flowing from the toe of the dump were about 35 degrees Fahrenheit in the summer of 1992, when temperatures of water flowing from the base of non-acid-generating waste dumps in the Black Hills that had been subjected to similar waste disposal techniques were over 50 degrees Fahrenheit. An ice block had formed within the rocks at the base of the waste dump due to barometric pumping that pulled in cold air during the winter. Another reason for the lower temperatures of discharge water may be explained, in part, by endothermic reactions that occur as metals precipitate from solution as AMD enters the more neutral receiving environment.

Environmental/Economic Assessment

From 1992 through 1994 the company conducted an intensive environmental and economic assessment. Expert company consultants were brought in to conduct the assessments and to develop mitigative plans. The DENR brought in its own consultants to review the reports and plans as well as to give advice that could be used in regulatory decisions. The Richmond Hill AMD mitigation plan has been subjected to the scrutiny of some of the world's leading experts in the field of AMD reclamation.

The environmental assessment included AMD predictive testing and geochemical analyses. Static testing included acid/base accounting (ABA) tests, net acid generating (NAG) pH tests, paste pH tests, and whole rock analyses. Kinetic testing included humidity cells, column leach tests, and mineralogical analyses. Samples were taken from drill core and cuttings, crusher composites, waste dump trenches, and pit walls.

Experts estimated that approximately 2.7 million tons of rock in the waste depository was acid-generating, representing all waste rock deposited in the dump since the end of 1989. Much of the exposed material in the pit was found to be acid-generating, contributing to contamination of shallow ground water below the pit floor. Some of the spent ore on the leach pads and rock within certain ancillary facilities also was found to be reactive. Reclamation costs were estimated for the various components of the site.

Other environmental assessments included hydrologic impact studies, metals-loading evaluations and mass balance assessments, aquatic impact studies, and identification of contaminant migration pathways and associated environmental receptors. After considering several short-term and long-term mitigative options, the company chose a course of action to address the immediate problems and made plans to implement long-term closure requirements (1).

All water quality data and results from the various environmental assessments are on file at the South Dakota DENR Minerals and Mining Program in Pierre, South Dakota.

DENR Enforcement Action and Bond Increase

In December of 1992, the DENR issued two Notices of Violation (NOV) to Richmond Hill for violating the state mine permit and state water quality standards. Enforcement negotiations continued until March of 1992 when a Stipulation and Stipulated Order was signed. This included a settlement of \$489,000 for alleged violations and specific requirements for short-term and long-term mitigation, water quality and biological monitoring, and provisions for postclosure maintenance and financial assurance. The order required that a long-term AMD mitigation/closure plan be submitted in the form of a formal amendment to the state mine permit. Applications to amend mine permits are subjected to a public review process by the state Board of Minerals and Environment.

Richmond Hill's original reclamation bond before the acid problem developed was \$1.1 million. In response to the economic assessment conducted after the acid problem developed, the bond was incrementally raised to \$10.7

million. The tenfold increase in bonding is testimony to the financial liabilities of AMD and improper sulfide waste management.

Short-Term Mitigation Actions

To counter the immediate problem of contaminated surface discharge down Spruce Gulch into perennial Squaw Creek in the early spring of 1992, a series of treatment ponds were constructed at the toe of the waste dump to chemically treat the dump effluent. Contaminated discharge was treated first with an anoxic limestone drain that proved ineffective. The limestone became armored with iron hydroxide, which rendered it ineffective in neutralization. Below the treatment ponds, a retention pond designed to accommodate the 10-year, 24-hour storm event was constructed. Treatment was accomplished first by the addition of soda ash, and later the additive was changed to caustic soda. The resulting metal hydroxide sludges can be removed periodically.

Partially treated water in the retention pond then is pumped to Richmond Hill's large, lined stormwater pond at the process facility that has a capacity to accommodate about 80 million gallons. The partially treated water undergoes significant dilution in the stormwater pond and is contained and made available for further treatment in a water treatment plant before discharge. Discharge to ground water can be effected via land application, which is regulated through a state ground-water discharge permit or to surface water through a National Pollutant Discharge Elimination System (NPDES) permit.

Other short-term mitigation actions included the following. The sulfide ore stockpile was removed from the waste dump and placed on the leach pads where resulting contamination could be contained. Diversion ditches were constructed around the Spruce Gulch waste dump to direct clean surface runoff from above the dump, around it. Certain amounts of lime, limestone, and alkaline fly ash were added to the waste dump at key locations for further neutralization. A semisealant material called Entac was sprayed on the waste dump in 1992 in an attempt to minimize infiltration of precipitation.

Migration of contaminated ground water was addressed by constructing a cutoff trench in the shallow alluvium across the valley below the waste dump. The resulting water is collected and directed to the treatment ponds.

Although all of the water in the retention pond is pumped to the lined stormwater pond, a certain amount of surface flow remains in Spruce Gulch below the retention pond. This water probably represents a combination of retention pond water seeping through the embankment and shallow ground water that is not cutoff at the trench and that surfaces at springs just below the pond embankment where alluvium pinches out to bedrock.

These treatment processes effectively remove metals and buffer pH. Sulfate and TDS are not removed effectively by base addition to the Spruce Gulch treatment ponds. Comparisons can be made of water quality data representing samples taken from the toe of the waste dump above the treatment ponds and samples taken from Spruce Gulch below the treatment system to determine the effectiveness of the control measures. The water quality data indicates that the combination of short-term control methods have proven quite successful at improving surface water quality below the waste dump.

Long-Term Mitigation Actions

After considering several remedial options, a long-term closure plan was chosen based on the tonnage calculations and identification of the locations of acid-generating rock obtained in the environmental assessment. System hydraulics, water balance, and other site-specific logistics also were considered before deciding on a plan. The state Board of Minerals and Environment reviewed and conditionally approved the mitigation/closure plan in February 1994.

The objective of the closure plan is to reduce the potential for long-term environmental risk to surface and ground water, promote long-term hydrologic and geotechnical stability, and maintain acceptable postclosure land uses.

The reactive waste rock from the dump (2.7 million tons) will be removed from Spruce Gulch and backfilled in 3-foot, compacted lifts in the pit impoundment. In addition to removing the reactive wastes, LAC Minerals decided to remove all 3.5 million tons of rock from the dump. A portion of the nonreactive waste rock will be used in the construction of the pit impoundment cap described below. Some of the acid-generating sulfide-spent ore will be removed from the leach pads in the same manner. As of this writing in June 1995, over 90 percent of the material from Spruce Gulch had been backfilled in the pit.

The determination as to what constitutes material to be removed to the pit impoundment is based on the following criteria: waste rock having a NAG pH of less than 3, which is indicative of an ABA of less than minus 5 tons/kiloton calcium carbonate, and a paste pH of less than 4.5.

After backfilling is complete, the waste rock and corresponding acid-generating pit surfaces will be graded to slopes between 3:1 and 6:1 and capped with a multimedia cover shown in Figure 1. The cap system overlying the compacted waste rock consists (from bottom to top) of the following: 6 inches of onsite crushed limestone, 18 inches of compacted low permeability manufactured soil, 4.5 feet of nonreactive crushed waste material for thermal/frost/root protection of the manufactured soil layer, and 4 to 6 inches of topsoil. The cap will be revegetated with a mixture of aggressive grass species to limit the establishment of deeply rooting woody species and trees that could damage the integrity of the soil liner.

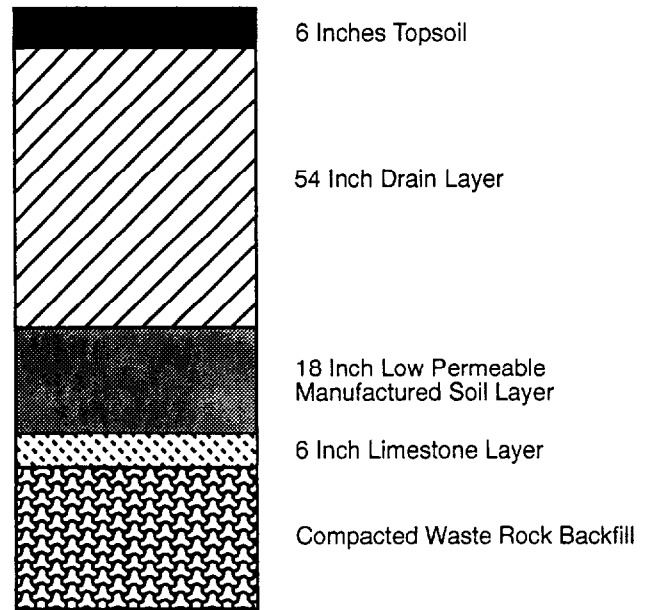


Figure 1. Cross section of Richmond Hill cap.

etated with a mixture of aggressive grass species to limit the establishment of deeply rooting woody species and trees that could damage the integrity of the soil liner. The cap will include a riprap-lined channel to manage runoff and control erosion.

The 18-inch low permeability layer (compacted, manufactured soil) is constructed in two 9-inch lifts and consists of nonreactive waste rock crushed to minus 1/2 inch and blended with about 13 percent bentonite to meet a field permeability criteria of 1×10^{-7} cm/sec. Natural onsite clay was considered, but was found to be of insufficient quantities and of too heterogeneous a nature to consistently meet the permeability criteria. The bentonite-amended material is blended in a pugmill and provides material consistency that allows better quality assurance and quality control during construction.

At the time of the Board of Minerals and Environment hearing, a specific closure plan for the leach pads had not been developed. Preliminary AMD predictive tests indicated that a certain amount of acid-generating spent ore is present within the material that will remain on the pads. Limestone will be thoroughly mixed with reactive spent ore that remains on the leach pad. A condition of the permit amendment requires that an updated closure and postclosure plan for the leach pads be submitted to the DENR for approval prior to mine closure.

The details of the approved plans and specifications (P&S) and the construction quality assurance (CQA) plan for all components of the reclaimed facility required to have such plans (i.e., cap systems and waste rock placement in impoundment) are on file at the DENR Minerals and Mining Program.

This approach to long-term mitigation offers the best chance of a walkaway situation, or as close to it as is technically and economically feasible. The backfill option allows for control of the site's water balance and avoids the need for perpetual water treatment of acid mine drainage. Extensive environmental data will be collected during the closure and postclosure period. Performance monitoring criteria are being developed to assess the success of reclamation and act as a trigger for initiating additional reclamation and/or maintenance work to ensure compliance with long-term reclamation goals.

Postclosure

The postclosure period begins at the time of reclamation surety release (i.e., mine closure) and lasts for a period not to exceed 30 years, unless the state Board of Minerals and Environment determines that a longer or shorter period of time is necessary for compliance with performance standards or design and operating criteria.

The company will submit postclosure maintenance and monitoring plans to the DENR for approval prior to the start of the postclosure period. This includes contingency measures that could be taken to mitigate recurring AMD from any completed component of the reclaimed site. Such measures might include:

- Addition of base material to waste rock.
- Capping or the improvement of capping systems.
- Recovery and treatment of contaminated ground water.
- Mitigation of acid-generating material at ancillary facilities.
- Removal of additional waste rock to the pit impoundment or other suitable location.
- Long-term water treatment of effluent from the pit impoundment or waste dump.

Cost estimates for implementing contingency measures will be included in the postclosure plan.

Prior to the start of the postclosure period, the company will submit a postclosure financial assurance in the amount of \$1.7 million to cover estimated postclosure care (this amount will be recalculated at the time of mine closure). Unless the postclosure period is altered, the financial assurance will be held for 30 years after reclamation surety release to ensure that the reclaimed site is stable and free of hazards; has self-generating vegetation, minimal hydrologic impacts, and minimal releases of substances that adversely effect natural resources; and is maintenance free to the extent practicable.

Performance Monitoring

During and after reclamation, the success of reclamation efforts will be assessed through certain performance monitoring indicators. Monitoring efforts will indicate whether each component of the reclaimed facility is functioning properly and whether additional touchup work is needed to meet closure objectives.

Performance monitoring will be based on the results of surface and ground-water sampling, biologic testing, and outputs of various monitoring devices designed to assess the integrity of the capping systems and AMD reduction in the reclaimed waste material. Such monitoring devices include: lysimeters installed at key locations within the pit impoundment designed to measure AMD reduction and infiltration rates, temperature and oxygen probes in the backfill designed to monitor sulfide oxidation rates, and thermistors installed within the low permeability soil layer designed to indicate whether "heat of reaction" from acid generation within the backfilled waste or frost penetration below the thermal protection barrier are compromising the integrity of the low permeability layer.

Each year LAC Minerals, the DENR, and other appropriate regulatory agencies will meet to review the performance monitoring data acquired during the previous year and collectively assess the success of reclamation. Authorities recognize that closure and postclosure objectives, as determined through environmental monitoring results, will take some time to be reached. Reclamation efforts should not be expected to reach these objectives immediately. Regulatory flexibility must be maintained to allow for this and to ensure that reclamation objectives are being approached over a reasonable amount of time. The annual performance meeting will allow for the identification of justifiable follow-up work to keep reclamation goals on track (4).

The Importance of the Link between Company Operations and Corporate Environmental Policy

Often local mine operations are owned by larger corporations. In many cases, the larger corporations have excellent environmental policies and advocate proper waste management practices and financial provisions for closure plans. LAC Minerals is such a corporation. In fact, LAC has a history of being actively involved with Canada's Mine Environment Neutralization Drainage (MEND) program, an international leader in the field of AMD prediction, prevention, and abatement.

As is true in many arenas—government included—policy and practice might not always run in parallel. In a mining scenario, company-level operations might not be in proper communication with corporate environmental

policy makers. This lack of communication can be particularly damaging when it occurs with regard to the management of sulfide wastes because of the magnitude of the financial and environmental liabilities posed by AMD problems. Regulatory agencies can become keenly aware of such shortcomings and can be drawn in when problems develop. The issue is raised here in a general sense, and is respectfully offered for industry consideration.

Gilt Edge Mine

Numerous abandoned mine reclamation projects have been conducted by active mine operators in the Black Hills of South Dakota on a voluntary basis. These efforts have resulted in a net improvement to the environment while lowering the environmental liability posed by the abandoned mine sites.

One of the more notable reclamation projects was conducted by Brohm Mining Corporation, which operates an active heap leach mine in the northern Black Hills. Tailings from mining operations at Gilt Edge in the early 1900s were placed by the "old-timers" in the drainage of Strawberry Creek, a perennial stream in its middle and lower reaches. The Gilt Edge tailings were situated on property controlled by Brohm Mining, adjacent to one of the open pits associated with the active, permitted mine operation.

The relic tailings originally contained relatively high concentrations of sulfide minerals. As the tailings continued to erode, they produced severe acid mine drainage for many decades along Strawberry Creek. Bear Butte Creek, a perennial stream classified as a marginal fishery into which Strawberry Creek flows, was impacted by acid runoff for varying distances below the confluence, depending on the season and contaminant load. In the late 1980s a pH of 1.9 was recorded in Strawberry Creek immediately below the tailings pile (5). Static tests conducted on the relic tailings in 1993 showed that much of the sulfides had oxidized, leaving behind a significant amount of stored oxidation products (acidity and heavy metals) as a result of previous oxidation reactions (6).

In the fall of 1993, Brohm Mining removed approximately 150,000 tons of reactive tailings from the upper reaches of Strawberry Creek. The tailings were mixed thoroughly with alkaline fly ash from a local coal-fired power plant at a rate that provides sufficient neutralizing potential for contained sulfides. The amended tailings were placed in a "high and dry" disposal area in compacted, 12-inch lifts, graded to a maximum slope of 3H:1V, and capped with a low permeability cover. The fly ash was applied to the tailings in haul trucks and mixed again with bulldozers prior to compaction as it was spread out in the disposal area.

Water was added to the fly ash/tailings mixture, which allowed hydration reactions to occur. This mixing resulted in achieving a pozzolanic (i.e., cementitious) behavior in the mixture, effectively isolating the reactive tailings from air and water. This type of AMD abatement procedure can be much more cost effective than using portland cement grout to achieve the desired reduction in permeability (7).

The tailings were amended with fly ash at a rate sufficient to ensure that the acid-neutralizing potential to acid-generating potential (ANP:AGP) ratio is greater than or equal to 3:1. The fly ash exhibited an average neutralizing potential of 467 tons/kiloton and was added to the tailings at an approximate rate of 25 tons/kiloton of tailings. This proportion was found to be sufficient to neutralize available acidity in the tailings and produce a net neutralization potential of 20 tons/kiloton in the amended tailings (6).

The amended tailings were capped with a low permeability clay liner in 1994. The requirements for the clay liner included a stipulation that it be compacted in 6-inch lifts to at least 90% modified proctor density or 95% standard proctor density. No rocks, sticks, or other debris larger than 2 inches in size were allowed in the liner materials. The permeability of the clay liner had to be equivalent to a 12-inch layer with a maximum permeability of 1×10^{-7} cm/sec. Approved CQA personnel were required to be present on site at all times during the placement of amended tailings and clay liner.

A gravity fed, leachate collection system consisting of geosynthetic material was placed at the bottom of the tailings depository to detect seepage through the cap and amended tailings. Seepage has never been detected since the cap was installed. Considering the added benefit of the pozzolanic nature of the amended tailings, seepage is not likely to be detected in the leachate collection system.

In addition to removing the approximately 150,000 tons of eroding streamside tailings in upper Strawberry Creek, additional historical tailings that had accumulated behind several abandoned beaver dams farther downstream were removed with a dozer and excavator. Removal with a vacuum truck was attempted but proved less efficient than the dozer and excavator.

In 1995, the DENR made use of funds available through the Western Governors' Association and the federal initiative to develop on-site innovative technologies (DOIT) to have the effectiveness of abandoned mine reclamation efforts evaluated on a "watershed basis." As part of this watershed study, conducted by the South Dakota School of Mines and Technology, Strawberry and Bear Butte Creeks were monitored for water quality during and after tailings excavation activities. This monitoring

was conducted to assess the effectiveness of the reclamation project. The results were related to preexisting water quality information. It was found that by employing a combination of best management practices (BMPs) during excavation work, increased sediment load downstream and exacerbation of AMD were kept to a minimum. BMPs included conducting the reclamation efforts in the autumn low flow season, diverting Strawberry Creek flow around work sites during excavation, ceasing excavation activities during precipitation events, and using adequate sedimentation and erosion control devices. Although a slight increase in total dissolved and suspended solids during remediation was noted, the increase was judged to be insignificant and showed little additional release of tailings downstream (8).

The tailings cleanup activities resulted in a significant improvement in water quality and aquatic habitat in Strawberry Creek. Total cost for the project was slightly over \$450,000. Reclamation was entirely funded by Brohm Mining. Discharges below Brohm's active mine operation, which had been of poor quality as a result of the historical tailings, are now in compliance with state Surface Water Discharge (i.e., NPDES) permit limitations.

Conclusions

Most aspects of modern mining in South Dakota have a history of proper regulation and pollution prevention. The only notable exception to this general rule concerns problems associated with acid-generating sulfide wastes.

AMD poses a significant threat to the environment and to the liability for sulfide mine operations, if not properly managed. Attention must be focused on preventing AMD at the source rather than mitigating impacts after the fact.

With the implementation of effective, and notably expensive, AMD reclamation practices such as those implemented at the Richmond Hill facility, adequate environmental protection can be achieved. Nonetheless, suitable mine waste management methods at active mine operations in the Black Hills, demonstrating that acid-generating sulfide wastes can be handled properly from the start of operations, are yet to be incorporated into South Dakota's regulatory history. In some cases, sulfide rock is mined in South Dakota and AMD problems do not occur. In some situations, mined sulfide rocks contain sufficient natural buffering capacity to prevent acid generation; in others, reactive sulfides are identified early and kept to a subcritical volume in the mine plan. Before the permitting of additional operations that include sulfide rock of the problematic nature can be realistically expected in South Dakota, however, "preventative" waste management practices must be developed. These practices must be put in place during all phases of the mining operation, from start-up to closure.

The Richmond Hill AMD problem, with its regulation, enforcement, and subsequent reclamation work, is the most complex heap leach mining-related environmental issue that has arisen in the Black Hills. The reclamation work at the mine represents the culmination of exhaustive environmental planning. This work is progressing in excellent fashion and with very promising results.

Backfilling, compacting, and capping the reactive waste in the Richmond Hill pit impoundment allows for control of the site's water balance and avoids the need for perpetual water treatment of AMD. With the exception of a limited amount of performance monitoring, this approach toward long-term reclamation offers the best chance of a walkaway situation, or as close to it as technically and economically feasible.

The cleanup of the acid-generating Gilt Edge tailings along Strawberry Creek represents one of the most significant abandoned mine cleanup efforts conducted in the Black Hills. This project is one of several such efforts undertaken by active mine operators in South Dakota to manage environmental problems caused by abandoned mines located on properties they control. Although South Dakota does not have an abandoned mine reclamation program, opportunities for cleanup of abandoned mine sites are pursued cooperatively as they arise. An intent to overcome regulatory barriers that might otherwise tend to stifle cleanup efforts has proven successful at keeping these reclamation projects out of the legal realm. This allows resources to be expended for on-the-ground site improvements, which is where they should be focused.

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Chapter 8.

The Mine Waste Technology Program and Technologies To Address Environmental Problems at Inactive Mine Sites

Martin Foote

Introduction

Two separate topics are covered in this paper. The Mine Waste Technology Program and a number of technologies that can be used to address mine waste. These technologies are categorized into treatment technologies, pathway interrupt technologies, and source control technologies.

In 1991 Congress established a pilot program for treating mine wastes in Butte, Montana. Under an Interagency Agreement (IAG), the U.S. Environmental Protection Agency (EPA) is collaborating with the U.S. Department of Energy (DOE) to implement this congressional directive. MSE, Inc., is the performing contractor for the Mine Waste Technology Program (MWTP).

The Mine Waste Technology Program

The MWTP covers the following activity areas:

- *Activity I*—Montana Tech identifies and prioritizes technical issues, waste forms, and waste sites as well as promising innovative treatment technologies. After further evaluation of these topics, Montana Tech recommends candidate sites and technologies for demonstration or research projects.
- *Activity II*—Montana Tech develops a Generic Quality Assurance Project Plan.
- *Activity III*—MSE proposes and then conducts large pilot- and field-scale demonstration projects for several innovative technologies that show promise for cost-effectively remediating local, regional, and national mining waste problems.
- *Activity IV*—Montana Tech develops and then implements a plan to conduct bench- and small pilot-scale research on several innovative technologies that

show promise for cost-effectively remediating local, regional, and national mining waste problems.

- *Activity V*—MSE prepares and distributes program reports and develops and conducts a series of symposia/workshops to present the interim and final results of the demonstration projects to user communities.
- *Activity VI*—Montana Tech develops and then implements a plan to establish training and educational programs on mine waste treatment technologies.

MWTP Organization

The MWTP is directed by the IAG Management Committee, whose roles, responsibilities, and authorities are described below.

Environmental Protection Agency

Program and technical oversight of the MWTP is the responsibility of the Sustainable Technology Division of the National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio. The NRMRL provides a project officer, who also is a member of the IAG Management Committee, a quality assurance officer, and support staff to the program. Additional technical oversight is provided by the EPA Region 8 office in Denver, Colorado, and the EPA Montana operations office, both of which provide a representative member to the IAG Management Committee.

Department of Energy

Program oversight is the responsibility of the Western Environmental Technology Office (WETO) of the DOE, Environmental Management (EM), Office of Technology Development. Under WETO, the Pittsburgh Energy Technology Center provides administrative support on envi-

ronmental as well as safety and health issues and on matters concerning regulatory compliance and operational conduct.

MSE, Inc.

MSE, the DOE contractor in Butte, Montana, is the principal performing contractor for the MWTP. MSE provides a Mine Waste Programs Manager, who is the point of contact for all mine waste activities, including program management and coordination, program status reporting, funds distribution, and communications.

Montana Tech

As a subcontractor to MSE, Montana Tech is responsible to the Mine Waste Programs Manager for all work performed under Activities I, II, IV, and VI.

Technical Integration Committee

The nine-member Technical Integration Committee (TIC), made up of representatives of the public and private sectors, reviews progress toward meeting program goals and advises the IAG Management Committee on pertinent concerns.

Industrial Integration Committee

An Industrial Integration Committee (IIC) provides a link between industry and the MWTP demonstration projects. The IIC solicits information on industry's remediation needs and requirements, provides evaluations of technology demonstrations, and assists in technology transfer as required under Activity V.

Activity III Project Descriptions

A brief description and status of each of the projects being conducted under Activity III and an overview of relevant Montana Tech activities are provided below.

Project 1—Remote Mine Site Demonstration

EPA requested that MSE develop a facility at a remote site for treatment of acidic metal-laden water. Given the nature of such sites, the facility would be required to operate on water power alone and without operator assistance for extended periods. The Crystal Mine, located 7 miles north of Basin, Montana, was chosen as the site for this technology demonstration because it is a good example of a remote mine site with a point-source aqueous discharge. The Crystal Mine demonstration facility treats a flow of water ranging from 10 to 25 gallons per minute, approximately one-half of the total discharge. The process consists of several unit operations: initial oxidation, alkaline reagent addition, final oxidation, ini-

tial solid-liquid separation, pH adjustment, and final solid-liquid separation.

Project 2—Clay-Based Grouting Demonstration

Inflow of surface and ground water into underground mine workings is a significant problem worldwide. The technology selected for this demonstration project, clay grouting, inhibits or eliminates this flow by injecting a fine-grained clay slurry into the flow pathways. By virtue of its chemical and physical characteristics, the grout sets up within these spaces to block ground-water flow. The distinguishing feature of clay-based grouts is that throughout the stabilization period they retain their plasticity and do not crystallize, unlike cement-based grouts. Clay-based grouting is being demonstrated at the Mike Horse Mine, located 15 miles east of Lincoln, Montana. This project consists of three phases: site characterization, grout formulation, and grout placement. The EPA Superfund Innovative Technology Evaluation (SITE) program provided sampling, characterization, and analytical data for the project.

Project 3—Sulfate-Reducing Bacteria Demonstration

The goal of this project is to demonstrate that the sulfate-reducing bacteria (SRB) technology can be used to slow or reverse the acid-generation process and improve water quality at affected sites. The Lilly/Orphan Boy Mine, near Elliston, Montana, was chosen for this demonstration. This technology can reduce the contamination of aqueous waste in three ways: 1) sulfate is reduced to hydrogen sulfide through the metabolic activity of the SRB, 2) the hydrogen sulfide reacts with dissolved metals, resulting in the formation of insoluble metal sulfides, and 3) bicarbonate produced by the sulfate reduction process increases the pH of the solution. Because SRB need a source of carbon in the form of a simple organic nutrient, an organic substrate composed of cow manure, decomposed wood chips, and alfalfa was added to the system. Application of the technology involves using the subsurface mine workings of the Lilly/Orphan Boy Mine as an in situ biological reactor. Pilot-scale testing of the technology was conducted at the WETO in Butte, Montana.

Project 4—Nitrate Removal Demonstration

The presence of nitrates in water can have detrimental effects on human health and the environment. Improving the economics of nitrate removal and reducing or eliminating the waste generated during nitrate removal are the goals of this project. To that end, the MWTP undertook an extensive search to evaluate innovative technologies that could be applied to the nitrate problem. Of the 19 technologies that were screened against selec-

tion criteria, three showed the most promise for making nitrate removal more cost effective and environmentally sound: ion exchange with a nitrate-selective resin, biological denitrification, and electrochemical ion exchange. This project involves the testing of combinations of these three technologies. The Mineral Hill Mine, near Jardine, Montana, was chosen for this demonstration. The process train for this project will allow technical evaluation of each technology combination as well as confirmation of preliminary economic studies. Because the nitrate problem is not exclusive to mining, data generated from the proposed test process train also could be relevant for other industries (e.g., for application to chemical processing plants, agricultural runoff, municipal water treatment).

Project 5—Biocyanide Demonstration

Cyanide is used in the mining industry to extract precious metals from ores and to improve the efficiency of metals separation in beneficiation. Cyanide, however, can be an acute poison and also has the ability to form strong complexes with several metals, resulting in the increased mobility of those metals. As such, cyanide can contribute to environmental problems in several ways. The McCoy/Cove Mine, near Battle Mountain, Nevada, was selected as the preferred site for this demonstration. The first goal of this project is to develop a reactor that will use the cyanide degrading effects of gelatinous bead-contained bacteria to degrade cyanide from mining wastewater. The bacteria within the beads and the method of placing the bacteria into the beads were developed by researchers at the Idaho National Engineering Laboratory (INEL) and the Center for Biofilm Engineering (CBE) at Montana State University, along with Selma University (SU). This gelatinous bead reactor will be tested in a side-by-side manner with another reactor design developed by Pintail Systems, Inc., of Aurora, Colorado. The second goal is to develop a method for using the bacteria for *in situ* remediation of cyanide-contaminated solid mining wastes. In this phase of the project, researchers will study the manner in which cyanide is held within heap leach and tailings piles and determine the forms of cyanide within these forms of solid wastes. Tests also will be conducted to determine the best way to use the bacteria to degrade these forms of cyanide within the solid waste pile itself.

In the remainder of this paper, technologies that can be used to treat mine waste are described.

Treatment Technologies

Adsorption

Adsorption is a process by which dissolved materials in a solution will adhere to the surface of other materials,

usually solids, introduced into that solution. Several adsorption mediums have been developed for this purpose, including activated carbon and charcoal, BIO-FIX beads, filamentous fungi biomass, humic and fulvic acids, low rank coals, and metal hydroxides.

Anoxic Limestone Drain

This device is used most often as a portion of a passive system. It is composed of a long (lengths greater than 50 meters have been used) trench lined with an impermeable liner and filled with pieces of limestone. The trench is covered by the same type of impermeable liner and then buried beneath a layer of clay and a vegetated crown. Acidic mine discharges are directed into the upper end of the covered trench and allowed to percolate down through the contained limestone. The limestone is dissolved slowly by the solution, which raises the alkalinity and pH of the solution. The effluent from the drain is directed into a settling pond to allow hydroxide precipitates to form and settle out of solution. These drains are functional only on acidic mine drainages that are low in ferric iron concentration and oxidation potential. If sizeable quantities of ferric iron exist in the inflow solution, ferric hydroxides will form within the drain and armor the limestone, rendering the drain ineffective.

Bioadsorption

Bioadsorption is a subform of the broader topic of adsorption by which biological materials such as BIO-FIX beads, humic and fulvic acids, and filamentous fungi biomass are used as the adsorption medium.

Biological Reduction

This process is defined as the chemical reduction of dissolved species by the action of biological processes. When dealing with the treatment of aqueous waste streams, this process is generally limited to the reduction of dissolved sulfate to hydrogen sulfide and the concomitant oxidation of organic nutrient compounds to bicarbonate within the aqueous solution. Several species of the *Desulfovibrio* family of bacteria will catalyze this type of reaction. These bacteria are hardy and can tolerate wide temperature swings (-5 to 50 degrees Celsius) and variation in solution pH (5 to 9). A pH below 5.0, however, will severely reduce the activity of these bacteria. The bacteria also can be inhibited by high concentrations of certain aqueous metal species such as copper and zinc. The bacteria do require reducing conditions within the solution and will not tolerate aerobic conditions for extended periods.

Chelation Chromatography

Chelation is a well-known chemical process. Chelating agents, complex organic chemicals that have more than one reactive site, are materials that are capable of forming more than one ionic bond with a substance dissolved in a solution. If the chelating agent can be attached to a surface, the dissolved material can then be removed from the solution by removal of the attached medium.

Chemical Oxidation

This process involves the addition of an oxidizing reagent to a waste stream. Some of the more common reagents used in this process are hydrogen peroxide, potassium permanganate, and sodium hypochlorate. The addition of one of these chemicals to the waste stream will oxidize the reduced forms of several of the dissolved metallic ions to the oxidized forms. In most situations, the oxidized ions hydrolyze to form insoluble hydroxide compounds at lower pHs than the reduced forms of the ions.

Chemical Precipitation

Chemical precipitation is probably the oldest method used to treat acidic, metal-bearing mine drainages. The method involves adding a chemical reagent to the mine effluent solution to facilitate a solid-forming reaction between the dissolved constituents of the mine effluent and the reagent within the waste stream. The solid materials formed are then removed from the water. Direct effects on the pH of the waste solution might or might not occur, depending on the reagent used. Chemical precipitation is a very large field comprising hundreds of potentially applicable processes.

Coagulation, Sedimentation, and Flocculation

These three generic processes have all been used, both naturally and in man-made methodologies, to remove suspended and/or finely divided particulate matter from aqueous streams. At least one of these generic processes will have to be used in conjunction with all of the previously described technologies, which produce a precipitate within the waste stream. These processes also will have to be used in conjunction with several other processes (i.e., ion-exchange, chelation, solvent extraction, and some adsorption processes) that require a clear liquid inflow to function efficiently.

Column Flotation

Column flotation functions on the same principle as simple flotation, except the structure of the flotation device is in the form of a vertical tube rather than a short,

wide cell. The length of the column and the use of froth wash water produce a very clean, highly concentrated solid product. Column flotation units also have been shown to be efficient in floating, and thus removing, very small particles from the slurry. This function would be most useful in the remediation of acidic mine discharges. The removal of these fine particulates from the waste stream in an efficient, cost-effective manner is essential for the efficient use of several of the other remediation methods.

Copper Cementation

This is an old and much used process for removing copper from acidic mine waters. The process involves adding metallic iron to the copper-bearing solution to cause the reduction of the more noble copper and the oxidation of the iron. Thus, the copper precipitates out of the solution as copper metal and the iron is dissolved. This process is very effective at removing copper from solution, but it does not decrease the quantity of dissolved solids in the solution as the amount of iron in solution is increased. Also, the pH of the solution is not effected by the process. The major reason for using this process is to produce a valuable product for resale. Using this process would be justifiable as a first step in a process stream as a means of mitigating the total remediation costs of a water.

Dilution

Dilution can be a major process in the reduction of dissolved constituents in acidic mine drainages in most natural settings. The process also could be used in conjunction with another process that produces an effluent stream that more than meets discharge specifications. A portion of untreated water could then be mixed with the highly treated water to produce a greater quantity of effluent that would still meet discharge specifications. Such secondary processes have been proposed for use with chelation, distillation, and freeze crystallization technologies to reduce the amount of water that would ultimately have to be treated.

Distillation

Distillation has been used for many years as a method of purifying water and other solvents. The process has been hypothesized as a means of cleaning acidic mine discharges and would be effective. The inefficiency and subsequent high energy cost of using this basic technique, however, is prohibitive. Another problem with using simple distillation as a means of cleaning mine waste streams arises from the quantity of dissolved solids in the inflow stream. A functional maximum for the dissolved solids contained in an inflow to a conventional distillation system is approximately 3,000 mg/L. This specific

value depends on the saturation level of the specific salts produced from the distillation process. High values of most dissolved solids in the inflow, however, usually result in numerous problems of scale buildup and precipitate formation.

Electrochemical Precipitation

In this process two carbon steel electrodes are placed into a waste stream. A continuous direct current is applied to the electrodes, causing the formation of ferrous hydroxide at the anode. This solid hydroxide adsorbs other metals from the waste solution and induces coprecipitation of other hydroxides, thereby generating a sludge containing the previously dissolved metals that can be removed from the solution. The carbon steel electrodes are continuously consumed and need to be replaced periodically.

Electrocoagulation

This process involves passing an electric current through the mine waste stream by means of metal surfaces to induce the precipitation of dissolved metal ions onto the metal surfaces. The electric current used in the process can be either direct or alternating. The electric potential is reversed periodically to prevent the deposition of excessive quantities of precipitate on the positive or negatively charged surfaces. The electrocoagulated waste solution is passed into a thickener or clarifier to remove the suspended particles.

Electrodialysis

In this process an electric potential is used to cause the movement of dissolved, positively and negatively charged, ionic materials through a semipermeable, hybrid membrane. As a result, the dissolved charged particles are concentrated into a brine that is separated from the treated water by the semipermeable membrane. The brine may comprise 15 to 25 percent of the original volume of the waste stream. This technology has been proven viable in the metals plating industry; however, it has not been demonstrated as functional in acidic mine drainages.

Electrokinetic Osmosis

This process is used to cause the movement of water through a porous material that inhibits the movement of particles along with the water. When particle movement is restricted by the presence of a porous medium and a direct electrical current is applied to the medium, cat-

ions will be attracted toward the cathode and anions toward the anode. If a porous medium is chosen, such as a clay that has a negative surface charge, the number of mobile cations will be larger than the number of mobile anions and a net movement of cations toward the cathode will result. Thus, this movement of cations tends to drag water toward the cathode.

Electrophoresis

This process uses an electrical potential introduced into the waste stream to cause the movement of particles and colloidal particulates toward the electrode, which is of the opposite charge to that of the particle. The movement of the colloidal particulates is caused by the interaction of the charged surfaces of the particles and the electrical potential introduced to the waste stream. The colloidal particles, one example of which is represented by the previously described metal hydroxides, lose their charge upon reaching the electrode toward which migration occurred and then coagulate as a precipitated sludge.

Electrowinning

This process is a form of electrophoresis combined with electrochemistry. One of the commercial applications of this process is called electroplating, in which thin coverings of a noble metal are deposited on metallic objects. The process uses a direct electric current applied to electrodes within the aqueous solution to attract the positively charged dissolved ionic material in the solution to the negatively charged electrode, where the metal ion is reduced and adheres to the electrode. The process results in adding a thin film of the metal to the electrode surface.

Evaporation

Evaporation has been used commercially to reduce the volume of aqueous brines that have been produced from the application of several technologies. Evaporation is distinguished from distillation in that the vapor phase is recondensed in distillation to produce a clean fluid; in evaporation the vapor is not recondensed but is allowed to escape. Some of the problems encountered with evaporation are the lack of a cleaned effluent stream, which can be a concern in some situations, and the precipitation of saturated solids from the evaporating fluid that have to be dealt with. The natural evaporation process, which makes use of solar energy, has been applied to the problem of wastewater disposal in many areas with dry, warm climates, but has not been shown to be effective in other climates.

Filtration and Ultrafiltration

Filtration is the process of separating suspended solids from their suspending liquids by passing the mixture through a porous medium that retains the solid material. Filtration as a means of removing solids from waste streams has been in use for centuries. Many modern practices and applications of filtration can be used as a step in the remediation of acidic mine drainages.

Ultrafiltration is a membrane technology that uses pressure applied on the liquid phase to separate macromolecular/colloidal solutes from that liquid phase of the solution. In essence, the liquid is driven through the membrane by the pressure and the large, dissolved solutes are retained. The technology has been applied in bench- and pilot-scale tests to the separation of oil-water emulsions. The technology also has been tested on the removal of very finely dispersed colloidal suspensions of metal hydroxides from wastewaters.

Freeze Crystallization

The application of freezing to the problem of solvent purification has been in use for quite some time; however, the use of this technology in the field of treating water-based mine discharges has been attempted only recently. The generic principle applied by this process is the natural rejection of dissolved contaminants from the crystal structures of a freezing solvent. Contaminants that are included in the solid fraction of the freezing liquid usually are included as engulfed particulates in larger crystals and not as chemical components of the crystal structure. Therefore, by partially freezing contaminated water into a slurry of very small crystals and a concentrated brine, a separation of contaminants and clean water, as ice, can be made. The clean ice crystals are separated from the brine, washed of any brine residuum, and melted to produce a cleaned effluent.

Froth Flotation

Froth flotation has been used for many years to separate specific particulate matter from water-based slurries. The method uses chemical reagents to produce a nonwetting surface on certain particles and then bubbles a gas, usually air, through the slurry. The particles with the nonwetting surfaces adhere to the gas bubbles and are carried to the top of the flotation vessel where the froth and slurry are separated.

Gas Hydrate Formation

Gas hydrates are solid materials formed when a gas, usually a low molecular weight hydrocarbon or carbon dioxide under high pressure, is introduced into water within a closed vessel. Contaminants found in the water

are rejected from the crystal structure of the solid hydrate. Large amounts of heat are given off from the hydrate-producing reactions because the reactions are exothermic. Several water molecules react with each of the gas molecules to form a specific gas hydrate. The small crystals of gas hydrate are removed from the waste stream and the original water-borne contaminants are concentrated in the remaining volume of brine. The solid gas hydrate is then decomposed, by warming or by lowering the pressure, into water and the original gas.

Ion-Exchange Processes

Ion-exchange processes have been used for many years to remove contaminants from many types of wastewater streams. The process removes metal ions and some anions from the waste streams by exchanging these ions for other ions that originally are held on the surface of the ion-exchange medium. The most common ions that are added to the waste stream are sodium, potassium, calcium, and chloride.

Physical Oxidation

This process involves agitation of the aqueous waste stream to increase the reaction between the waste stream and the oxygen in the air. The results of the process are the same as the chemical oxidation process, that is, precipitation of insoluble hydroxide compounds due to hydrolysis.

Reverse Osmosis

This membrane technology uses high pressures applied to the contaminated fluid to force the solvent phase of the fluid through a semipermeable membrane, concentrating the contaminants in a remnant brine. The process has been applied commercially to the desalinization of brackish water and pilot plant-scale operations have been used on several different types of wastewater. The process usually will recover up to 75 percent of the inflow water efficiently, but difficulties have been encountered in attempting to increase this value, dependent on the concentration and chemistry of the dissolved contaminants.

Solvent Extraction

This technique is used commercially to remove dissolved metal ions from acidic solutions. The largest use for this process is in the copper mining industry, but the process also has been used at zinc-producing facilities and several other types of metal-producing plants. The process brings an organic liquid into contact with the acidic mine discharge. Ions dissolved in the aqueous waste solution become concentrated within the organic liquid. The mix-

ture of organic and aqueous liquids then is directed into a tank where the organic liquid separates from the aqueous material due to immiscibility. The loaded organic liquid is stripped of dissolved metals by sulfuric acid and recycled. The metals then can be removed from the acidic stripping solution by electrowinning or crystallization.

Pathway Interrupt Technologies

Alkaline Reagent Addition

The addition of alkaline reagents, both solids and liquids, to acid-generating waste piles and to underground mine workings has been used as a means of mitigating the production of acidic mine drainages for some time. This process is based on the neutralization process, which also uses this type of reagent. The liquid reagents have been used on waste piles and on surface recharge areas for waters within underground mine workings. The solid materials have been used with solid waste piles, contaminated soils, and underground mine openings.

The use of the liquid reagents has proven to be disappointing due to the rapid depletion of the reagent by precipitation and the channeling of the reagent solution within the waste piles. Capping waste piles with solid alkaline reagents, by simply layering the reagent, tends to form a hardened crust of iron-rich solids within and immediately below the reagent layer. Although these crusts tend to form a barrier to movement of water, they are penetrated easily by plant roots and erosion and thus are not considered to be good long-term remediation solutions. Mixing the reagent with the waste material over a depth of several feet has been shown to be a more viable methodology.

Capping and Revegetation

This process is used as a method of decreasing the production of acidic components emanating from mine waste piles. The quantity of acid being generated from waste dumps and tailings piles can be decreased and possibly eliminated by stopping the flow of water and oxygen into the pile. Attempts have been made to prevent this flow by recontouring the piles and then capping them with an impervious layer of material, usually a clay underlain by a layer of solid alkaline reagent such as limestone. Some of the clays used have been supplemented with salt solutions. The capping clay layer then is buried with a layer of gravels and one of soil and later revegetated. A secondary beneficial aspect of this process is the establishment of conditions in the deeper portions of the capped piles to reduce or eliminate the effects of oxidizing bacteria.

Chemical Stabilization

This process involves the addition of chemical additives to mine waste piles and abandoned and active mine workings to isolate the acid-generating minerals and thus prevent the formation of acidic components by the reaction of these minerals with oxygen and water. The process is similar or identical to alkaline reagent addition discussed above.

Phosphate Addition

Phosphate anions will react with iron to produce iron phosphate, a highly insoluble solid. This reaction is the basis for this technology. Phosphatic solutions have been sprayed on test piles to assess the process in the same way that alkaline reagents have been tested. Phosphatic solutions, like alkaline solutions, have been added to the recharge areas for water in abandoned underground mine workings in an effort to mitigate the acid being generated in the wall rocks of these workings. Solid phosphate-bearing ores also have been mixed with test piles to determine the functionality of the process.

Sulfide Extraction

A large number of mineral processing technologies could be used to remove the acid-generating minerals from solid mine wastes and therefore render the majority of the waste mass harmless. The process of froth flotation, described above, can be used for this purpose. Other mineral processing techniques, such as gravity separation and magnetic separation, also could be used for this purpose. To date, however, the majority of these methods have not been tested as to their ability to remove pyrite and other acid-producing minerals from mining wastes.

Source Control Technologies

Bactericide Addition

This process involves the addition of a material to the solid mine waste that will inhibit or destroy the ferroxidans bacteria that aid in the oxidation of the sulfide minerals and thus facilitate production of acidic drainages. The most common of these materials is sodium laurel sulfate, which is an ingredient in detergent. This material inhibits the ability of the bacteria to survive in acidic mediums by damaging the protective slime coating that covers the bacteria. In general, these processes have been effective only for limited periods of time due to the effective life span of the reagents. Newer, timed release versions of these materials have been developed.

Grouting

Numerous methods have been considered, developed, and tested to prevent the movement of water in the subsurface. Grouting is one of these technologies. Grout is a material that is used in many sealing-type operations in the geotechnical industry. In the proper situation, grouting can be used as a method of preventing acid generation. The theory behind the method is quite simple: An impermeable barrier is developed in the form of a grout curtain or other assemblage to prevent ground water from coming in contact with minerals having acid generating capabilities. A grout curtain is established by injecting grout into a series of boreholes, while the material is under pressure, and allowing it to solidify. The cementitious material permeates the various openings and structures in the rock and seals them.

In Situ Vitrification

This process involves the use of electricity or another external energy source to melt the waste material and thus produce an impermeable glass that has very low leachability and acid-production capabilities. The process has been used to remediate contaminated sediments and soils. The process could be functional for fine-grained tailings but would not be of much use on waste dumps with large masses and void spaces. The melting process reduces the overall volume of the waste; therefore, the area has to be backfilled to reduce the surface subsidence.

Inundation and Saturation

This process is simply the storage of tailings and other solid mine wastes underwater. This technology is based on an attempt to reduce or terminate the production of acid and the subsequent leaching of metals from solid mine wastes by inhibiting the contact of oxygen with the wastes. Evidence suggests that the chemical reactivity of sulfide-based tailings is reduced by such methods of storage. The amount of oxygen that is soluble in water at saturation is approximately 8 parts per million, which

is much less than the amount of oxygen found in air (+/- 20 percent). Thus, the oxidation potential of water is much less than that of air or moist air.

Reducing Atmosphere

As stated, the source of acid generation in the vast majority of mine wastes is the oxidation of sulfide bearing minerals. This oxidation process, often accelerated by biological processes, requires the presence of oxygen to initiate and continue the reaction. By creating an atmosphere in the vicinity of the acid production sites that is devoid of or very low in oxygen, the acid-producing reactions will be hindered. This process functions naturally in several underground mines where carbon monoxide/dioxide-rich atmospheres can be found in poorly ventilated areas. The introduction of these or other gases to sealed, secure mine workings in the form of smoke or another gaseous mixture might constitute a low cost, effective source-control type of mechanism, but this approach would be difficult to implement.

Sulfide Extraction

See description in Pathway Interrupt section.

Temperature Reduction

The rate of acid production is slowed if the temperature of the reaction is reduced. This slowing is also true for reactions catalyzed by biological processes. Therefore, researchers have envisioned that reducing the temperature at the site of the acid production by an artificial method could be used as a source-control type of technology for reducing acid production. This process might not be feasible for mine waste piles or for large, complex mine systems. The methodology might be viable, however, for use in small-scale, underground, abandoned operations that do not exhibit large amounts of geothermal heat production. Such processes may prove most effective for mining operations based in northern latitudes and high altitudes.

Chapter 9.

Innovative Approaches to Addressing Environmental Problems for the Upper Blackfoot Mining Complex: Overview

Judy Reese

Project Location

The Upper Blackfoot Mining Complex (UBMC), also known as the Heddleston Mining District, is located approximately 16 miles east of Lincoln, Montana, in Lewis and Clark County (Figure 1). It consists of numerous historic mine sites, including but not limited to, the Mike Horse, Anaconda, Mary P., Edith, Paymaster, and Carbonate (Figure 1). The distance from the Carbonate Mine to the Mike Horse Mine is approximately 3 miles. The Heddleston District is situated within the headwaters area of the Big Blackfoot River, which originates at the confluence of Anaconda and Beartrap Creeks.

Regional Setting

The UBMC lies within a high, forested basin bounded by the continental divide to the north, northeast, east, and southeast. Elevations along the divide range from 5,600 to 7,200 feet above mean sea level (msl). The elevation of the Lower Carbonate Mine site is 5,200 feet above msl and the Mike Horse Mine is approximately 5,600 feet above msl. Average annual precipitation in this area is approximately 21 inches per year (1), with roughly two-thirds of the precipitation as snowfall (2). A weather station located 2 miles north of the UBMC recorded the lowest temperature on record prior to 1970 in the contigu-

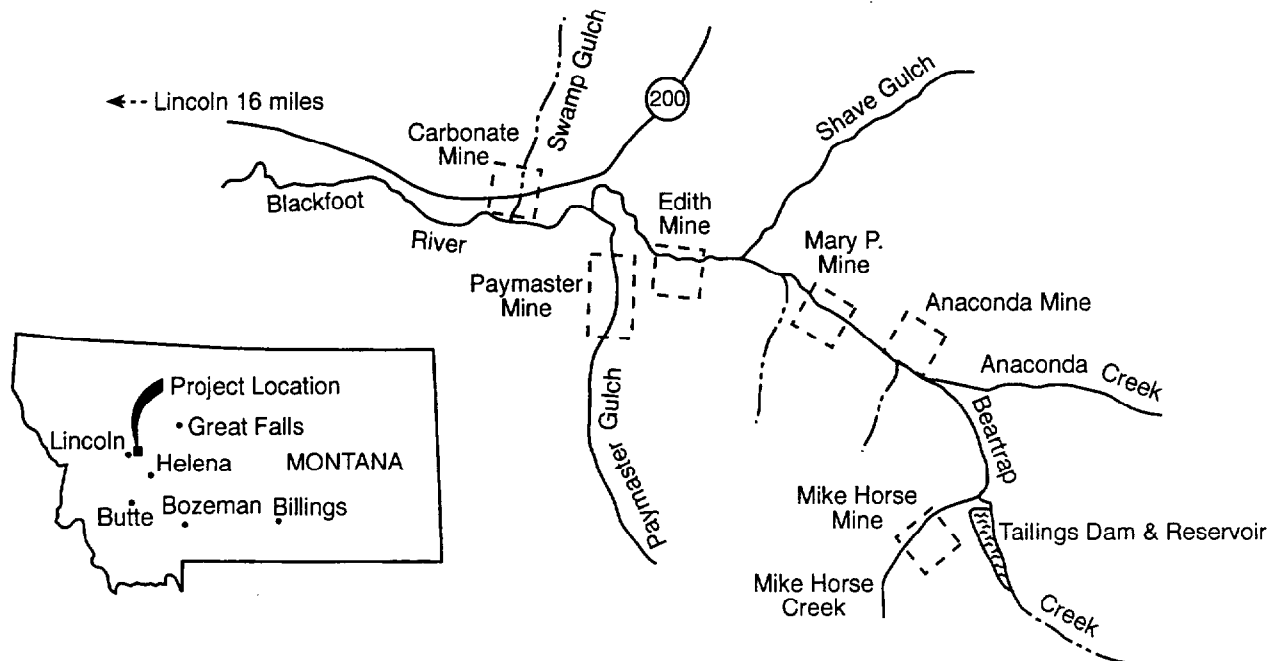


Figure 1. Upper Blackfoot Mining Complex.

ous United States (minus 70 degrees Fahrenheit on January 20, 1954) (1).

Geology and Mineralization

The rocks within the UBMC area range in age from Precambrian Spokane Formation to Tertiary intrusives and include recent alluvial deposits. Late Proterozoic age diorite sills and Tertiary age stocks, sills, and dikes of quartz porphyry and monzonite porphyry intrude the Spokane quartzite and argillite rocks. Two types of mineralization, silver-lead-zinc veins and copper-molybdenum porphyry are present within this area. The silver-lead-zinc mineralization occurs along northwest trending fractures and to a lesser degree along northeast oriented fractures. Historically, mining was concentrated along this fracture-controlled mineralization (3).

Historical Mining Activity

Silver-lead-zinc ore was first discovered at the UBMC in 1898 by Joseph Heitmiller. Minerals exploration activities continued through the early 1980s. Silver, lead, zinc, and copper were mined from this area from 1898 through 1955 with minor gold extracted prior to 1900 (4). Mining was conducted by several individuals and small companies from 1898 through 1945. ASARCO purchased most of the private landholdings in 1945 and owned and operated the Mike Horse Mine and Mill, as well as the town of Mike Horse, from 1945 through 1955. The Mike Horse Mine was the largest in the district. It consisted of 10 underground working levels, which were driven along mineralized veins up to 2,000 feet long. Total production from the Heddleston District was minor, in part due to its remote location. The district produced 450,000 tons of ore, of which 385,000 tons were produced from the Mike Horse Mine, during 1945 to 1952 (4).

The Anaconda Company leased the ASARCO holdings from 1964 through 1981. From 1962 through 1973, Anaconda conducted an extensive exploration program that resulted in the delineation of a 93-million-ton near-surface copper-molybdenum porphyry ore body (about one-half percent copper) located east of Paymaster Creek. In addition to its private holdings, ASARCO continues to hold unpatented claims within the UBMC. The unpatented land within and surrounding the UBMC area is owned by the U.S. Forest Service.

Environmental Degradation

Historical mining practices resulted in contamination of surface water, ground water, soils, and stream sediments. The sources of contamination include mine wastes and tailings (Table 1) as well as acid mine drainage from several adits located throughout the complex. The primary contaminants of concern from these sources include zinc,

cadmium, iron, manganese, aluminum, copper, and lead. Acid mine drainage from the Mike Horse Mine 300-level adit (Table 2) is the primary source of surface water and stream sediment degradation within (5,6) and downstream of the UBMC (5,6,7). Flows from this adit vary from 10 to 140 gallons per minute (gpm) (8). The pH typically ranges from 5.4 to 6.3 (9) with an occasional low in the range of 4 to 4.6 (10). Relative to the Mike Horse adit discharge, acid mine drainage from adits located at the Anaconda, Paymaster, and other mine sites are minor sources of contamination, with flows of between less than 1.0 to 7.5 gpm.

Tailings from the Mike Horse Mill were used to construct a tailings impoundment within the Beartrap Creek drainage. Mill tailings were conveyed via wooden flumes to the impoundment site from 1916 through 1953 (4). In 1975 the Beartrap Creek tailings impoundment failed, releasing approximately 200,000 cubic yards of tailings into Beartrap Creek and the Upper Blackfoot River (11).

Table 1. Upper Blackfoot Mining Complex Mine Wastes and Tailings

Contaminants	Ranges (mg/kg)
Aluminum	3,278-18,240
Arsenic	42-3,555
Cadmium	1-134
Copper	59-7,405
Lead	112-21,803
Manganese	11-8,540
Mercury	50-3,400
Zinc	23-4,333

Table 2. Mike Horse Mine Adit Water Quality (Totals)

Contaminants	Ranges (mg/L)	sMCL ^a
Aluminum	0.14 - 1.3	0.2
Cadmium	0.02 - 0.2	0.005 (MCL)
Copper	0.15 - 1.8	1.0
Iron	4.2 - 74.0	0.3
Lead	0.005 - 0.48	0.015 (MCL)
Manganese	8.7 - 53.0	0.05
Sulfate	346.0 - 2,927.0	250.0
Zinc	26.0 - 90.0	5.0

^a sMCL = secondary maximum contaminant level.

The dam was reconstructed later in 1975 by the Anaconda Company.

A study conducted prior to the 1975 dam breach showed bed sediment enrichment of cadmium, copper, and zinc as well as coatings of iron-manganese oxyhydroxides within the upper reaches of the Blackfoot River (5). Prior to the dam breach, an extensive natural wetland system mitigated transport of contaminants downstream. The dam breach channelized the marshes, facilitating unimpeded transport of contaminants downstream.

Concentrations of copper and cadmium in surface water exceeding acute and chronic toxicity threshold values were found to be highest near the sources and extended the farthest downstream during spring flows (6,7). The observed rapid decrease of solute contaminants below the source is probably related to the precipitation of iron oxyhydroxides (12) and high concentration of sulfate (13). Elevated concentrations of sulfate and bioavailable cadmium and zinc extended the farthest downstream (6). The general downstream order of mobilization of bioavailable metals is cadmium, zinc > copper > arsenic, nickel (12). Elevated levels of zinc, copper, and cadmium were periodically detected as far as 10 miles downstream of the UBMC (7).

Levels of arsenic and nickel are not reported in Tables 2 and 3 because these metals are not significant contaminants of concern at this time. Elevated levels of nickel (0.12 to 0.15 mg/L) above the maximum contaminant level (MCL) have been reported only four times since 1972 and all have been associated with the Mike Horse adit discharge. Geochemical analyses for arsenic from the Anaconda and Mike Horse adit discharges have found intermittently elevated levels (1973, 1989, 1990; 0.04, 0.058, 0.042 mg/L, respectively). Arsenic is being monitored as a chemical of concern, however, because the arsenic anion form that determines the extent of adsorption, coprecipitation, and surface complexation is greatly affected by pH; and the alkaline drains (i.e., limestone used to raise pH) at the Mike Horse and Anaconda sites will certainly alter the pH of both systems.

Table 3. Upper Blackfoot Mining Complex Ground-Water Quality (totals)

Contaminants	Ranges (mg/L)	sMCL
Aluminum	0.7 - 10.3	0.2
Cadmium	0.2	0.005 (MCL)
Iron	2.2 - 164.2	0.3
Manganese	0.1 - 105	0.05
pH	2.7 - 7.3	6.5 - 8.5

Downgradient ground-water samples from three wells and four piezometers located in proximity to potential contaminant sources at the Anaconda, Mary P., Edith, Paymaster, and Carbonate mine sites were collected in November 1992 and in February and May 1993. The results of these sampling episodes are presented in Table 3 with only metal and pH values that exceeded MCLs or secondary MCLs listed. Ground-water contamination extending over 1,000 feet downgradient of the UBMC is evidenced by samples collected from a well located in a wetland area approximately 1,200 feet west of the Carbonate Mine site. This well had elevated levels of cadmium, lead, manganese, and iron during the same three sampling events (14).

Reclamation History

The UBMC was a Montana Department of State Lands Abandoned Mine Bureau reclamation project from 1987 through 1990. Very little remediation work was conducted during this time. In 1991, the Montana Legislature transferred jurisdiction of the site from the Department of State Lands to the Montana Department of Health and Environmental Sciences' State Superfund Program. In June of 1991, the state noticed ASARCO and the Atlantic Richfield Company (ARCO) (ARCO purchased the Anaconda Company in 1977) as the potentially liable parties under the Montana Comprehensive Environmental Cleanup and Responsibility Act for the remediation of the UBMC. During the fall of 1993 ASARCO and ARCO completed the phase I remedial investigation/feasibility study sampling and analysis for the UBMC. In April of 1993, ASARCO and ARCO began a 5-year voluntary interim remedial action program at the UBMC. The state is reviewing all remediation plans and conducting oversight of the voluntary remediation field activities. The state, ASARCO, and ARCO have not entered into an agreement regarding the voluntary action; consequently, ASARCO and ARCO are conducting all remediation activities at their own risk.

Voluntary Interim Remedial Actions

The schedule for completed, in-progress, and proposed UBMC construction activities is delineated in Table 4. ASARCO and ARCO began voluntary interim remedial actions at the Carbonate and Mike Horse mine sites in September 1993. Mine wastes and tailings in the Lower Carbonate were removed, limed, and placed in a repository located at the Upper Carbonate Mine area. A stream diversion was built along an upper reach of Mike Horse Creek and construction of the Mike Horse Mine treatability pond began. Also, a reach of Mike Horse Creek adjacent to the treatability pond was reclaimed.

Table 4. Upper Blackfoot Mining Complex Voluntary Interim Remedial Actions (5-year schedule)

Mine Site	1993	1994	1995	1996	1997
Carbonate Removal/reclamation Repository	_____	_____			
Mike Horse Pond Water Treatment Repository		_____	_____	_____	_____
Anaconda Removal/reclamation Water treatment			_____	_____	_____
Paymaster Water treatment Reclamation				_____	_____
Edith and Mary P. Removal			_____		
Tailings Pond Revegetation				_____	

In 1994, the Upper Carbonate repository was completed and reclamation of the Lower Carbonate area was nearly completed. Construction of the Mike Horse treatability pond continued with the installation of the pond liner and the building of the pond spillway. Other activities in 1994 included relocation of a 318-foot section of Mike Horse Creek, excavation and removal of hydrocarbon contaminated soils at the Mike Horse Mine site, and preparation of the Mike Horse Mine repository site. Approximately 7,300 cubic yards of waste material was removed from the Lower Anaconda mine area and relocated to the Mike Horse Mine repository site. New monitoring wells were installed at the Anaconda, Carbonate, and Mike Horse mine sites.

Proposed remediation activities for 1995 include the following:

- Removal of the remaining Lower Anaconda mine wastes and tailings.
- Removal of the Edith and Mary P. waste piles to the Mike Horse repository.
- Completion of the Mike Horse Mine repository.
- Completion of the Mike Horse Mine treatability pond.
- Installation of an alkaline drain and hydraulic seal in the Mike Horse adit.
- Installation of an alkaline drain at the Anaconda Mine adit.

- Construction of the phase I wetland treatment cells at the Anaconda Mine site.
- Construction of a pipeline from the treatability pond to the phase I wetland cells.
- Connection of the pond discharge to the pipeline.
- Reclamation of the Upper Anaconda Mine and Middle Mike Horse Mine waste piles.
- Miscellaneous revegetation work at the Lower Carbonate wetland area.

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Chapter 10.

Innovative Approaches to Addressing Environmental Problems for the Upper Blackfoot Mining Complex: Voluntary Remedial Actions

J. Chris Pfahl

Background

After ASARCO and Atlantic Richfield Company (ARCO) (the Companies) received notices in February 1992 from the state of Montana that they were liable parties for the cleanup of the Upper Blackfoot Mining Complex (UBMC) site, they quickly entered into an internal cost-sharing agreement and developed a strategy for addressing issues raised by the state and cost-effectively cleaning up the historic mining site. As required by the February 1992 notice letter, the Companies submitted a draft final remedial investigation/feasibility study (RI/FS) work plan for the UBMC in July 1992 and began the sampling and data collection necessary for the RI/FS. Collected data indicated that more than 90 percent of the metal loadings to the Blackfoot River was coming from the Mike Horse adit. Thus, the Companies prepared work plans for addressing the Mike Horse adit discharge and two other sources of water quality degradation.

In April 1993, the Companies met with the Montana Department of Health and Environmental Sciences and presented work plans for the preliminary remedial actions at the UBMC. The meeting resulted in a verbal agreement (subsequently documented in a letter to the Companies, dated May 26, 1993) to allow voluntary remedial actions at the UBMC, subject to various provisions, in lieu of performing the RI/FS, which typically is required at state Superfund sites. In August 1993, the Companies hired a contractor and cleanup activities began at the UBMC.

Cleanup Approach

The Companies developed an approach for addressing the sources of mining-related metals loadings in the surface waters at the UBMC. The approach consists of:

- Performing all voluntary cleanup activities under the existing State and Federal permit systems. (A list of permits obtained by the Companies is included in Table 1.)

Table 1. Permits Required for Voluntary Cleanup of the Upper Blackfoot Mining Complex

Permit	Description	Agency
404 Permit	Addresses locating a structure, excavating, or discharging dredged or fill material in U.S. waters	U.S. Army Corps of Engineers
Montana Pollutant Discharge Elimination System (MPDES)—Point source	Addresses point-source discharges of pollutants into state surface waters	Montana Department of Health and Environmental Sciences, Water Quality Bureau (MDHES-WQB)
3A Permit	Addresses short-term exemption from surface-water quality standards for construction sites to State waters	MDHES-WQB
MPDES—General Stormwater Permit	Addresses discharge of storm water from construction sites to State waters	MDHES-WQB
MPDES—Construction Dewatering—General Discharge Permit	Addresses discharge of waste water resulting from dewatering of ground water and/or surface water from construction sites, well pump tests, and/or well development to state waters	MDHES-WQB
310 Permit	Addresses work in or on stream channels or banks and water use or diversion, per Montana's Natural Streambed and Land Preservation Act	Lewis and Clark County Conservation District

- Consolidating numerous waste rock piles and accumulated tailing into engineered repositories located

in disturbed areas that are high and dry (i.e., away from direct contact with surface water).

- Obtaining Montana Pollutant Discharge Elimination System (MPDES) permits for the adit discharges and constructing passive water treatment systems to treat water sufficiently to achieve applicable discharge standards.
- Constructing run-on and infiltration controls to provide adequate hydrologic isolation of mine wastes.
- Recontouring and revegetating areas disturbed by mining activity, including construction of the mine waste repositories.
- Constructing run-on/infiltration controls and/or adit bulkheads to restrict the migration of water through acid-generating mineralized zones, limiting the production of acid and metal enriched mine drainage.
- Continuing to monitor surface- and ground-water quality to assess the effectiveness of the completed cleanup activities.

The Companies developed a comprehensive, site-wide cleanup plan based on these standard mine reclamation measures. The specific actions to be taken at each subarea of the UPMC are outlined in the following sections of this paper.

Carbonate Mine

The Carbonate Mine is located adjacent to Montana Highway 200 at the base of Rodgers Pass. Although sampling indicated the mine was not a significant source of metals for the Blackfoot River, it was considered a high priority for reclamation due to its visibility from Highway 200, the main highway between Missoula and Greatfalls, Montana.

The Carbonate site consists of a one-half acre tailing pond and mine waste rock dump situated in a wetlands adjacent to the highway and a hillside mine waste rock dump located approximately 500 feet north of the highway. Cleanup of the site consisted of excavating and moving approximately 20,000 cubic yards of mine waste and tailings from the wetlands to an engineered repository constructed on top of the hillside mine waste rock dump. Because of excessive moisture in the excavated tailings, quicklime was incorporated into the material at a rate of 8 percent by weight to achieve adequate compaction when the materials were placed in the repository. In addition to drawing out moisture, the quicklime provided the additional benefit of neutralizing the acid-generating potential of the tailings and mine waste rock.

After all mine waste rock and tailings were removed from the lower Carbonate, topsoil was applied and the area was reclaimed as a wetland. Surface-water run-on con-

trols were constructed around the repository, the repository was capped with a claymax geotextile liner, 12 inches of topsoil were spread over the repository, and the area was reseeded.

Mike Horse Adit Discharge

The Mike Horse adit is located on Mike Horse Creek, approximately 1 mile upstream of the headwater of the Blackfoot River (the confluence of Beartrap and Anaconda creeks) (Figure 1). The Mike Horse adit (at the 300 level of Mike Horse Mine) is the lowest surface opening of the Mike Horse Mine, which produced approximately 450,000 tons of lead zinc ore between 1878 and 1955.

Water flow measurements taken by the Companies upstream of the Mike Horse adit indicated a significant reduction in the surface-water flow rate in the area where Mike Horse Creek crossed the outcrop of the Mike Horse vein structure. The Companies assumed that this water was "leaking" into the mine and exiting via the Mike Horse adit. To reduce this obvious surface-water inflow, in 1993 a dam was constructed upstream of the vein outcrop to direct the surface-water flow to a pipeline. The pipeline discharges the water into the natural stream channel down from the outcrop. Effects of the surface-water diversion can be seen in Figure 2, which is a graph of adit discharge over time.

The Mike Horse Mine adit has a moderate discharge rate (approximately 40 gpm during late summer through winter, with a typical maximum flow of approximately 100 gpm during spring run-off). The adit drainage is slightly acidic (a pH ranging from 5.2 to 6.4, with median pH at about 6), has moderate to high dissolved metals concentrations (maximum concentrations of iron at 72 mg/L and zinc at 89 mg/L), and has high sulfate concentrations (typically greater than 1000 mg/L). More generally, the mine adit discharge can be characterized as lightly to moderately acidic, of moderate to high ionic strength, and as a calcium-magnesium-iron sulfate solution.

The basic treatment train concept for this mine adit discharge is to increase the pH of the water by utilizing an adit anoxic limestone drain; oxidize and precipitate iron in a pretreatment basin; provide additional intermediate treatment for dissolved and suspended iron compounds in a modified surface-flow wetland; polish residual metals in a series of subsurface-flow wetland cells; and, finally, provide finishing of the discharge in surface-flow cells to reaerate effluent (e.g., reintroduce dissolved oxygen, release residual hydrogen sulfide) immediately prior to release to the Upper Blackfoot River. Figure 3 is a schematic of the treatment train.

Initial passage of the anoxic, acidic mine drainage over coarse, high-calcium limestone (at grades greater than 90 percent calcium carbonate) will add alkalinity to the

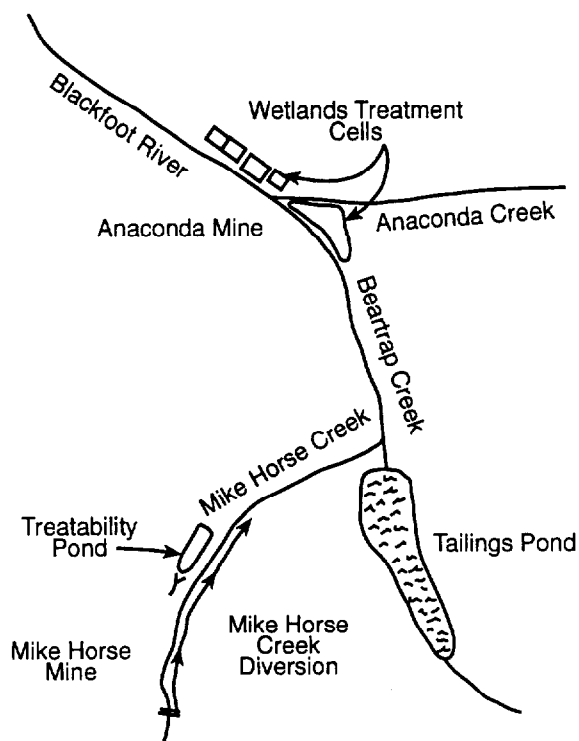


Figure 1. Location of the Mike Horse Mine.

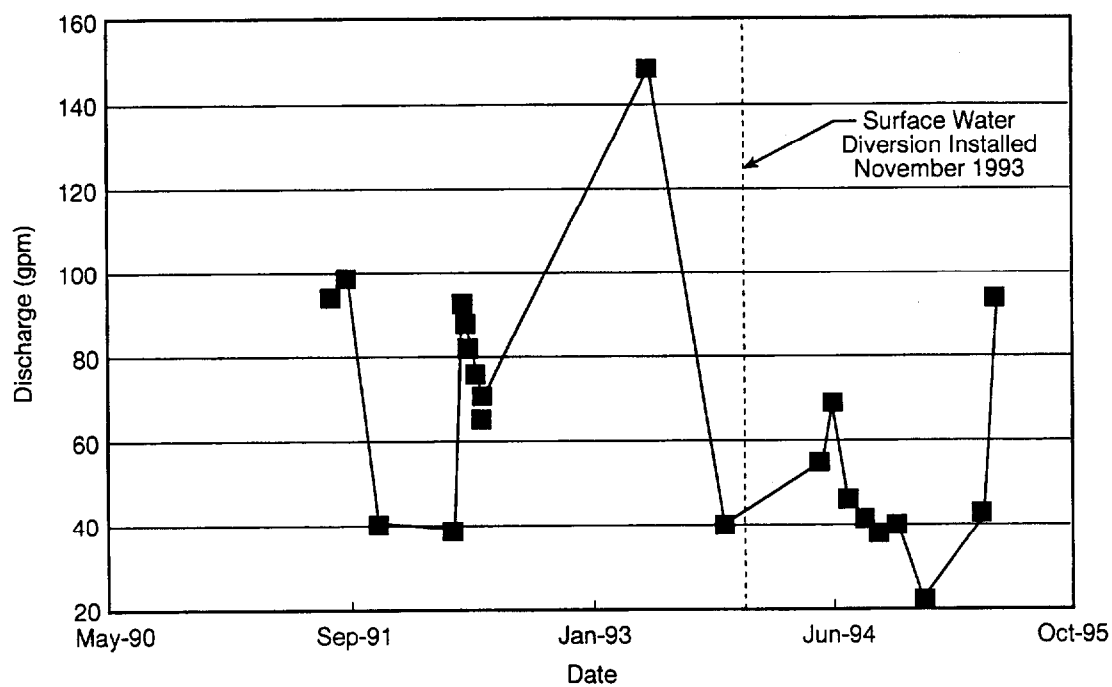


Figure 2. Mike Horse adit discharge from May 1990 to October 1995.

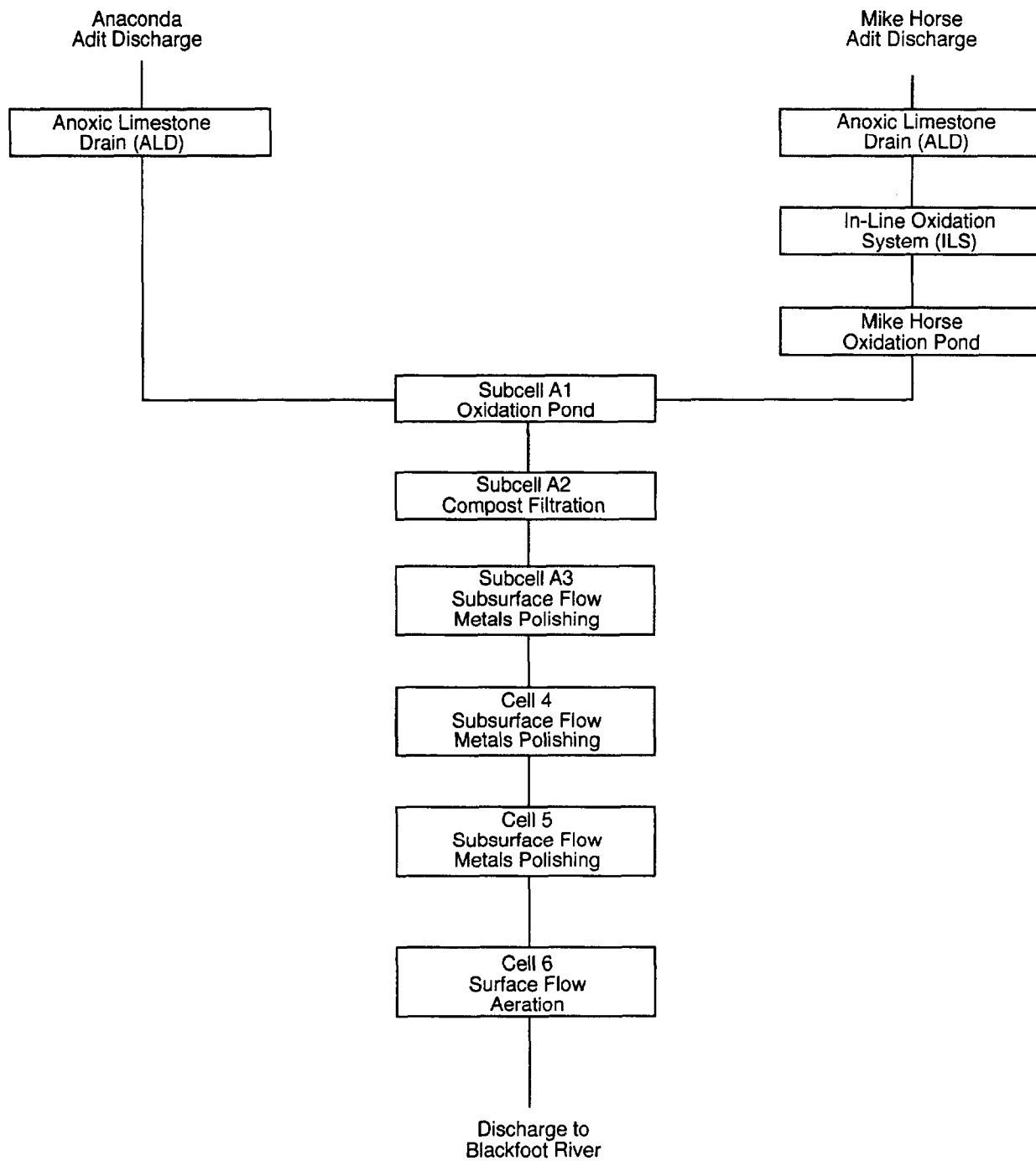


Figure 3. Schematic of the treatment process for discharge from the Mike Horse Mine adit.

system and encourage rapid oxidation of ferrous iron downgradient as the drainage enters the oxidation pond. If the anoxic condition of the adit discharge can be maintained by appropriate plugging of the adit and if iron is predominantly in the ferrous state, calcite in an anoxic limestone drain (ALD) should not armor (i.e., become coated with gypsum) when in contact with these waters. Armoring of the calcite by calcium sulfate formation has not been reported to be a problem in ALDs, although stability calculations (i.e., Eh and pH curves) suggest that some gypsum formation may occur above pH 4. For the proposed UBMC treatment scheme, this ALD will be placed within the Mike Horse adit behind a 6-foot thick concrete plug.

The objective of the Mike Horse adit plug is to control mine water drainage from the tunnel, to ensure that the ALD remains submerged, and to develop static water pressure. Once the plug is installed, sufficient pressure will develop to provide for enhanced aeration by forcing the water under pressure through the jet pumps. The maximum expected head behind the Mike Horse adit plug is approximately 80 feet, although the jet pumps normally will operate at lower heads. The 80-foot maximum head was chosen to allow for a margin of safety that would prevent flooding of the Mike Horse 200 level and the possibility of a discharge from caved access tunnels at the 200 level. The plug will be installed in an area of competent rock approximately 200 to 400 feet from the portal.

Discharge from the adit will be conveyed via pipeline to an in-line oxidation system (ILS) consisting of jet pumps, which inject air into the water, and static mixers, which mix the air with the water, to promote rapid oxidation of the dissolved iron. Discharge from the ILS is directed to a lined oxidation pond constructed just in from the Mike Horse adit portal. The pond has a capacity of 600,000 gallons, giving it an estimated 3 to 6 day retention time. While detained in the pond, the majority of the iron should precipitate as iron hydroxide and form a sludge on the pond bottom. The Companies anticipate that the sludge will need to be pumped from the pond and disposed on an annual basis. Discharge from the pond will be conveyed via pipeline approximately 1 mile to the constructed wetland treatment system at the Anaconda Mine site.

Anaconda Adit Discharge

The Anaconda Mine is located in the hillside to the north of the confluence of Mike Horse Creek and Beartrap Creek (see Figure 1). The mine, which was developed from 1919 to 1923, during 1933, and again in 1939 to 1940, consists of two original shafts and two adits with workings on several levels extending to a depth of about 325 feet. The lower level adit is referred to in this paper as the Anaconda adit. The ore mined at the Anaconda Mine until 1939 was processed offsite with some ore reportedly processed in the mill at the Mike Horse Mine.

An ore processing mill was installed at the Anaconda site in 1940 that produced approximately 50 tons of tailings.

The Anaconda adit discharge is smaller than that from the Mike Horse adit, with rates on the order of about 1 to 2 gpm and a maximum flow of about 3 gpm during spring run-off. The discharge typically is acidic (pH ranging from about 3.0 to 6.4) and contains moderate dissolved metals concentrations (21 to 76 mg/L iron and 1 to 8 mg/L zinc). At the Mike Horse adit, an ALD will be placed in the Anaconda adit behind a 2-foot thick flow-through concrete plug designed to keep the ALD submerged. Drainage will be directed to a secondary oxidation pond (subcell A1 of the constructed wetland treatment system), where the discharge will be commingled with drainage from the Mike Horse adit.

Constructed Wetland Treatment System

The locations of the constructed wetland treatment cells are shown in Figure 1. These locations comprise most of the relatively flat area available at the UBMC. The rectangular wetland cells located below the confluence of Anaconda and Beartrap creeks comprise the Phase I system, built in 1995, and the additional cell shown between Anaconda and Beartrap creeks is located on the site of a contemplated Phase II wetland system. The need for the Phase II system will be based on the performance of the Phase I system. Also, construction of the Phase II system is uncertain due to difficulties in obtaining permission to use the relatively flat public lands on which the system would be built.

The Phase I wetland treatment system comprises four cells: Cell A (comprised of subcells A1, A2, and A3), Cell 4, Cell 5, and Cell 6. The schematic arrangement of these cells is shown on Figure 3. The Phase II wetland system would be hydraulically upgradient of the Phase I system and would be comprised of Cells 1, 2, and 3. The Phase I system is described below.

As previously discussed, discharge from the Mike Horse adit will undergo primary treatment in the in-adit ALD, the ILS system, and the primary oxidation pond located near the Mike Horse Mine. Discharge from the Anaconda adit will undergo initial treatment within the ALD installed in the Anaconda adit. These pretreated discharges will be commingled in the initial portion of Cell A (subcell A1). Subcell A1 consists of a small, lined oxidation pond where ferrous iron in the Anaconda adit discharge and remaining ferrous iron in the Mike Horse adit discharge should become oxidized to ferric iron and settle out. Such settling is important from an operational standpoint due to the tendency of iron oxy-hydroxides to plug the front end of constructed wetland treatment cells, diminishing the quantity of flow that can be treated. The free water surface of subcell A1 will inundate subcell A2, which constitutes a two-layer system. The upper layer consists of

a mixture of compost and gravel; the lower layer consists of gravel only, again underlain by a liner. Flow from the free water surface should move vertically downward through the compost unit to the gravel unit, allowing additional filtration of any remaining iron oxy-hydroxides. Periodic replacement of the compost unit, if required, would constitute an operations and maintenance item. Wood fiber and sewage sludge are used in the compost unit.

Flow from the lower layer of subcell A2 will move horizontally into subcell A3, and then into Cells 4 and 5. Each of these cells are 1) lined, 2) comprised of gravel through which all flow generally is at subsurface, and 3) vegetated with local wetland plant species. Anaerobic conditions in the gravel should invoke a variety of polishing processes to remove divalent metal cations that are present in the adit discharges. Such processes include adsorption to biofilms, precipitation as immobile metal sulfides, and physical filtration. Flow controls at the downgradient ends of subcell A3, Cell 4, and Cell 5 will allow manipulation of hydraulic gradients and thus will control residence/treatment times within the wetlands.

The final treatment cell, Cell 6, comprises a lined surface-flow finishing cell with baffles to increase residence time. This cell should reaerate wetland effluent, releasing hydrogen sulfide and adding oxygen prior to discharge of the effluent to the Upper Blackfoot River. This cell also should allow final polishing of the adit discharges to be performed by contact with surface biofilms.

Miscellaneous Mine Dumps and Future Activities

Several mine waste rock dumps ranging in size from several hundred cubic yards to 25,000 cubic yards are scattered throughout the UBMC. These dumps contain heavy metals and are believed to affect the surface-water quality. All of the accessible mine waste rock dumps will be moved and consolidated into two onsite repositories constructed similarly to the Carbonate repository described above. The main repository is located immediately downstream of the Mike Horse oxidation pond at the historic location of the Mike Horse mill. A smaller repository will be constructed adjacent to the Paymaster Mine to contain the wastes from that mine.

Other reclamation activities to be performed in the future will consist of direct revegetation of the Mike Horse tailing impoundment and surface disturbances at the upper Mike Horse Mine workings and riparian area enhancements to the upper Blackfoot River in areas historically affected by heavy metals.

Expectations are that when all reclamation activities are completed, the water quality in the Upper Blackfoot River will be improved significantly and, when coupled with riparian enhancements, will result in an improved fishery in the river and tributary streams.

Chapter 11.

Innovative Approaches to Addressing Environmental Problems for the Upper Blackfoot Mining Complex: Grouting as a Hydrogeological Control for Acid Rock Drainage Reduction

A. Lynn McCloskey

Introduction

The U.S. Environmental Protection Agency (EPA) has directed MSE, Inc., through the Mine Waste Technology Program (MWTP), to evaluate and develop the subsurface application of a clay-based grout. Spetstamonazhgeologia (STG) Enterprises, a Ukrainian company, has developed the grouting technology selected for demonstration at the Mike Horse Mine site (1). This point-source control technology involves injecting clay-based grout into an underground mine workings. Reduction of water inflow to underground mine workings will decrease the volume of impacted water discharging from the 300-level portal and has the potential to improve the quality of the water system downstream from the mine. The water quality improvements would result from a reduction of contaminant transport, acid generation, and discharge from the mine portal.

MWTP Activity III, Project 2, Clay-Based Grouting Demonstration Project, is funded by EPA and jointly administered by the Agency and the U.S. Department of Energy (DOE) through an Interagency Agreement. Program oversight is provided by the Western Environmental Technology Office (WETO) of the DOE, Environmental Management (EM), Office of Technology Development. WETO administrative support is provided by the Pittsburgh Energy Technology Center for matters concerning the environment, safety and health, as well as regulatory compliance and operational conduct.

The Mike Horse Mine site was selected for demonstration of the clay-based grouting project. As noted in presentations about the Upper Blackfoot Mining Complex (see papers by Judy Reese and Chris Pfahl in this document), slightly acidic waters containing elevated levels of heavy metals discharge from the 300-level portal of the Mike Horse Mine directly into Mike Horse Creek. The mine discharge has been recognized by the state of Montana as one of the major contributors of metal loading into the Upper Blackfoot River (2).

The project consists of four major phases: 1) site characterization, 2) grout formulation, 3) grout production and placement, and 4) evaluation and monitoring. The project is designed to test and evaluate the grouting technology but not to achieve site remediation.

Site Characterization

Development and application of clay-based grout requires acquiring information using an integrated approach. Thus, the source of water infiltrating the underground mine workings and the hydrogeological system must be defined in terms of the local and regional geology, hydrogeology, geochemistry, geophysics, and past mining history, all of which are considerations relevant to the grout formulation. Critical data required for development of the grout formulation and placement of the grout include, but are not limited to:

- Hydrogeology (i.e., hydraulic conductivity).
- Physical and structural geology (i.e., fracture density and aperture).
- Physical and mechanical rock properties (i.e., strength).
- Geochemical/mineralogical properties (i.e., rock types and compositions along with the chemical makeup of the ground water).

Grout Formulation

Clay-based grouts are visco-plastic systems that comprise structure-forming cement and clay-mineral mortar. The STG clay-based grout selected for application at ASARCO's Mike Horse Mine is a system made up of environmentally benign elements, of which kaolinitic/illitic clay is a major constituent. The distinguishing feature of clay-based grout is that throughout the entire sta-

bilization period the grout retains its plasticity and does not crystallize, as do cementitious grouts. Moreover, clay-based grout does not shear or deteriorate during minor rock movement and therefore can be used at mining sites where blasting is conducted. Because of good rheological characteristics, the clay grouts are not easily eroded during injection to high-flow conditions. Also, due to the finely dispersed clay particles, a greater fracture penetration is realized than with cementitious grouts. The overall properties of clay-based grouts depend on the physical-mechanical properties of the initial clay mineral as well as the properties of the cement and the chemical reagents added.

Additional reasons for demonstrating and applying the clay-based grouting technology exist also. These include past successes with clay grouting in the Ukraine, other unified countries, and the former Eastern Block nations; the ability of the grout to eliminate flows of up to 4,000 gallons per minute; the low maintenance and longevity of the grout; and the rheological properties of the grout.

Grout Production and Placement

The Clay-Based Grouting Demonstration Project site is located approximately 1,000 feet due south of the Mike Horse Mine's 300-level portal (Figure 1). The grout injection holes are located directly north of ASARCO's dam, by drillhole DH3. Each hole was drilled at an angle (35, 45, and 60 degrees from horizontal) and perpendicular to the Mike Horse Fault/Vein system (to the extent possible) (Figure 2). As illustrated in Figure 2, even though the dam reduces surface water in the area, the shallow ground water in the drainage is able to infiltrate through the subsurface alluvial material and into the fault/fracture system. As indicated, the grout is placed within the grout injection boreholes. Packers then are placed in the holes so the grout can be directionally placed in the selected interval.

STG Enterprises has found in studies that three distinct stages are encountered in the injection and setup of clay grouts (1). The first stage is a timeframe in which the rate of structural strength development is slow. This period must correspond with the time it takes to mix and pump the grout. If the setup of the grout is premature, fouling of the pumping equipment may occur. If the development of structural strength takes much longer than the mixing and pumping, then the material may be exposed to hydraulic properties of the unit that result in failure or at least weakening of the grout.

The second stage in the placement and setup of clay grouts is a period when the structural strength of the material develops much more rapidly. The required time is controlled by addition of the appropriate amount of structure-forming reagents.

The third stage in the placement and setup of clay grouts produces the final strength of the grout, during addition of the final reagent. The grout's final strength is a predetermined, calculated value that establishes the material's design for the injection event. Each of the above-described stages can be controlled by proper grout formulation design.

Once the proper grout is formulated at the project site, the material can be injected, using a positive displacement slurry pump, through the grout lines and packer system at a maximum header pressure of 600 pounds-force per square inch.

Grout Evaluation and Monitoring

The technology evaluation will be performed by MSE, Inc., under the MWTP, and by SAIC, under the Superfund Innovative Technology Evaluation (SITE) program. Parameters used for the evaluation will include:

- *Potentiometric surface fluctuations.* Six monitoring wells have been placed within the project site area. Three monitoring wells are in a defined shallow aquifer and three are in the deep aquifer system. From these wells, the direction of flow trends toward the mine workings (SW). Fluctuations in the static water levels after grouting (indicating a flow direction trending to the north [downstream]) could be determined to be a direct indication of grout influence.
- *Surface water fluctuations.* Flumes and weirs have been placed in all surface water flows south of the Mike Horse Mine's 300-level portal. These will be used to define the water balance of the Mike Horse Creek's flow regime and to determine if any trends and immediate responses can be recognized during grout injection.
- *Water flow fluctuations at the 300-level portal.* Two continuous monitoring systems have been placed at the 300-level portal of the Mike Horse Mine. These monitoring stations will show any immediate responses to the grouting and will indicate any apparent trends.
- *Hydraulic conductivity changes.* Slug, pump, and packer tests were performed on the system during pre- and post-grouting.
- *Core drilling to determine dispersivity of the grout.* SAIC will redrill the areas where grout has been placed. From these drill holes, SAIC will determine the dispersivity and physical properties of the grout and will evaluate the ability of the grout to reduce the permeability of the fracture system.

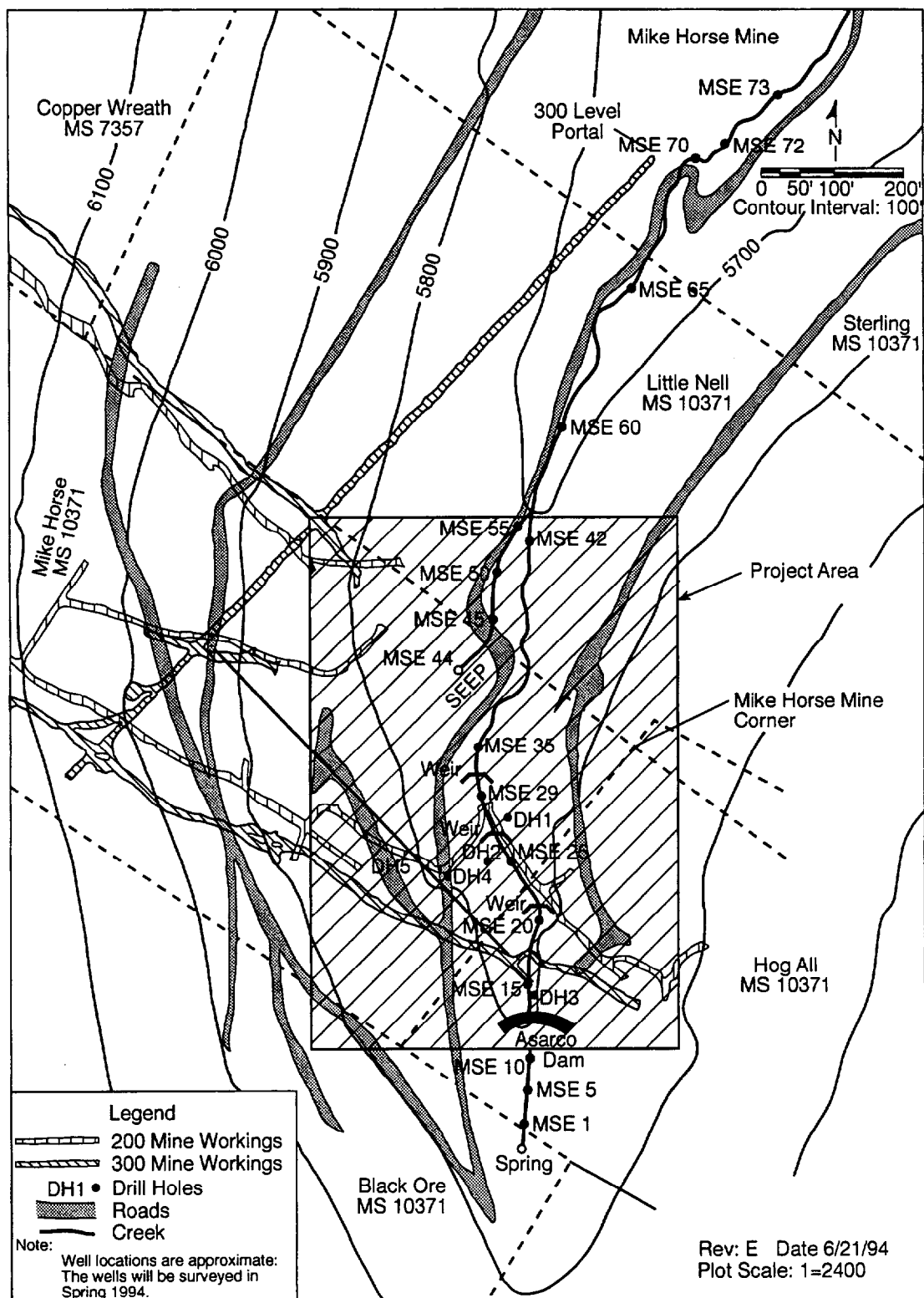


Figure 1. Mike Horse Mine site map with project area.

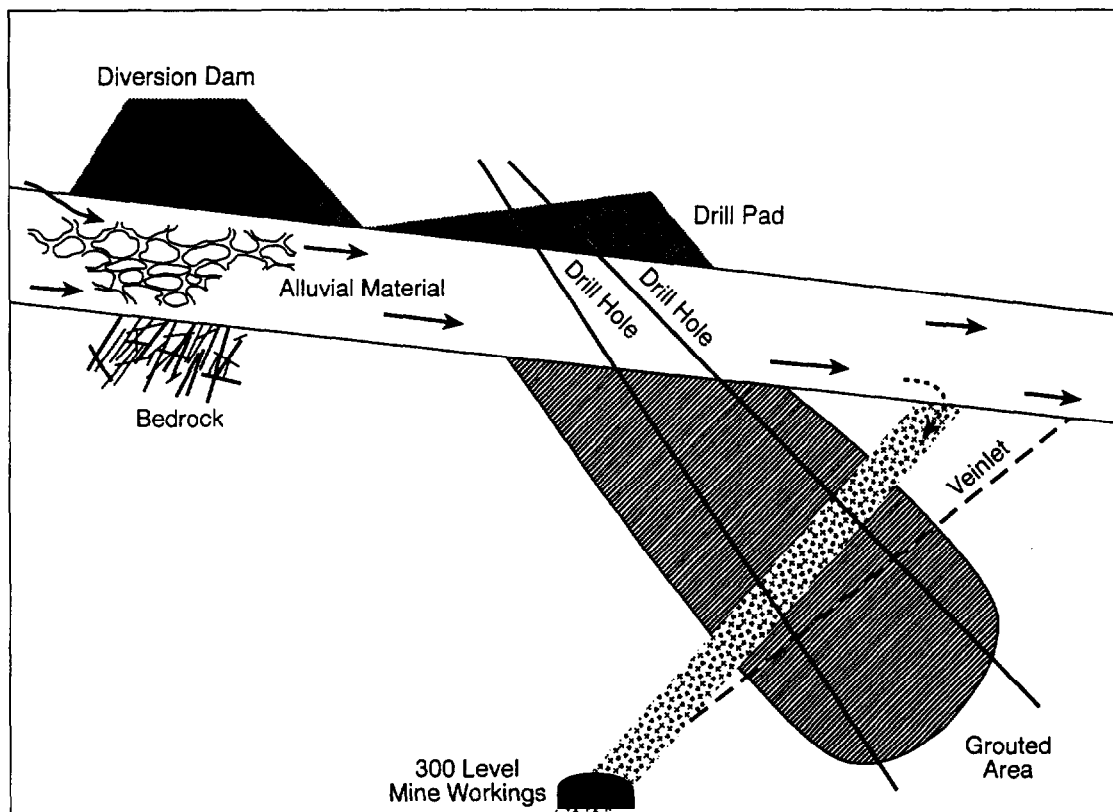


Figure 2. Conceptual cross section of the project area (looking west).

These parameters then will be evaluated to assess the changes that have occurred as a result of the injection of the clay-based grout.

Project Status

Site characterization for the Clay-Based Grouting Demonstration Project was completed during August 1994. Grout formulation was performed in the Ukraine and was finalized in May 1994. Grout placement was initiated during September 1994 and completed during November 1994. At the time of writing (July 1995), the Clay-Based Grouting Technology evaluation is in progress.

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Appendix B Contributors

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Dr. Cohen received a B.A. in biophysics from Temple University in Philadelphia. He also received a Ph.D. in environmental sciences and engineering from the University of Virginia, where he combined the disciplines of water quality engineering, water chemistry, hydrology, and applied math. He has worked as a project chief in the National Research Program at the U.S. Geological Survey and currently is associate professor of environmental science and engineering at the Colorado School of Mines. Dr. Cohen has been working on treatment, geochemistry, and transport of mine drainage materials for 5 years. In addition, he has studied the distributions of ^{239,240}plutonium and ¹³⁷cesium in regions of the Rocky Mountains' front range both affected and unaffected by the Rocky Flats Plutonium Weapons Plant. Also, he has participated in studies of surface runoff, storm runoff, graphic information systems, and stream transport modeling. He has reviewed the U.S. Department of Energy's Treatment Plans and Treatment Reports and made suggestions for additional remediation technologies.

Dr. Cohen has received the First Prize for Environmental Projects from the American Consulting Engineers' Council for development of treatment systems for acid mine drainage. He is the recipient of a Certificate of Special Recognition from the U.S. Congress for environmental work associated with U.S. Department of Energy nuclear weapons plants. He was selected to review the National Five Year Plan for Environmental Remediation of the Weapons Plants. He has published numerous papers in journals such as the Journal of the American Society of Civil Engineers, Limnology and Oceanography, and others. He has worked on contaminant problems in Charlotte Harbor (FL), Chesapeake Bay, San Francisco Bay, the Potomac River, and Clear Creek and the Eagle River (CO). Currently, Dr. Cohen teaches courses on contaminant transport, water quality, water quality modeling, and hydrology at the Colorado School of Mines. He has designed curriculum and coordinated the Hazardous Materials Management Program for professionals dislocated from the energy and minerals industry.

Thomas V. Durkin
South Dakota Department of Environment and Natural Resources
Office of Minerals and Mining
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Mr. Durkin has an A.S. in biology from Nassau Community College, a B.S. in earth science from Adelphi University, and an M.S. in geology from the South Dakota School of Mines and Technology. He is a certified professional geologist. He has worked as a commissioned officer in the U.S. National Oceanic and Atmospheric Administration Corps and as a mine regulator for the state of South Dakota for the past 8 years.

Mr. Durkin is employed by the South Dakota Department of Environment and Natural Resources as a hydrologist in the Office of Minerals and Mining. His duties have involved him with the geochemical aspects of mine wastes and mine waste management issues relating to large-scale surface gold mines in the Black Hills. He is concerned particularly with regulating problems associated with acid mine drainage and developing effective prevention, control, and reclamation requirements. He is a member of the Western Governors' Association Mine Waste Task Force

and the Abandoned Mine Waste Working Group of the Committee to Develop Onsite Innovative Technologies. He is a member of the American Institute of Professional Geologists, the Society of Mining, Metallurgy and Exploration, Inc., and the South Dakota Academy of Science.

Martin Foote
Mine Waste Technology Pilot Program
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Butte, MT

Dr. Foote has a B.S. in chemistry and an M.S. in geochemistry from Montana College of Mineral Science and Technology, and a Ph.D. in geology from the University of Wyoming. He has worked as a geologist, geochemist, and consultant to the mining industry for 11 years. He also has worked with both federal and state regulatory organizations in environmental remediation, permitting, and development.

Dr. Foote is employed by MSE as a technical project manager for the Mine Waste Technology Pilot Program. This program is funded by U.S. Environmental Protection Agency (EPA) and jointly administered by EPA and U.S. Department of Energy (DOE) to conduct research and field demonstrations on new and innovative technologies for treating or remediating mine wastes. He has served on the Technology Screening Group for the In Situ Remediation Integrated Program and reviewed grant applications for the Small Business Innovation Research Program for DOE.

Jonathan G. Herrmann
National Risk Management Research Laboratory
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Mr. Herrmann holds a B.E. in civil engineering from Youngstown State University and an MBA in marketing from Xavier University. He is a licensed professional engineer in the state of Ohio and a diplomate in the American Academy of Environmental Engineers. Mr. Herrmann has worked in the area of environmental protection since 1975 and began his career in the Region VIII Office of EPA, located in Denver, Colorado. Mr. Herrmann has worked in the private sector, for a hazardous waste disposal firm, CECOS/CER, in the early-1980s, and has been with EPA's Office of Research and Development for almost 16 years.

For the past 4 years, Mr. Herrmann has assisted one of the Division Directors for the National Risk Management Research Laboratory located in Cincinnati, Ohio, being responsible for both administrative activities and special projects in support of the Laboratory's overall mission and goals. Mr. Herrmann has recently been involved in rolling out EPA's Environmental Technology Verification Program, which will evaluate and verify the performance of various types of environmental technologies so as to speed their commercialization both domestically and abroad.

A. Lynn McCloskey
Mine Waste Technology Pilot Program
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Ms. McCloskey has an M.S. in mining engineering, with a hydrogeology option, and a B.S. in geological engineering from the Montana College of Mineral Science and Technology in Butte, MT.

She has worked for MSE Inc. for several years. Some of the projects she has been responsible for in her tenure at MSE include designing remedial technology applications for mining and mining-associated wastes for bench- and pilot-scale demonstrations, providing geotechnical services for building new water treatment facilities, conducting environmental audits for commercial and private property, and designing leak detection systems for waste ponds, underground storage tanks, and heavy metals soil.

At present she is manager of an innovative project involving a clay-based grouting technology, under the Mine Waste Technology Pilot Program. This program is funded by EPA and jointly administered by EPA and DOE under an Interagency Agreement. The project involves using integrated processes to evaluate an entire hydrogeological and geological system.

J. Chris Pfahl
ASARCO, Inc.
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Mr. Pfahl has a B.S. in mining engineering from the Montana College of Mineral Science and Technology. He is a licensed professional engineer in the states of Idaho and Colorado and a licensed professional land surveyor in Idaho. He has been employed by ASARCO in various engineering, supervisory, and management positions for the past 17 years.

Mr. Pfahl is a site manager with ASARCO. He is responsible for all of ASARCO's activities at the Bunker Hill Superfund site at Kellogg, ID; the Triumph Proposed Superfund site at Sun Valley, ID; the Upper Blackfoot Mining Complex State Superfund site at Lincoln, MT; and several inactive mine site reclamation projects in Colorado, Idaho, and Montana.

Judy Reese
Montana Department of Environmental Quality
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Judy Reese has a B.S. in geology from Wayne State University and an M.S. in environmental studies from the University of Montana. She also has grades 7-12 teaching certification in earth science and chemistry. Ms. Reese worked in minerals exploration for 8 years for Utah International, BHP-Utah International, Placer Dome, and Meridian Gold Company.

Ms. Reese has worked for the Montana Department of Health and Environmental Sciences Solid and Hazardous Waste Bureau's state Comprehensive Environmental Cleanup and Responsibility Act (CECRA) and federal (CERCLA) Superfund programs since 1991. She is the project manager of the Upper Blackfoot Mining Complex site, and she is responsible for all CECRA-related aspects of the site. She also manages a few other CECRA sites and participates on the Clark Fork River Site-Specific Water Quality Criteria Committee.

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Dr. Robertson has a B.Sc. in civil engineering and a Ph.D. in rock mechanics from the University of Witwatersrand, South Africa. After a few years spent working for a mining company as a rock mechanics engineer and for an engineering company doing specialized site investigation and foundation designs and contract supervision, Dr. Robertson became a cofounder of the firm Steffen, Robertson and Kirsten (SRK), Inc., Consulting Geotechnical and Mining Engineers. He now heads the firm Robertson GeoConsultants. He has 28 years of experience in mining geotechnics, of which the last 10 years have been devoted extensively to geoenvironmental engineering for mine sites.

Dr. Robertson was responsible for developing the engineering capabilities of the North American practice of SRK over 17 years and has specialized personally in technology for the safe and environmentally protective disposal of mine tailings and waste rock, acid mine drainage prediction and modeling, mine closure plan development, and financial assurance and remediation of abandoned mines. He has been extensively involved in the preparation and writing of a number of manuals on these subjects, which are now widely used in the mining industry. In addition, he gives regular short courses and consults internationally to mining companies and regulatory authorities on these topics. He serves on a number of advisory boards, including the University of British Columbia Board of Studies for the Geological Engineering Program and the Mine Waste Technology Pilot Program (Butte, MT), as well as on a number of mining project-specific review boards.

William B. Schmidt
Division of Environmental Research
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Mr. Schmidt has worked for the federal government for 22 years in areas related to mining and minerals processing. After graduating from the Colorado School of Mines and before joining the government in 1971, he worked for 8 years in the private sector, mostly on assignments related to tunneling and construction engineering.

Mr. Schmidt has managed various government programs related to regulation of coal mining, mining research, and metallurgical research. For the U.S. Department of Energy, he served as director of the Office of Coal Technology, where he was responsible for a \$70 million per year coal mining and preparation research program. At the U.S. Department of Interior's Office of Surface Mining (OSM), he was assistant director for Program Operations and Inspection, responsible for OSM's enforcement, oversight, and Abandoned Mined Lands (AML) programs. Mr. Schmidt has visited Europe and Asia a number of times as a government technical expert. He works for the Bureau of Mines in Washington, where he is chief of the Division of Environmental Technology. In this position, in addition to his research program management responsibilities, he oversees the Bureau's technical assistance to the U.S. Forest Service, EPA, and other agencies in the environmental cleanup arena.

Leslie C. Thompson
Pintail Systems, Inc., Aurora, Colorado

Ms. Thompson received a B.S. in biology from Purdue University and has continuing education and graduate course work in geochemistry, environmental engineering, and environmental microbiology. She has worked as a chemist, microbiologist, and chief of research and development of bioremediation processes in mining and engineering companies. She has over 20 years of experience in chemical manufacturing, mining, and waste remediation.

Ms. Thompson is employed at Pintail Systems as vice president of research and development. Her responsibilities include management of the environmental research program, oversight of field engineering, and development of innovative biotreatment processes for industrial waste remediation. Under her leadership, new bacterial treatment processes have been developed for control of acid mine drainage, heavy metal wastes, complexed metal cyanides, nitrates, phenolic wastes, and aromatic hydrocarbons from petroleum and coal gasification production operations. Ms. Thompson is a member of the American Chemical Society, the Society of Mining Engineers, the Metallurgical Society, the American Society of Microbiologists, and the Mining and Metallurgical Society of America.

Dirk Van Zyl
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Dr. Van Zyl has a B.S. (honors) in civil engineering from the University of Pretoria, South Africa, and an M.S. and Ph.D. in civil engineering from Purdue University. As a researcher, consulting engineer, and university professor, he has over 20 years of civil/geotechnical engineering experience and is a registered professional engineer in 11 states.

Dr. Van Zyl is director of mining in the Denver office of Golder Associates Inc. He is responsible for technical and marketing efforts for mine waste disposal, mine closure, and heap leach projects. He also provides engineering design and regulatory support in negotiations for permits. He has supported regulatory development in the United States and internationally. He is a member of the Society of Mining, Metallurgy, and Exploration, Inc., the American Society of Civil Engineers, and the South African Institute of Mining and Metallurgy. He has published over 50 technical papers, research reports, and books, and served as editor of conference proceedings. He has coordinated and presented numerous short courses for the Society of Mining, Metallurgy, and Exploration, Inc., and the U.S. Forest Service.

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