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MINE WASTE TECHNOLOGY PROGRAM

Technology Testing for Tomorrow's Solutions

2001 ANNUAL REPORT

MINE WASTE TECHNOLOGY PROGRAM

EPA DOE Montana Tech Implemented by MSE, Inc.

EPA/DOE

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2001 ANNUAL REPORT

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Mine Waste Technology Program
Interagency Agreement Management Committee
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Prepared for:

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VISION STATEMENT FOR THE BUTTE MINE WASTE TECHNOLOGY PROGRAM

THE PROBLEM

Mining activities in the United States (not counting coal) produce between 1 and 2 billion tons of mine waste annually. These activities include extraction and beneficiation of metallic ores, phosphate, uranium, and oil shale. Over 130,000 of these noncoal mines, concentrated largely in nine western states, are responsible for polluting over 3,400 miles of streams and over 440,000 acres of land. About seventy of these sites are on the National Priority List for Superfund remediation. In the 1985 Report to Congress on the subject, the total noncoal mine waste volume was estimated at 50 billion tons, with 33% being tailings, 17% dump/heap leach wastes and mine water, and 50% surface and underground wastes. Since many of the mines involve sulfide minerals, the production of acid mine drainage (AMD) is a common problem from these abandoned mine sites. The cold temperatures in the higher elevations and heavy snows frequently prevent winter site access. The combinations of acidity, heavy metals, and sediment have severe detrimental environmental impacts on the delicate ecosystems in the West.

PHILOSOPHY/VISION

End-of-pipe treatment technologies, while essential for short-term control of environmental impact from mining operations, are a stopgap approach for total remediation. Efforts need to be made on improving the end-of-pipe technologies to reduce trace elements to low levels for applications in ultra-sensitive watersheds and for reliable operation in unattended, no power situations. The concept of pollution prevention, emphasizing at-source control and resource recovery, is the approach of choice for the long-term solution. Our objective in the Butte Mine Waste Technology Program is not to assess the environmental impacts of the mining activities, but it is to develop and prove technologies that provide satisfactory short- and long-term solutions to the remedial problems facing abandoned mines and the ongoing compliance problems associated with active mines, not only in Montana but throughout the United States.

APPROACH

There are priority areas for research, in the following order of importance:

Source Controls, Including In Situ Treatments and Predictive Techniques
It is far more effective to attack the problem at its source than to attempt to deal with diverse and dispersed wastes, laden with wide varieties of metal contaminants. At-source control technologies, such as sulfate-reducing bacteria; biocyanide oxidation for heap leach piles; transport control/pathway interruption techniques, including infiltration controls, sealing, grouting, and plugging by ultramicrobiological systems; and AMD production prediction techniques should strive toward providing a permanent solution, which of course is the most important goal of the program.

Treatment Technologies
Improvements in short-term end-of-pipe treatment options are essential for providing immediate alleviation of some of the severe environmental problems associated with mining, and particularly with abandoned ore mines.

Because immediate solutions may be required, this area of research is extremely important for effective environmental protection.

Resource Recovery
In the spirit of pollution prevention, much of the mining wastes, both AMD (e.g., *over 25 billion gallons* of Berkeley Pit water) and the billions of tons of mining/beneficiation wastes, represent a potential resource as they contain significant quantities of heavy metals. While remediating these wastes, it may be feasible to incorporate resource recovery options to help offset remedial costs.

THE PARTNERSHIPS

In these days of ever-tightening budgets, it is important that we leverage our limited funding with other agencies and with private industry. The Bureau of Land Management and Forest Service actively participate by providing sites for demonstrations of the technologies. It is important where these technologies have application to active mining operations to achieve cost-sharing partnerships with the mining industry to test the technologies at their sites. Fortunately, the program has strong cooperation from industry. Within the U.S. Environmental Protection Agency, the Butte program is coordinated and teamed, where appropriate, with the Superfund Innovative Technology Evaluation (SITE) program to leverage the funding and maximize the effectiveness of both programs. We have strong interaction, cooperation, and assistance from the mining teams in the EPA Regional Offices, especially Regions 7, 8, 9, and 10. Several joint projects are underway, and more are planned.

A considerable resource and willing partner is the University system (such as Montana Tech of the University of Montana, University of Montana–Missoula, Montana State University–Bozeman, and the Center for Biofilm Engineering), which can conduct the more basic type of research related to kinetics, characterization, and bench-scale tests at minimal cost to the program, while at the same time providing environmental education that will be useful to the region and to the Nation. The Butte Mine Waste Technology Program supports cooperative projects between the educational system and the mining industry, where teams of students conduct research of mine site-specific problems, often with monetary support from the industry. The results are made available to the industry as a whole and to the academic community.

THE SCIENCE

The research program is peer-reviewed annually by the Technical Integration Committee (TIC), who technically reviews all ongoing and proposed projects. The TIC is composed of technical experts from the U.S. Environmental Protection Agency and the cooperating agencies, academia, environmental stakeholders, and industry and their consultants.

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PROGRAM MANAGER'S EXECUTIVE SUMMARY

The Mine Waste Technology Program (MWTP) Annual Report for fiscal 2001 summarizes the results and accomplishments for the various activities within the Program. The MWTP has met its goals by providing assistance to the public and forming cooperative teams drawn from government, industry, and private citizens. The funds expended have returned tangible results, providing tools for those faced with mine waste remediation challenges.

After 11 years, everyone involved with the MWTP can look with pride to the Program's success. Technology development and basic research has proceeded successfully through the efforts of MSE Technology Applications, Inc. (MSE) and its prime subcontractor Montana Tech.

MSE has developed thirty-four field-scale demonstrations, several of which are attracting attention from the stakeholders involved in the cleanup of mine wastes.

Montana Tech has developed twenty bench-scale projects, five of which are ongoing during 2001.

Numerous activities are associated with the development of a field-scale demonstration. Among these activities are acquiring federal and state permits, securing liability limiting access agreements, developing and adhering to health and safety operation plans, and complying with the National Environmental Policy Act and other federal and state environmental oversight statutes.

The Program has received substantial support from state and federal agencies, the mining industry, environmental organizations, and numerous associations interested in mining and development of natural resources at state, regional, and national levels.

Montana Tech continued the post-graduate degree program with a mine waste emphasis. The quality of short courses offered by Montana Tech is becoming highly recognized among the mine waste remediation community.

The MWTP recognizes its major accomplishments and looks forward to providing new and innovative technologies; meeting the challenges of mine waste remediation; and providing economical, permanent solutions to the nation's mineral waste problems.

Jeff LeFever
MSE MWTP Program Manager

INTRODUCTION

Mining waste generated by active and inactive mining production facilities and its impact on human health and the environment are a growing problem for Government entities, private industry, and the general public. The nation's reported volume of mine waste is immense. Presently, there are more than sixty mining impacted sites on the U.S. Environmental Protection Agency's National Priorities List.

Environmental impacts associated with inactive and abandoned mines are common to mining districts around the country, as shown in Table 1.

Total estimated remediation costs for these states range from $4 to $45 billion.

Health effects from the predominate contaminants in mine waste range from mild irritants to proven human carcinogens, such as cadmium and arsenic. The large volume of mine wastes and consequential adverse environmental and human health effects indicates an urgency for cleanup of abandoned, inactive, and active mining facilities. The environmental future of the United States depends in part on the ability to deal effectively with mine waste problems of the past and present, and more importantly, to prevent mine waste problems in the future.

The fiscal year (FY) 1991 Congressional Appropriation allocated $3.5 million to establish a pilot program in Butte, Montana, for evaluating and testing mine waste treatment technologies. The Mine Waste Technology Program (MWTP) received additional appropriations of $3.5 million in FY91, $3.3 million in FY94, $5.9 million in FY95, $2.5 million in FY96, $7.5 million in FY97, $6.0 million in FY98 and FY99, $4.3 million in FY00, and $3.9 million in FY01.

The projects undertaken by this Program focus on developing and demonstrating innovative technologies at both the bench- and pilot-scale that treat wastes to reduce their volume, mobility, or toxicity. To convey the results of these demonstrations to the user community, the mining industry, and regulatory agencies, MWTP includes provisions for extensive technology transfer and educational activities. This report summarizes the progress of the MWTP in FY01.

Table 1. Number and types of sites and abandoned mine lands in Western Region.

State	Estimated Number of Sites or Land Areas	Classification and Estimated Number
Alaska	10,910 sites	mine dumps - 1,000 acres disturbed land - 27,680 acres mine openings - 500 hazardous structures - 300
Arizona	95,000 sites	polluted water - 2,002 acres mine dumps - 40,000 acres disturbed land - 96,652 acres mine openings - 80,000
California	11,500 sites	polluted water - 369,920 acres mine dumps - 171 acres mine openings - 1,685
Colorado	20,229 sites covering 26,584 acres	polluted water - 830,720 acres mine dumps - 11,800 acres disturbed land - 13,486 acres mine openings - 20,229 hazardous structures - 1,125
Idaho	8,500 sites covering 18,465 acres	polluted water - 84,480 acres mine dumps - 3,048 acres disturbed land - 24,495 acres mine openings - 2,979 hazardous structures - 1,926
Michigan	400–500 sites	Accurate information not available.
Montana	19,751 sites covering 11,256 acres	polluted water - 715,520 acres mine dumps - 14,038 acres disturbed land - 20,862 acres mine openings - 4,668 hazardous structures - 1,747
Nevada	400,000 sites	Accurate information not available.
New Mexico	7,222 sites covering 13,585 acres	polluted water - 44,160 acres mine dumps - 6,335 acres disturbed land - 25,230 acres mine openings - 13,666 hazardous structures - 658
Oregon	3,750 sites	polluted water - 140,800 acres mine dumps - 180 acres disturbed land - 61,000 acres mine openings - 3,750 hazardous structures - 695
South Dakota	4,775 acres	Accurate information not available.
Texas	17,300 acres	Accurate information not available.
Utah	14,364 sites covering 12,780 acres	polluted water - 53,120 acres mine dumps - 2,369 acres disturbed land - 18,873 acres mine openings - 14,364 hazardous structures - 224
Wisconsin	200 acres	Accurate information not available.
Wyoming	5,000 acres	Accurate information not available.

Information was collected from the following sources and is only an estimate of the acid mine drainage problem in the West.

-Bureau of Land Management
-Bureau of Mines
-Mineral Policy Center
-National Park Service
-U.S. Department of Agriculture
-U.S. Department of the Interior
-U.S. Forest Service
-U.S. Geological Survey
-U.S. General Accounting Office
-Western Governor's Association Mine Waste Task Force Study

PROGRAM OVERVIEW

FISCAL 2001 PROGRAM

This Mine Waste Technology Program (MWTP) annual report covers the period from October 1, 2000, through September 30, 2001. This section of the report explains the MWTP organization and operation.

MISSION

The mission of the MWTP is to provide engineering solutions to national environmental issues resulting from the past practices of mining and smelting metallic ores. In accomplishing this mission, the MWTP develops and conducts a program that emphasizes treatment technology development, testing and evaluation at bench- and pilot-scale, and an education program that emphasizes training and technology transfer. Evaluation of the treatment technologies focuses on reducing the mobility, toxicity, and volume of waste; implementability; short- and long-term effectiveness; protection of human health and the environment; community acceptance; and cost reduction.

The statement of work provided in the Interagency Agreement between the U.S. Environmental Protection Agency and the U.S. Department of Energy identifies six activities to be completed by MWTP. The following descriptions identify the key features of each and the organization performing the activity.

ACTIVITY I: ISSUES IDENTIFICATION

Montana Tech of the University of Montana (Montana Tech) is documenting mine waste technical issues and innovative treatment technologies. These issues and technologies are then screened and prioritized in volumes related to a specific mine waste problem. Technical issues of primary interest are Mobile Toxic Constituents—Water/Acid Generation; Mobile Toxic Constituents–Air, Cyanide, Nitrate, Arsenic, Pyrite, Selenium, and Thallium; and Pit Lakes. Wasteforms reviewed related to these issues include point- and nonpoint-source acid drainage, abandoned mine acid drainage, streamside tailings, impounded tailings, priority soils, and heap leach-cyanide/acid tailings. In addition, under this task Montana Tech produced a CD-ROM based summary of the Program in two volumes—Annual Report and Activities in Depth. The CDs can be obtained from the personnel listed in the Contacts Section of this report. The Annual Report data is also available on the web at www.epa.gov/ORD/NRMRL/std/mtb.

ACTIVITY II: GENERIC QUALITY ASSURANCE PROJECT PLAN

In 2001, EPA approved the Quality Management Plan for the MWTP. This plan provides specific instructions for data gathering, analyzing, and reporting for all MWTP activities.

ACTIVITY III: PILOT-SCALE DEMONSTRATIONS

Pilot-scale demonstration topics were chosen after a thorough investigation of the associated technical issue was performed, the specific wasteform to be tested was identified, peer review was conducted, and sound engineering and cost determination of the demonstration were formulated.

MSE continued thirteen field-scale demonstrations during fiscal 2001. One field demonstration, Selenium Treatment, was completed. Ten projects were begun: 1) Passive Arsenic Removal Demonstration; 2) Prevention of Acid Mine Drainage Generation from Open-Pit Mine Highwalls; 3) Remediating Soil and Groundwater with Organic Apatite; 4) Remediation Technology Evaluation at the Gilt Edge Mine; 5) Acidic/Heavy Metal-Tolerant Plant Cultivars Demonstration, Anaconda Smelter Superfund Site; 6) Remote Autonomous Mine Monitor; 7) Microencapsulation to Prevent Acid Mine Drainage; 8) Bioremediation of Pit Lakes (Gilt Edge Mine); 9) Biological Prevention of Acid Mine Drainage (Gilt Edge Mine); and 10) Ceramic Microfiltration System Demonstration.

ACTIVITY IV: BENCH-SCALE EXPERIMENTS

Montana Tech successfully completed three projects during fiscal 2001: 1) Pit Lake System–Characterization and Remediation for the Berkeley Pit; 2) Pit Lake System–Deep Water Sediments/Pore Water Characterization and Interactions; and 3) Pit Lake System–Biological Survey of the Berkeley Pit. Four projects were begun: 1) an investigation to develop a technology for removing thallium from mine waste; 2) sulfide complexes formed from depositing mill tailings into a pit lake; 3) artificial neural networks as an analysis tool for geochemical data; and 4) Pit Lake System Characterization and Remediation of Berkeley Pit–Phase III. In addition, Project 11, Pit Lake System Characterization and Remediation for Berkeley Pit–Phase II, which assesses the effect of organic carbon, wall rock/water interactions, bacteria for natural remediation, and the effect of redepositing neutral tailings into the Berkeley Pit was in progress.

ACTIVITY V: TECHNOLOGY TRANSFER

MSE is responsible for preparing and distributing reports for the MWTP. These include routine weekly, monthly, quarterly, and annual reports; technical progress reports; and final reports for all MWTP activities. MSE also publicizes information developed under MWTP in local, regional, and national publications. Other means of information transfer include public meetings, workshops, and symposiums.

ACTIVITY VI: EDUCATIONAL PROGRAMS

Montana Tech has developed a post-graduate degree program with a mine waste emphasis. The program contains elements of geophysical, hydrogeological, environmental, geochemical, mining and mineral processing, extractive metallurgical, and biological engineering.

ORGANIZATIONAL STRUCTURE

MANAGEMENT ROLES AND RESPONSIBILITIES

Management of the Mine Waste Technology Program (MWTP) is specified in the Interagency Agreement. The roles and responsibilities of each organization represented are described below. The MWTP organizational chart is presented in Figure 1.

U.S. ENVIRONMENTAL PROTECTION AGENCY

The Director of the National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio, is the principal U.S. Environmental Protection Agency Office of Research and Development representative on the Interagency Agreement Management committee. NRMRL personnel are responsible for management oversight of technical direction, quality assurance, budget, schedule, and scope.

DEPARTMENT OF ENERGY

The Director of the National Energy Technology Laboratory (NETL) is the principal U.S. Department of Energy (DOE) representative on the Interagency Agreement Management committee. NETL personnel provide contract oversight for the MWTP. MSE Technology Applications, Inc. (MSE) is responsible to NETL for adherence to environmental, safety and health requirements; regulatory requirements; National Environmental Protection Act requirements, and conduct of operations of all projects.

MSE TECHNOLOGY APPLICATIONS, INC.

MSE, under contract with DOE, is the principal performing contractor for MWTP. The MWTP Program Manager is the point of contact for all mine waste activities. The Program Manager is responsible for program management and coordination, program status reporting, funds distribution, and communications.

An MSE project manager has been assigned to each MWTP project and is responsible to the MWTP Program Manager for overall project direction, control, and coordination. Each project manager is responsible for implementing the project within the approved scope, schedule, and cost. MSE also provides all staff necessary for completing Activities III and V and oversight of Activities II, III, IV, and VI.

MONTANA TECH OF THE UNIVERSITY OF MONTANA

As a subcontractor to MSE, Montana Tech of the University of Montana is responsible to the MWTP Program Manager for all work performed under Activities I, II, IV, and VI. The responsibility for overall project direction, control, and coordination of the work to be completed by Montana Tech is assigned to the MWTP Montana Tech Project Manager.

TECHNICAL INTEGRATION COMMITTEE

The Technical Integration Committee (TIC) serves several purposes in the MWTP organization: 1) TIC reviews new proposals and ranks them at a meeting held in Butte, Montana; 2) it reviews progress in meeting the goals of the MWTP and alerts the Interagency Agreement Management Committee to pertinent technical concerns; 3) it provides information on the needs and requirements of the entire mining waste technology user community; and 4) it assists with evaluating technology demonstrations as well as technology transfer. This committee is comprised of representatives from both the public and private sectors.

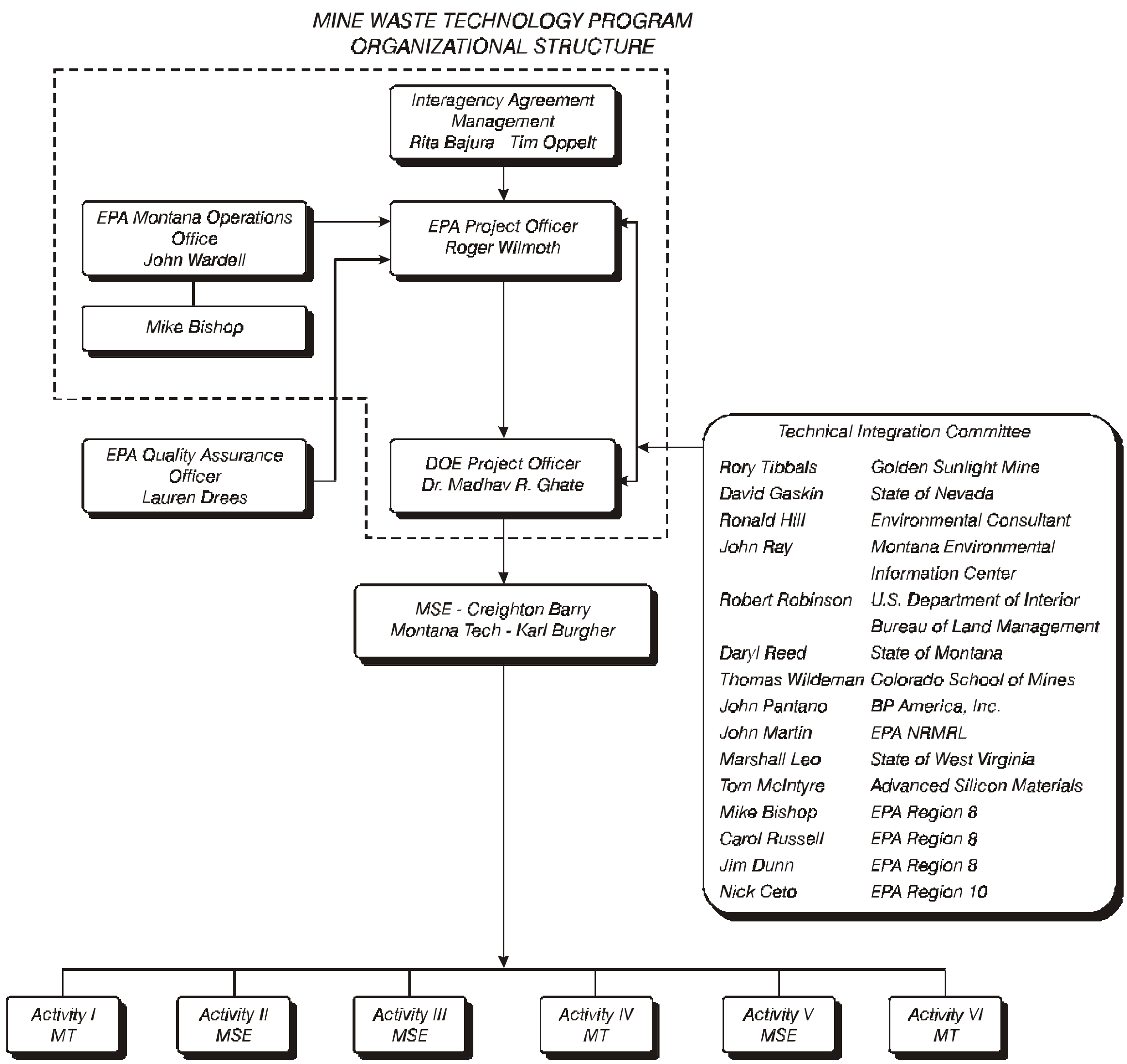


Figure 1. MWTP organizational chart.

DESCRIPTIONS, ACCOMPLISHMENTS, AND FUTURE DIRECTION

This section describes the Mine Waste Technology Program (MWTP) Activities I through VI and includes project descriptions, major project accomplishments during fiscal 2001, and future project direction.

ACTIVITY I OVERVIEW ISSUES IDENTIFICATION

This activity focuses on documenting mine waste technical issues and identifying innovative treatment technologies. Issues and technologies are screened and prioritized in volumes related to a specific mine waste problem/market.

Following completion of a volume, appendices are prepared. Each appendix links a candidate technology with a specific site where such a technology might be applied. The technology/site combinations are then screened and ranked.

Technical Issue Status

The status of the volumes approved for development includes:

- Volume 1, Mobile Toxic Constituents—Water and Acid Generation, complete.
- Volume 2, Mobile Toxic Constituents—Air, complete.
- Volume 3, Cyanide, complete.
- Volume 4, Nitrate, complete.
- Volume 5, Arsenic, complete.
- Volumes 1-5 Summary Report, complete.
- Volume 6, Pyrite, complete.
- Volume 7, Selenium, complete.
- Volume 8, Thallium, complete.
- Volume 9, Pit Lakes, in progress.

The status of the appendices for approved projects includes:

- Volume 1, Appendix A (Remote Mine Site), complete.
- Volume 1, Appendix B (Grouting), complete.
- Volume 1, Appendix C (Sulfate-Reducing Bacteria), complete.
- Volume 3, Appendix A (Biocyanide), complete.
- Volume 4, Appendix A (Nitrate), complete.

These documents can be reviewed at the web site, www.epa.gov/ORD/NRMRL/std/mtb.

ACTIVITY II OVERVIEW QUALITY ASSURANCE

The objective of this activity is to provide support to individual MWTP projects by ensuring all data generated is legally and technically defensible and that it supports the achievement of individual project objectives. The primary means of carrying out this activity is the Quality Assurance Project Plan, which is written for each project. This plan specifies the quality requirements the data must meet, states the project objectives, describes all sampling and measurement activities, and contains standard operating procedures, when applicable. Other functions of this activity include reviewing technical systems, validating data, implementing corrective action, and reporting to project management.

The U.S. Environmental Protection Agency approved the MWTP Quality Management Plan in 200l.

ACTIVITY III OVERVIEW PILOT-SCALE DEMONSTRATIONS

The objective of this activity is to demonstrate innovative and practical remedial technologies at selected waste sites, a key step in proving value for widespread use and commercialization. Technologies and sites are selected primarily from the prioritized lists generated in the Volumes from Activity I, or they may be a scale-up from bench-scale experiments conducted under Activity IV.

ACTIVITY III, PROJECT 3: SULFATE-REDUCING BACTERIA DEMONSTRATION

Project Overview

Acid generation typically accompanies sulfide-related mining activities and is a widespread problem. Acid is produced chemically, through pyritic mineral oxidation, and biologically, through bacterial metabolism. This project focuses on a source-control technology that has the potential to significantly retard or prevent acid generation at affected mining sites. Biological sulfate reduction is being demonstrated at an abandoned hard-rock mine site where acid production is occurring with associated metal mobility.

Technology Description

For aqueous waste, this biological process is generally limited to the reduction of dissolved sulfate to hydrogen sulfide and the concomitant oxidation of organic nutrients to bicarbonate. The particular group of bacteria chosen for this demonstration, sulfate-reducing bacteria (SRB), require a reducing environment and cannot tolerate aerobic conditions for extended periods. These bacteria require a simple organic nutrient.

This technology has the potential to reduce the contamination of aqueous waste in three ways. First, dissolved sulfate is reduced to hydrogen sulfide through metabolic action by the SRB. Next, the hydrogen sulfide reacts with dissolved metals forming insoluble metal sulfides. Finally, the bacterial metabolism of the organic substrate produces bicarbonate, increasing the pH of the solution and limiting further metal dissolution.

At the acid-generating mine site chosen for the technology demonstration, the Lilly/Orphan Boy Mine near Elliston, Montana, the aqueous waste contained in the shaft is being treated by using the mine as an in situ reactor. A substrate composed of cow manure, wood chips, and alfalfa was added to promote growth of the organisms. This technology will also act as a source control by slowing or reversing acid production. Biological sulfate reduction is an anaerobic process that will reduce the quantity of dissolved oxygen in the mine water and increase the pH, thereby, slowing or stopping acid production.

The shaft of the Lilly/Orphan Boy Mine was developed to a depth of 250 feet and is flooded to the 74-foot level. Acid mine water historically discharged from the portal associated with this level.

Pilot-scale work at the MSE Technology Applications, Inc., Testing Facility in Butte, Montana, was performed in fiscal 1994 prior to the field demonstration. The objective of these tests was to determine how well bacterial sulfate reduction lowers the concentration of metals in mine water at the shaft temperature (8 ºC) and pH (3).

Status

During fiscal 2001, the field demonstration was again monitored on a regular basis. Figure 2 presents a cross-section of the mine and technology installation.

During the past year of monitoring, the data generally demonstrated a decrease in metals concentrations (see Figure 3), with the exception of manganese, which SRBs do not effectively remove. An increase in metals was observed during spring runoff as occurred in prior years; however, the levels decreased when flow rates returned to normal. Field demonstration monitoring has been ongoing for 7 years. Monitoring was scheduled to be completed in June 2001 but was extended until October 2002.

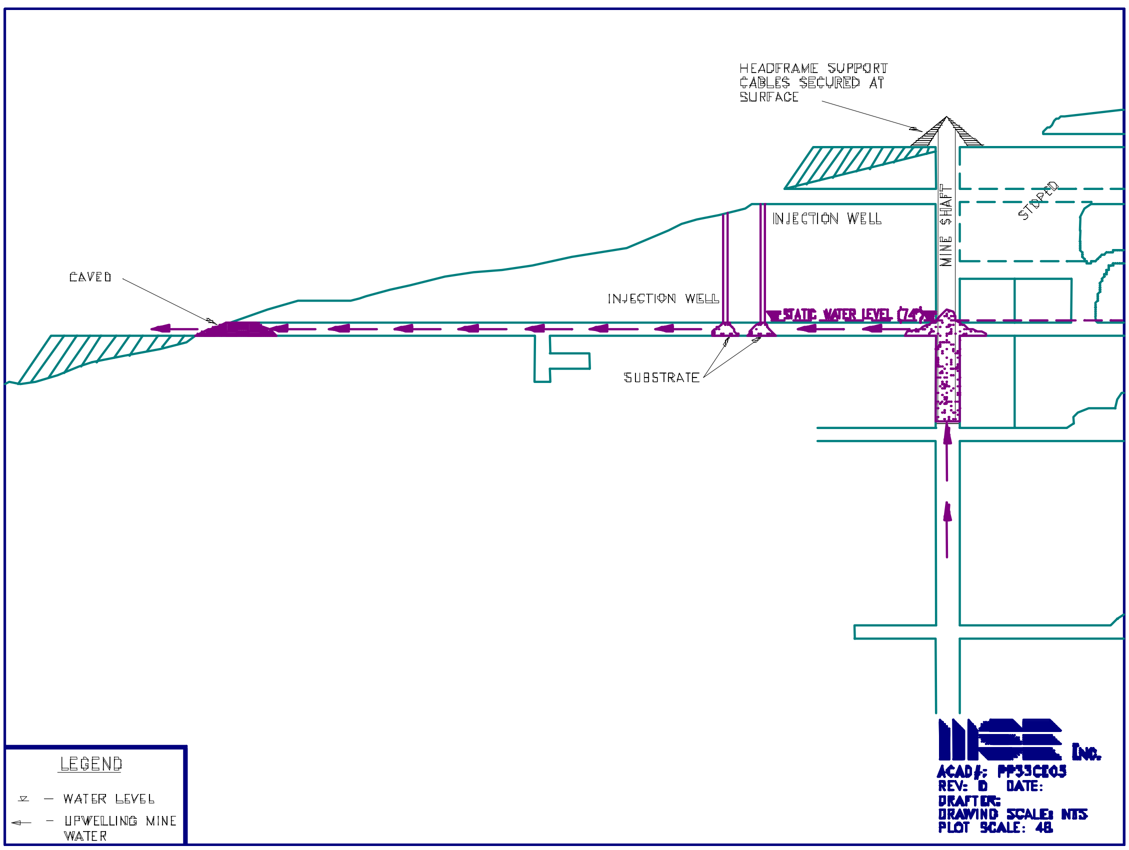


Figure 2. Cross-section of the Lilly/Orphan Boy Mine and the technology installation.

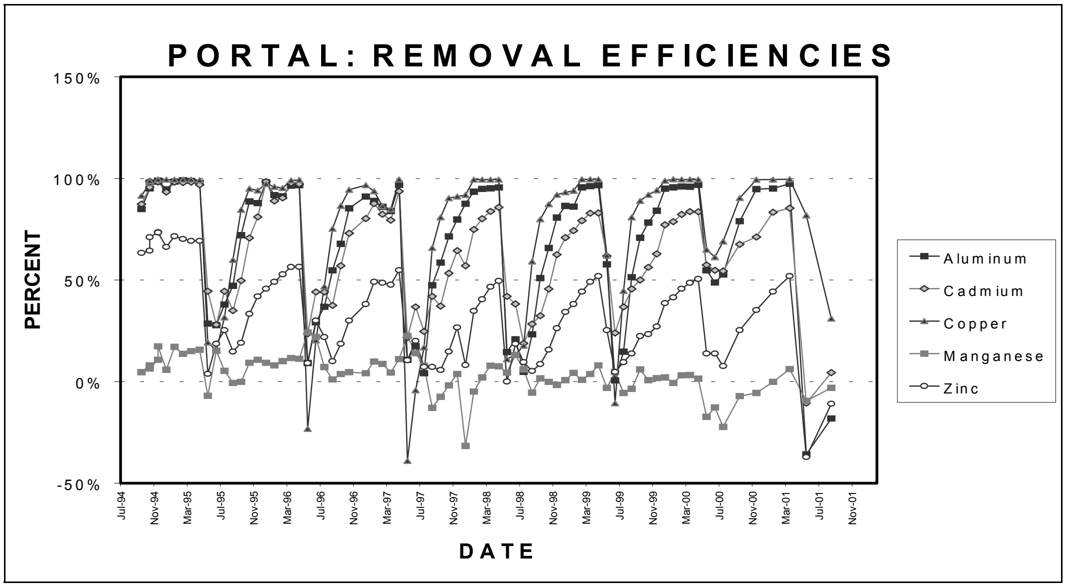


Figure 3. Metal removal efficiency at the Lilly/Orphan Boy Mine.

ACTIVITY III, PROJECT 8: UNDERGROUND MINE SOURCE CONTROL

Project Overview

A significant environmental problem at abandoned underground mines occurs when the influx of water contacts sulfide ores and forms acid and metal-laden mine discharge. The Underground Mine Source Control Project demonstrated that grout materials can be used to reduce and/or eliminate the influx of water into the underground mine system by forming an impervious barrier that results in reduced, long-term environmental impacts of the abandoned mine.

Technology Description

Groundwater flow is the movement of water through fractures, fissures, or intergranular spaces in the earth. Some of the fractures are naturally occurring; others were the result of blasting during mining.

For this demonstration, a closed-cell, expandable polyurethane grout was injected into the fracture system that intercepts the underground mine workings. The demonstration consists of three phases: 1) extensive site characterization; 2) source control material identification and testing; and 3) source control material emplacement.

Phase One, completed in 1999, consisted of characterization studies, including hydrogeological, geological, geochemical, and geophysical information gathering directly related to the mine and its operational history.

Phase Two encompassed source control material testing. Approximately 40 materials were tested according to ASTM methods for acid resistiveness, shear strength, plasticity, compressive strength, compatibility, and viscosity. The source control grout material selected for injection was Hydro Active Combi Grout, a closed-celled, expandable polyurethane grout manufactured by de neef Construction Chemicals, Inc. When compared to a cement-based source control material, this material offered the following advantages: greater retention of plasticity; less deterioration due to the acidic conditions and during rock movement; and better rheological characteristics.

Status

The Miller Mine near Townsend, Montana, was selected for the demonstration because the underground workings were accessible, it has a point-source discharge into the underground workings, the slightly acidic inflow is laden with heavy metals, and the inflow could be potentially controlled using the source control technology.

Phases One and Two were completed in March 1999. Phase Three, the field emplacement (shown in Figure 4), was completed in October 1999.

First year monitoring results indicate that the water flow into the underground mine was reduced from 10 to 15 gpm to approximately 1 to 1.2 gpm as a result of Phase III field emplacement.

In April 2000, additional grout was emplaced to reduce the flow into the mine as low as possible. The result was a reduction in flow from 1.2 to .6 gpm.

Figure 4. Grout emplacement in the underground mine workings.

ACTIVITY III, PROJECT 12: SULFATE-REDUCING BACTERIA REACTIVE WALL DEMONSTRATION

Project Overview

Thousands of abandoned mine sites in the western United States impact the environment by discharging acid mine drainage (AMD) to surface water or groundwater. Acid mine drainage is formed when sulfide-bearing minerals, particularly pyrite, produce oxygen and water in a chemical reaction that results in an increased acidity of the water (lowered pH), and increased concentration of dissolved metals and sulfate.

At many abandoned mine sites in the West, conventional treatment strategies for AMD (e.g., lime neutralization) are not feasible because of the remoteness of the mine locations, insomuch as a lack of a power source and limited site accessibility in winter. Sulphate-reducing bacteria (SRB) are capable of reducing the sulfate to sulfide, decreasing the load of dissolved metals in the effluent by precipitating metals as sulfides, and increasing the pH of the effluent. To demonstrate the feasibility of using SRB passive technology for mitigation of AMD emanating from the toe of a waste rock pile, three bioreactors were built at the abandoned Calliope Mine site located near Butte, Montana.

Technology Description

The Calliope mine site includes a collapsed adit discharging water into a large (66,000 cubic yards) waste rock pile. This relatively good quality water flows over the top of the waste rock and accumulates in a small lower pond at the toe of the pile. The AMD is mostly produced by atmospheric water that infiltrates the waste rock pile and reappears on the surface at the toe of the pile enriched in metals and with a pH of 2.6. This AMD also flows to the pond where it mixes with good quality water and lowers its pH. A portion of the water that accumulates in the pond was diverted for treatment to three engineered SRB bioreactors.

The quantity of AMD that recharges the pond is related to the amount of atmospheric water that infiltrates into the waste rock pile. Except for the first 8 months of operation, atmospheric precipitation was well below normal. Consequently, the amount of low pH AMD laden with metals decreased, and the quality of water in the pond improved. The pH increased, and the load of metals decreased, bringing concentrations of iron (Fe), aluminum (Al), and manganese (Mn) in the influent AMD below the target treatment levels for the project.

The SRB bioreactors constructed at the Calliope abandoned mine site in the fall of 1998 were approximately 70 feet long, 14 feet wide, and 6 feet high. They were placed in parallel (see Figure 5) downstream from the pond, allowing the AMD to be piped to and treated in the reactors using gravity flow. The bioreactors were designed to evaluate the SRB technology applied under different environmental conditions.

Two bioreactors were placed in trenches. One was constructed above the ground using a 12-foot-wide metal half-culvert to investigate the impact of seasonal freezing and thawing on SRB activity. To evaluate the efficiency of the SRB at optimal pH and oxidation-reduction potential (E_H), two of the reactors contained a passive pretreatment section to increase the alkalinity of the AMD.

The reactors were designed to flow at a rate of 1 gallon per minute. Bioreactor performance was monitored monthly by taking pH, E_H, dissolved oxygen, and temperature measurements, and collecting samples of influent and effluent for chemical analysis. The analytes included SRB population; pH; E_H; dissolved oxygen; alkalinity; and concentrations of sulfate, sulfide, dissolved metals, aluminum (Al), arsenic (As), cadmium (Cd), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn).

Each bioreactor was filled with a combination of organic matter and cobbles placed in discrete chambers (see Figures 5 and 6). Reactors II and IV also have a crushed limestone chamber. Each of these media was expected to play a certain role in the treatment train. 1) The organic matter, an electron donor and carbon source for the SRB, was provided as an 80% to 20% by volume mixture of cow manure and cut straw. The cow manure was also the SRB source. The cut straw was added to provide secondary porosity to the mix and to prevent settling of the medium. 2) For the pretreatment section, a chamber with cow manure was included to lower the E_H of AMD. 3) Crushed limestone provided the buffering capacity to increase the pH of AMD in the pretreatment section. 4) Cobbles placed in the reactive, primary treatment section of the bioreactor were supposed to provide stable substrate for bacterial growth.

Chambers filled with organic carbon or limestone were each 5 feet long; whereas, chambers filled with cobbles were 50 feet long. Such dimensions were selected based on the literature review and information acquired through the bench-scale test that was conducted in the MSE Technology Applications, Inc., laboratory in 1998. Preliminary results of the bench-scale test, at the time of the bioreactor's design, indicated the required residence time in the reactors should range from 3 to 5 days. This resulted in the bioreactors being sized for a flow rate of 1 gallon per minute. To provide flexibility, the flow and hydraulic head control systems placed in the bioreactors ensure a much wider range of the residence time.

The main challenges were to design the organic carbon chambers so the AMD would permeate through the entire cross-sectional area without channeling and to ensure that the organic substrate did not settle. These goals were achieved by placing the organic substrate in the cellular containment system (CCS) (U.S. Patent No. 6,325,923) consisting of 10 lifts of TerraCell™ (see geogrid in Figure 6) that would limit settling of the organic matter to each individual cell if it occurred. The TerraCell™ material, commonly used in landscaping for slope stabilization and made of high density polyethylene, was used to form CCS to house the organic matter. The CCS prevented the organic matter from settling to the bottom of the bioreactor, thus, fostering the flow of AMD through the entire cross-sectional area without channeling. Each layer (lift) of TerraCell™ was positioned at 60 degrees off the horizontal plane so that the cells of each lift would be partially offset with respect to the cells of adjacent lifts. Each lift was 6 inches thick (as measured along the horizontal direction of flow) and contained 11-inch by 8.5-inch rhombohedral-shaped cells.

Status

The bioreactors operated from December 1998 to July 2001, when they were decommissioned.

The decommissioning activity included an autopsy of the solid matrix material that was not accessible during the operational time. Autopsy sampling included collecting solid matrix samples for chemical analyses to determine concentrations of total metals (Al, As, Cd, Ca, Cu, Fe, Mg, Mn, and Zn), sulfate, sulfide, nitrogen, phosphorous, and total organic carbon (TOC) in the chambers of organic matter and limestone. Bacteriological analyses were also conducted to determine SRB population in the organic substrate and in the limestone. Because the cobbles did not have a visually discernible film of bacteria or chemical precipitate, no solid matrix samples were collected from these chambers.

Aqueous samples were also collected from the previously inaccessible bottom of the crushed limestone and cobble chambers and analyzed for total and dissolved metals.

The autopsy revealed a convoluted biochemical environment that was probably caused by the dramatic change in the AMD chemistry after the first 10 months of operation. The material examined during the autopsy showed the mixed results of processes that were occurring at low pH and a reasonably high load of metals with the subsequent reactions that were characteristic for water of neutral pH laden with much less of the dissolved metals.

Interpretation of monthly monitoring results combined with the autopsy findings allowed for the formulation of a number of conclusions and recommendations, the most essential of which are listed below.

- The CCS worked very well in preventing settling of the organic matter and ensuring uniform flow of AMD throughout the entire cross section of the organic carbon with no preferential flow paths (channeling).

- Configuring the bioreactors to accommodate flow in a horizontal plane (rather than in the vertical direction) was successful. Problems that were experienced with reductions in flow rate turned out to be associated with the AMD distribution system that was plugged by iron and aluminum hydroxide precipitates. This hindrance, however, is common to both configurations.

- The SRB establishment in the bioreactors took time. Once established and supplied with organic matter, they maintained a population of E+4 most probable number (MPN)/milliliter or higher in the aqueous phase at temperatures ranging from 2 to 16 ºC.

- The SRB average population of 2.06E+6 MPN/cubic centimeter in the solid matrix of organic matter was two orders of magnitude greater than the SRB population present in the aqueous phase.

- The AMD in the bioreactors was notably stratified with respect to oxidation-reduction potential that was up to 400 millivolts lower at the bottom of the bioreactors than at the top. Because maintaining reduced conditions is required for SRB, the bioreactors should have been more carefully isolated from atmospheric air. A plastic liner placed on top of the bioreactors is preferred over the straw bails used for this project.

- Only Zn, Cu, and Cd were being removed as sulfides due to SRB activities. Changes in concentrations of other metals (Fe, Mn, Al, and As), which do not necessarily precipitate as sulfide, seemed to be affected by SRB only in an indirect manner by responding to increased pH caused by SRB activity.

- For the Calliope site climatic and hydrochemical conditions, the thresholds for removing Zn, Cd, and Cu were approximately 500 micrograms per liter (µg/L), 5 µg/L, and 80 µg/L, respectively. These thresholds were slightly lower for Bioreactors II and IV than for Bioreactor III, which did not include a pretreatment cell. This indicates that the removal thresholds were dependent on the configuration of the bioreactor but were not affected by the shutdown and freezing of a bioreactor during winter.

- Most of the metal sulfides that were formed due to the SRB activity precipitated within the organic matter. The same seems to be true for the rest of the metals that must have formed hydroxides and carbonate compounds. The role of the cobble chamber was limited to a collection sump for a small mass of precipitates that escaped the organic matter chambers. This demonstrated that there was no need for the large cobble chamber, which could have been substituted with a smaller "trap" sump.

- The abundance of TOC present (20% by weight) in the organic matter chamber at the end of the project demonstrated that the bioreactors would have worked equally efficiently with a much smaller supply of organic carbon, provided the same residence time of AMD was maintained. Since the organic matter mass inhibits permeability, it is prudent to reduce the ratio of organic carbon to the permeability enhancing component (e.g., gravel, shell, etc.) and have more permeable medium.

- Since most of the material that caused plugging was found within and adjacent to the outlets of the AMD distribution system, there is a need to devise a system that would allow for occasional breakdown and removal of that material. Such a system might involve only a few outlets rather than the three dozen used in this design. It may include ports extended to the ground surface that would facilitate blowing in combustion engine exhaust to destroy plugging material that would then be removed by bailing.

Overall, the project documented that SRB technology, as applied in this demonstration, is effective in removing Zn, Cu, and Cd by precipitating them as sulfides. Removal mechanisms for Fe, Al, Mn, and As were overshadowed by a dramatic change of the quality of the influent AMD. The results of the project have also allowed the formulation of an important recommendation regarding the design and construction of SRB bioreactors.

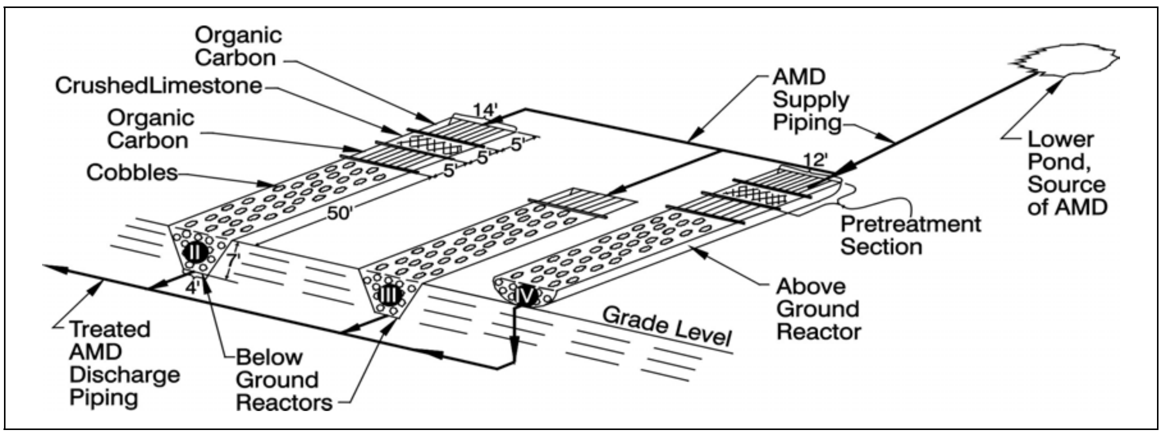


Figure 5. Layout of bioreactors.

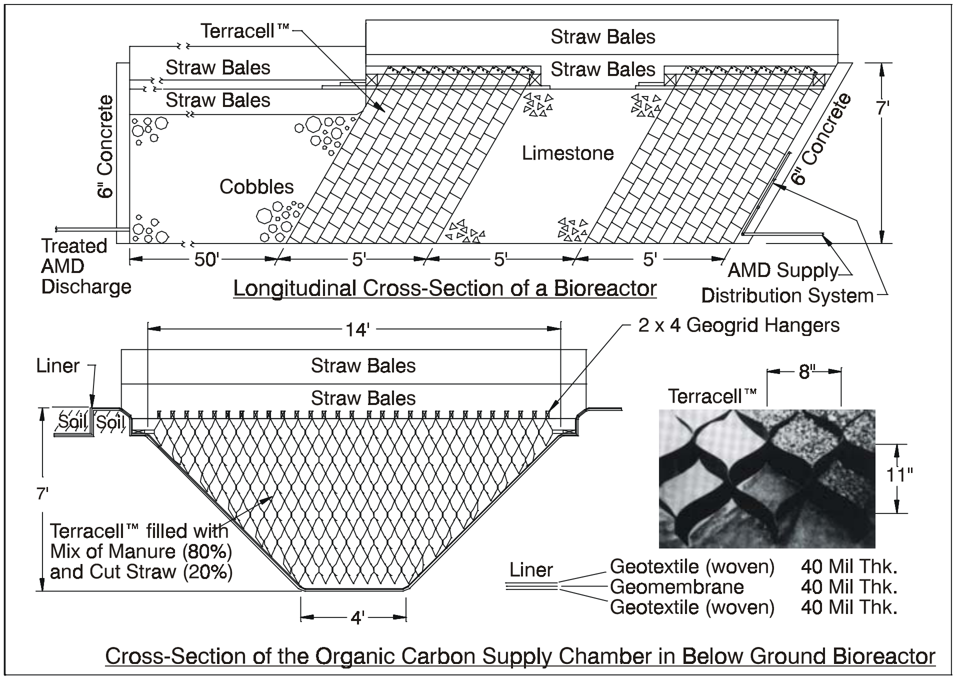


Figure 6. Bioreactors design.

ACTIVITY III, PROJECT 14: BIOLOGICAL COVER DEMONSTRATION

Project Overview

Acidic, metal-laden waters draining from abandoned mines have a significant environmental impact on surface and groundwater throughout the nation and the world. Specifically, the State of Montana has identified more than 20,000 abandoned mine sites, on both public and private lands, resulting in more than 1,300 miles of streams experiencing pollution problems.

Acid mine drainage arises from tailings and waste rock containing sulfide minerals and lacking acid-consuming carbonate minerals. Sulfide minerals, such as pyrite (FeS_2), are oxidized to form sulfate when water containing oxygen infiltrates tailings and waste rock. This process can be described by the following reaction:

$$4FeS_2 + 15O_2 + 2H_2O \rightarrow 4Fe^{3+} + 8SO_4^{2-} + 4H \qquad (1)$$

The activity of bacteria, such as *Thiobacillus ferrooxidans*, which are capable of oxidizing inorganic sulfur compounds, greatly accelerates this reaction. The ferric iron (Fe^{3+}) produced in the above reaction also contributes to pyrite oxidation:

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+. \qquad (2)$$

T. ferrooxidans is also capable of oxidizing ferrous iron (Fe^{2+}) produced in the above reaction:

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O. \qquad (3)$$

Although the above reaction consumes some acidity, the ferric iron produced is capable of oxidizing more pyrite and producing much more acidity (via reaction 2).

The key to breaking this cycle is preventing the initial oxidation of pyrite. Bound with iron, the sulfur in pyrite is unable to participate in the microbially catalyzed reactions that cause acid generation. Preventing oxygen infiltration into tailings and waste rock is necessary to prevent oxidation of pyrite and subsequent acid generation. An innovative method to prevent oxygen transport into tailings is constructing and maintaining a biologically active barrier on the surface of the tailings. This barrier is made up of microorganisms that consume dissolved oxygen from the infiltrating water, thereby, maintaining the reducing conditions necessary for pyrite to remain bound in mineral form.

MSE Technology Applications, Inc. and researchers at the Center for Biofilm Engineering at Montana State University are investigating the microbial processes involved with establishing and maintaining subsurface and near surface microbial barriers for hydraulic control and microbially catalyzed reactions. Biofilm barrier technology has been successfully tested in laboratory and field-scale systems where permeability reductions of five orders of magnitude were achieved. During these tests, it was also shown that biofilm barriers can successfully remove oxygen from infiltrating waters to trace levels.

By conducting this demonstration, the Mine Waste Technology Program is illustrating the ability of microbial biomass to reduce the permeability of mine tailings and remove oxygen from infiltrating water, thereby, reducing the generation of acid mine drainage. This technology promises to be a cost-effective approach for stabilizing and remediating acid-generating abandoned mine tailings.

Technology Description

A biologically active zone is established in the tailings by adding a nutrient solution to the surface of the tailings pile. The nutrient solution contains low cost ingredients that serve as sources of carbon and energy for microbial growth, as well as sources of nitrogen, phosphorous, and necessary micronutrients. The nutrient solution is formulated to stimulate indigenous oxygen-consuming microorganisms, as well as sulfate-reducing bacteria (SRB). In some cases, a microbial inoculum containing appropriate microorganisms may have to be added. The oxidation of carbon compounds in the nutrient mixture by microorganisms depletes oxygen from infiltrating water. Also, bacterial cells and associated extra-cellular polymers occupy free pore space within the tailings matrix, greatly reducing permeability. The reduction of water volume flowing through the tailings and depletion of oxygen as water passes through the barrier will mitigate pyrite oxidation and subsequent acid generation. The anaerobic conditions and production of organic acids by fermentative bacteria will also promote SRB growth. The SRB activity is desirable because it neutralizes acid and stabilizes metals by H_2S-mediated metal sulfide precipitation. After establishing the biological barrier, periodic nutrient treatments are applied to maintain the barrier.

Status

The site selected for implementing this technology is the Mammoth tailings site located in the South Boulder Mining District approximately 18 miles from Cardwell, Montana. Two lined test cells were constructed at the field site in the fall of 1999. An initial nutrient treatment was applied to one of the test cells (treated cell) in the fall of 1999 (see Figure 7). Additional nutrient treatments were applied to the treatment cell in the spring and summer of 2000 and 2001. The control (untreated) cell received an equivalent amount of water to that applied to the treatment cell during nutrient treatments. Other than the nutrient or water treatments, all water entering the test cells was due to natural precipitation. The test cells were not operated during the winter months when they were frozen.

The nutrient formulation used for the initial treatment and treatments applied in 2000 included molasses as a carbon and energy source, urea as a source of nitrogen, and potassium phosphate. Drainage from the treated cell had a slightly higher pH than drainage from the untreated control cell. The mean dissolved metal concentration in effluent from the treated cell relative to the control cell was 76% lower for aluminum, 90% lower for copper, and 38% lower for zinc. Drainage from the control cell exceeded the maximum contaminant level (SMCL) for copper (1.0 mg/L), while the copper concentration in drainage from the treated cell remained below the SMCL. These results indicate the molasses-based treatment improved the water quality of drainage from the tailings at the mammoth site.

Laboratory column tests conducted in the winter of 2000–2001 indicated whey-based nutrient treatments were superior to molasses-based treatments for preventing acid mine drainage generation. The effect of molasses treatments, as determined by increased drainage pH, lasted 1–2 months; whereas, whey treatments influenced effluent pH for approximately 6 months. Whey-based nutrient solutions were applied to the treatment cell during the spring and summer of 2001.

Whey is a byproduct of cheese manufacturing that contains organic carbon primarily in the form of lactose and protein. The results of the whey treatments in the field test were similar to those observed for the molasses-based treatments with a slightly higher pH and lower concentrations of dissolved aluminum, copper, and zinc in drainage from the treated cell relative to the control cell. Thus, the increased effectiveness of whey-based treatments over molasses-based treatments observed in the laboratory experiments was not apparent in the field test. This is likely the result of the much higher dosages of the whey in the nutrient solutions used to treat tailings in the laboratory experiments. Further research is needed to optimize the dosage rates and composition of nutrient solutions, although these parameters are likely dependant on properties of the specific tailings to be treated. Overall, the results indicate that this is a promising technology for source control of acid mine drainage.

Figure 7. Application of nutrient solution to the test cells at the Mammoth site.

ACTIVITY III, PROJECT 15: TAILINGS SOURCE CONTROL

Project Overview

Processing metallic ores to extract the valuable minerals leaves remnant material behind called tailings. In the case of sulfide mineral-bearing ores, process tailings often contain large quantities of sulfide minerals that do not meet the economic criteria for extraction. These remnant sulfide minerals are usually pyrites and nonextracted ore minerals. The exposure of these minerals to air and water often leads to detrimental environmental conditions such as increased sedimentation in surface waters due to runoff events, increased wind borne particulate transport, generation of acid mine drainage, and increased metals loading in surface and groundwaters.

Technology Description

The objective of this demonstration was to identify potential source control materials and apply one or more of them at a selected site. The demonstration consists of two phases: 1) site characterization and materials testing; and 2) materials emplacement and long-term monitoring and evaluation.

Phase one consisted of the site characterization studies, including hydrogeological, geological, and geochemical information directly related to the tailings impoundment. The materials testing and development involved testing, evaluation, and formulation of source control materials for application at the selected site.

Phase two will encompass the application of three select source control materials at the demonstration site and an evaluation of the material application and feasibility. Long-term evaluation of the materials will include air borne particulate testing, moisture profiles generated from reflectometers, in situ permeability tests (using Guelph Permeameters), ex situ permeability tests, and freeze/thaw testing (flexible wall permeameter).

Status

The Mammoth Tailings site located adjacent to the historic mining town of Mammoth, Montana (see Figure 8) was the project site selected. Material testing was completed during the first quarter of 2000. Three source control materials were applied at the site during the summer of 2001. These materials included two, polymeric cementitious grouts that incorporate the tailings material as a filler material (IESCRETE and Krystal Bond) and a spray-applied, modified polyurea chemical grout. Following a year of moisture testing and material evaluation, the project is scheduled to be completed by the end of calendar year 2002.

Figure 8. Mammoth Mine Tailings site.

ACTIVITY III, PROJECT 16: INTEGRATED PASSIVE BIOLOGICAL TREATMENT PROCESS DEMONSTRATION

Project Overview

The objective of this project is to develop technical information on the ability of an integrated passive biological reactor to treat and improve water quality at a remote mine site. This technology offers advantages over many acid mine drainage (AMD) treatment systems because it does not require a power source or frequent operator attention. For this demonstration, the technology will treat the acidic aqueous waste by removing toxic, dissolved metallic and anionic constituents from the water in situ and increasing the pH so the effluent is near neutral.

Technology Description

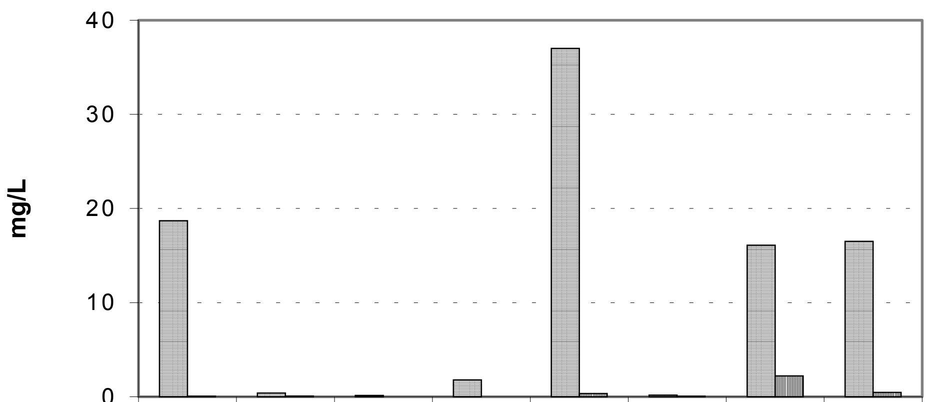
The technology uses a series of biological processes for the complete mitigation of AMD by concentrating and immobilizing metals within the reactors and raising the pH of the water. Both anaerobic and aerobic bacteria are used. The bacteria are fed inexpensive waste products such as feedlot wastes. The sulphate-reducing bacteria (SRB) are a group of common bacteria that are able to neutralize AMD and remove toxic metals. When supplied with sulfate (present in mine water) and a carbon source (composed of 50% cow manure and 50% walnut shells), SRB produce bicarbonate and hydrogen sulfide gas. Figure 9 shows the metals removal results. Bicarbonate neutralizes AMD while hydrogen sulfide gas reacts with metal ions to precipitate them as insoluble metal sulfides. Aerobic bacteria are used to mitigate metals, such as iron and manganese, which are not removed satisfactorily by SRB. The result will be an integrated biological system capable of completely and passively mitigating AMD. The field system is depicted in Figure 10.

In the first phase of the project, laboratory testing was performed to identify design parameters for the field design.

The second phase of the project was the design and construction of an integrated passive biological treatment system to treat AMD at the Surething Mine located in Southwest Montana.

Status

The construction of the field-scale system was completed in fiscal 2001.



	Al	As	Cd	Cu	Fe	Pb	Mn	Zn
In	18.7	0.374	0.138	1.78	37	0.163	16.1	16.5
Out	0.051	0.064	0.004	0.006	0.336	0.04	2.21	0.458

Figure 9. September 2001 metal concentrations.

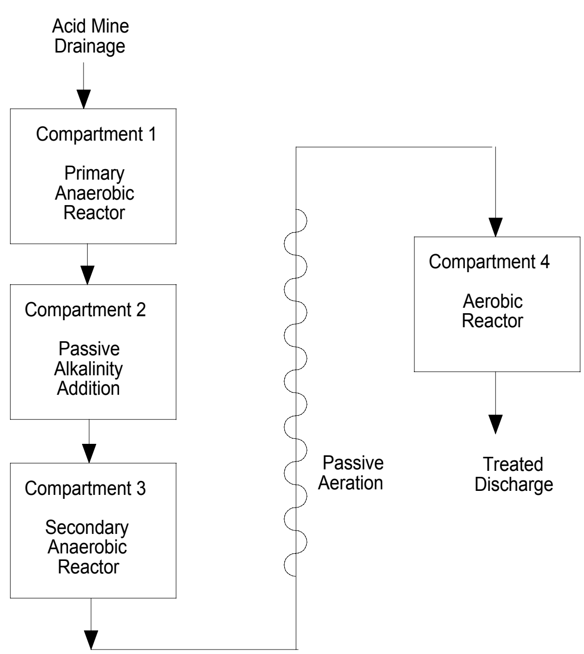


Figure 10. Field system for integrated passive biological treatment process demonstration.

ACTIVITY III, PROJECT 16A: SULFATE-REDUCING BACTERIA-DRIVEN SULFIDE PRECIPITATION DEMONSTRATION PROJECT

Project Overview

Acid mine drainage (AMD), produced by chemical and biological oxidation of sulfide minerals, consists of acidic water containing high concentrations of sulfate and dissolved metals. Pollution of ground and surface water by AMD is problematic at both active and inactive mine sites. The use of sulfate-reducing bacteria (SRB) to treat AMD is a promising alternative to conventional treatment methods. SRB oxidize organic matter under anaerobic conditions using sulfate as a terminal electron acceptor, resulting in sulfate removal and the formation of sulfide and bicarbonate ions. The sulfide produced can react with dissolved metals in AMD, removing them from solution as insoluble metal-sulfide complexes. The alkalinity (bicarbonate) produced by SRB metabolism is capable of buffering the acidity of AMD.

Technical challenges in designing an SRB treatment system for AMD include the fact that the acidity and high metal concentrations of AMD can be inhibitory or toxic to the bacteria. Furthermore, the production of insoluble metal sulfides and hydroxides in SRB bioreactors, as well as the production of microbial biomass, can lead to plugging of the reactor systems. These challenges are being overcome in this project using a novel two-stage SRB treatment system. Bench-scale tests were conducted at the MSE Testing Facility in Butte, Montana, to demonstrate the feasibility of the concept. A field-scale test system was constructed at Golden Sunlight Mine near Whitehall Montana. Initial results indicate the field scale system is very effective for treating AMD emanating from a large waste rock pile.

Technology Description

The SRB treatment system being evaluated in this project consists of a two-stage reactor design to separate the abiotic and biotic reactions occurring during AMD treatment. In the first stage of the process (settling pond), AMD is mixed with water containing sulfide and alkalinity generated by SRB metabolism in the second stage of the process (bioreactor). Following the abiotic buffering and metal-precipitation reactions occurring in the settling pond, the partially treated AMD enters the bioreactor. The sulfate necessary for SRB growth is provided by the AMD, and organic carbon (methanol) is added to the settling pond. A portion of the treated AMD from the bioreactor effluent is recycled to the settling pond, while the remainder is discharged. This system design prevents direct exposure of the SRB to the acidic metal-laden AMD and prevents clogging of the biorector with metal precipitates.

Status

Bench-scale testing of this technology was completed in 2001. Acid mine drainage from the Midas dump, a large waste rock pile, at Golden Sunlight Mine was used in these tests. Results of the bench-scale tests indicated this was a feasible technology for treating AMD from the Midas dump. Data from the bench-scale tests was also used to estimate an appropriate recycle rate for operating the field-scale system. The field-scale system was constructed at Golden Sunlight Mines in the summer of 2001 and began operation in the fall of 2001. The system was designed to treat drainage from the Midas dump, which is produced at rates of 1 to 3 gallons per minute. Initial results indicate the system is significantly improving the water quality of AMD from the dump. The pH of the AMD from the Midas dump was 2.7 ± 0.1, while the pH of the bioreactor effluent has ranged from 5.3 to 6.4.

The system has also been effective for removing dissolved aluminum, copper, iron, and zinc from the drainage. Overall, the results to date indicate this is a very effective system for treating AMD.

ACTIVITY III, PROJECT 19: SITE IN SITU MERCURY STABILIZATION TECHNOLOGIES

Project Overview

This demonstration project is being conducted in conjunction with the U.S. Environmental Protection Agency's Superfund Innovative Technology Evaluation Demonstration Program. Mercury contamination often is a critical problem at mine sites, and there is a recognized need to identify technologies for mercury remediation. The application of an in situ mercury stabilization technology would provide an alternative treatment to completely removing mercury-contaminated materials from remote abandoned mine sites. As part of the overall project, MSE Technology Applications, Inc. (MSE) is responsible for conducting technology assessment activities to comparative mercury stabilization tests using mercury-contaminated material.

The Sulphur Bank Mercury Mine (SBMM) in Clear Lake, California, was chosen as the source of mercury contaminated mining wastes for this demonstration project. This abandoned mine located in a geothermal active area was historically mined for mercury and sulfur. It is now part of a 120-acre superfund site containing tailings, rock piles, and a pit lake. The mine tailings are located upgradient and extend into and along the shoreline of Clear Lake. The development of an in situ mercury treatment/stabilization technology could be used to address the significant mercury contamination problems at the site.

Technology Description

The main objective of this effort is to determine a suitable method for in situ mercury stabilization. An extensive treatability study was performed on two mercury contaminated SBMM materials by three types of stabilization technologies. The primary objective of this study was to determine the effectiveness of the three stabilization technologies (silica encapsulation, phosphate, and sulfide) in reducing the quantity of leachable mercury from SBMM material. Waste material evaluated in this study consisted of “white material” from the south white gate pile and “yellow material” from the north yellow pile. The white material was the primary test material due to its demonstrated ability to produce consistent and detectable levels of leachable mercury. The yellow material was included because it is a common material at the site, even though it yields lower levels of leachable mercury.

To evaluate the performance of the three technologies, the leachable and mobile mercury (defined as the mercury in the <25-Fm filtered leachate fraction) from control columns receiving no treatment was compared to the leachable and mobile mercury in the treatment columns. Specifically, the objective was to achieve a 90% reduction in the total mass of mercury leached from each treatment relative to the control over a 12-week continuous column leaching study. The mass of mercury for each treatment and control was calculated by multiplying the mercury concentration of the <25-Fm fraction collected each week by the volume of leachate collected, averaging the mass for each set of replicate treatment or control columns, and summing the total for the 12 weeks. The white material was used to evaluate the primary objective in the column study, and each treatment or control was run as triplicate columns. As a secondary objective, and with no quantitative reduction goals, the yellow material was evaluated over a 12-week period in the column tests. In addition to mercury in the leachate, the following parameters were measured: pH, redox potential, sulfate, sulfide, conductivity, alkalinity/acidity, turbidity, and other metals (arsenic, iron, and antimony).

In addition to the column tests, kinetic testing using the humidity cell procedure was run on the control white material (no treatment) and treated white material. Humidity cell testing, detailed in ASTM D 5744-96, is a protocol designed to meet kinetic testing regulatory requirements for mining wastes and ores. In this test method, the sample is subjected to alternate periods of dry air, moist air, and water leaching in an effort to simulate the weathering process that the ore would undergo in a natural environment.

Status

The predemonstration leachability studies revealed that the dominant form of leachable mercury was in a particulate and mobile form. These studies indicated that leaching with a meteoric solution released particulates that remained suspended in solution and, therefore, could be mobile in a groundwater and/or surface water hydraulic system. Levels of dissolved mercury were low in these leaching studies. A continuous column leaching test design was used to collect effluent samples over a 12-week period to evaluate leachable mercury in mobile (<25 Fm) and dissolved (<0.45 Fm) fractions from treated and control columns. The conventional phosphate treatment dramatically increased the levels of mobile mercury (<25 Fm fraction) over the course of the 12-week study. A 94.7% increase in the total mass of mercury leached occurred relative to the control. Sulfide treatment did not appear to be effective in reducing the levels of mobile mercury in the column tests. There was no significant difference in the cumulative levels of mobile mercury in the effluent from the sulfide treatment relative to the control. Silica microencapsulation was effective in reducing mobile mercury (<25 Fm) very close to the 90% reduction goal of the study. However, the dissolved mercury portion (<0.45 Fm) of the mobile fraction increased by approximately 200% relative to the control.

ACTIVITY III, PROJECT 21: INTEGRATED PROCESS FOR TREATMENT OF BERKELEY PIT WATER

Project Overview

The objective of this project is to develop integrated, optimized treatment systems for processing Berkeley Pit water. The Berkeley Pit is an inactive open-pit copper mine located in Butte, Montana. Currently containing approximately 30 billion gallons of acidic, metals-laden water, the Berkeley Pit is filling at a rate of approximately 3 million gallons per day and is a good example of acid rock drainage.

Two optimized flow sheets will be developed for this project. One flow sheet is to be oriented toward minimizing the overall cost of water treatment to meet discharge requirements—this will include not only water treatment equipment but also sludge handling/management. The other flow sheet is to be oriented toward also meeting discharge requirements but includes the recovery of products from the water (copper, metal sulfates, etc.) to potentially offset treatment costs and result in overall better economics.

Technology Description

The project will evaluate proven technologies [e.g., precipitation (oxide/hydroxide, sulfide), ion exchange, cementation, solvent extraction, electrolysis, filtration options, etc.] as well as technologies with credible pilot-scale supporting data. Technology with only laboratory testing history or with unverifiable pilot-scale data will not be considered. The goal is to assemble the sequence of unit operations resulting in the most attractive overall economics, without relying on relatively unproven technologies.

Status

In FY 2001, a report documenting small-scale testing to evaluate the effects of returning settled sludges to the Berkeley Pit was completed and issued. Information was gathered on a variety of process options, including the use of high-density sludge, and spreadsheets were prepared evaluating a variety of metal recovery options to evaluate the economics of potential modifications. Options evaluated included copper recovery as a sulfide, followed by roasting to other forms; zinc recovery as a sulfide and by solvent extraction, also followed by various downstream process options; aluminum recovery as an oxide; and various others. Preliminary results showed that most of the metals present cannot be profitably recovered due to their low value and dilute concentrations. Sulfide precipitation is an attractive way to separate and recover copper and zinc, but sulfide products are of very low value, and on-site upgrading is needed to potentially be profitable. Copper recovery is viable but may not be more attractive than using the existing cementation plant. Profitable zinc recovery is very marginal at current prices. Future plans are to issue a project final report in FY 2002.

ACTIVITY III, PROJECT 22: PHOSPHATE STABILIZATION OF MINE WASTE CONTAMINATED SOILS

Project Overview

The project goal is to provide information to support technical feasibility and regulatory acceptance of phosphoric acid-based in situ stabilization of lead in residential soils at the Joplin, Missouri National Priorities List Site. The ultimate goal is to demonstrate this technique is a cost-effective alternative to excavation and haulage of metal-contaminated soils to a waste repository.

Technology Description

The remediation approach involves mixing commercial grade phosphoric acid and a trace of potassium chloride into near surface soils, followed by pH adjustment (e.g., with lime addition) to attain paraneutrality. As a result, soluble lead is converted to pyromorphite, a highly insoluble and environmentally stable mineral. Subsequently, lead uptake from rooting zone soils (into aboveground plant biomass) and into the bloodstream of young children (from the gastrointestinal tract) is significantly reduced.

Status

The following activities were completed in fiscal 2001: sampling and analysis of soil and plant materials collected from the field test plot; dosing of young swine with soils from the test plot; and laboratory characterization of the treated soils. The overall results for mill tailings receiving 1 percent by weight phosphoric acid (as described above) were very promising. It appears as though this treatment will significantly reduce public health and environmental risks due to exposure to these contaminated soils. Additional work to verify the pig dosing results will be completed in FY 2002 and will be documented in the final project report.

ACTIVITY III, PROJECT 23: REVEGETATION OF MINING WASTE USING ORGANIC AMENDMENTS AND EVALUATE THE POTENTIAL FOR CREATING ATTRACTIVE NUISANCES FOR WILDLIFE

Project Overview

The objectives of this project are to demonstrate the use of organic amendments to enhance the establishment and growth of grass on lead mine tailings and to evaluate the affect of those amendments on plant uptake of metals. Two sources of compost and an organic fertilizer derived from municipal sewage treatment plant sludge were incorporated into two types of tailings near Desloge, Missouri, and the replicated plots were planted with grass. Both types of tailings (fine-textured floatation tailings and course-textured gravity separation tailings referred to as chat tailings) contain elevated concentrations of lead, zinc, and cadmium. This project will be evaluated for three growing seasons.

Thousands of abandoned mine and mineral processing sites throughout the United States are very unattractive and can be a significant environmental hazard. The federal government and responsible parties need to develop cost-effective remedial approaches to effectively manage these large areas that are contaminated with a wide variety of metals. Natural revegetation is often prevented in these areas because of low pH, phytotoxic concentrations of metals, poor physical structure for plant growth, nutrient deficiencies, and slopes too steep for plant establishment. Mine waste reclamation research frequently includes the addition of organic soil amendments, since mine waste materials are typically subsurface in origin and have minimal organic content. However, the diversity of organic amendments used and the lack of uniformity within each category of material make comparisons among sites and studies difficult. In addition, while it is generally agreed that organic amendments are capable of stabilizing mine waste metals, the potential for post reclamation impacts to wildlife due to plant uptake of those metals requires further research.

Technology Description

MSE Technology Applications, Inc., established field plots at the Big River Mine Tailings Site and the Leadwood Chat Tailings Site in Missouri in the spring of 2000. The plots were evaluated to determine vegetation establishment, biomass production, and plant uptake of metals. Procedures for establishing, maintaining, and evaluating the plots will be broadly applicable and reproducible so that subsequent studies at other locations will produce comparable information. The three organic amendments are milorganite, ormiorganics compost, and St. Peters compost. These amendments were applied at a low, medium, and high application rate. Each amendment/application rate combination was replicated four times including a control plot that only received the inorganic fertilizer at both sites, totaling 80 plots. The plant species for the demonstration was tall fescue (Kentucky variety). The plots were monitored monthly from May through September 2000. The project will be evaluated for three growing seasons.

Status

Figure 11 shows the Leadwood Chat Tailings site prior to planting, Figure 12 shows the site after the first growing season, and Figure 13 shows the site after the second growing season. Figure 14 shows the Big River Mine Tailings site prior to planting, Figure 15 shows the site after the first growing season, and Figure 16 shows the site after the second growing season.

The results from the second year growing season were compared to the first year growing season. Preliminary results indicate that the cover and production results had less vegetation compared to the first year, which is largely due to the dry season without irrigation. However, the compost treatments have a considerable amount of vegetation compared to the controls. In general, both cover and production were correlated with increasing application rates for all treatment, which shows the benefits from higher application rates. Overall, the plots have easily vegetated and compost appears to reduce metal uptake into the plants foliage compared to the control plots.

Additional results of the second growing season will be discussed in a Summary Report to be issued in April 2002. The project will be evaluated for a third growing season, and a Final Report will be issued in March 2003.

Figure 11. Leadwood Chat Tailings site prior to planting.

Figure 12. Leadwood Chat Tailings site after first growing season.


Figure 13. Leadwood Chat Tailings Site after second growing season.


Figure 14. Big River Mine Tailings site prior to planting.


Figure 15. Big River Mine Tailings site after first growing season.


Figure 16. Big River Mine Tailings Site after second growing season.

ACTIVITY III, PROJECT 24 IMPROVEMENTS IN ENGINEERED BIOREMEDIATION OF ACID MINE DRAINAGE

Project Overview

Acid mine drainage (AMD) emanates from many abandoned mine sites in the western United States. Such drainage, having an elevated content of dissolved metals and low pH, presents an environmental problem that needs to be economically addressed. Sulfate-reducing bacteria (SRB) have the ability to immobilize dissolved metals, by precipitating them as sulfides, and increase pH provided that a favorable biochemical environment is created. Such conditions may be created by constructing artificial wetlands, if space is not limited, or converging the AMD flow to an engineered passive SRB reactor.

A SRB reactor contains an organic-carbon chamber that is vital for its operation. A life span of a properly designed reactor depends on the organic carbon supply, permeability of organic-carbon chamber, and the capacity of the reactor to accumulate precipitated sulfides.

When the source of organic carbon is depleted, or becomes unavailable, because permeability of the organic matter decreased due to settling processes or physical or chemical encapsulation, the bioreactor will cease operating. To reactivate such a bioreactor, the organic carbon source has to be either replenished or rejuvenated. Therefore, it is desirable to: 1) maximize the time interval between such operations; and/or 2) be able to predict the longevity of the carbon source to economically optimize the reactor's size.

Similarly, when the capacity of the bioreactor's chamber that was designed to hold precipitated sulfides is exhausted, the sulfides will either break through or the reactor will plug ceasing its operation.

This project addresses engineering improvements that include replacing the organic carbon supply-system in a SRB reactor and refining how the reactor is sized.

Technology Description

Engineered improvements of SRB reactors are to be accomplished by implementing the four tasks listed below.

Task I–Selecting Optimal Media with Organic Carbon

The optimal media needs to: 1) contain a sufficient amount of organic carbon; 2) be used economically as passive SRB bioreactors; and 3) have high potential to be permeable when saturated with water. Determination of the optimal organic carbon media will be done through a literature study. A database was set up that included the media technical parameters, records of use, availability, price index, etc.

Task II–Designing a Permeability and Contact Time Enhancing System (PACTES)

PACTES will ensure a good supply of organic carbon and will maintain good permeability of the organic matter throughout the predicted life of the reactor.

Task III–Designing an Organic Carbon Replaceable Cartridge System (RCS)

A replaceable cartridge system will be easy to install and replace in a bioreactor, particularly at a remote location.

To ensure that PACTES and RCS systems are compatible, their development was symbiotic. Work on each system included the following phases: 1) developing a list of concepts for each system; 2) narrowing the list to the most (one) applicable solution; 3) laboratory testing of the selected solution; 4) preparing the design document; 5) constructing the prototype of the RCS combined with PACTES; and 6) bench-test study of the constructed prototype.

Task IV–Developing a Computer Software to Simulate SRB Activities in the Bioreactor

The software will enable a designer to efficiently design and size a bioreactor by quantifying the expected rate of organic carbon depletion and the volume of SRB activity by-products.

Status

Task I was completed, and a report of the findings entitled *Evaluation of Organic Substrates for the Growth of Sulfate-Reduction Bacteria to Treat Acid Mine Drainage* was prepared. The report contained the Microsoft Access database that included information obtained from more than 90 publications that identified 36 organic substrates; among them, 7 substances were direct, e.g. methanol, lactate, etc., and 29 were indirect, e.g. manure, sludge, wood waste, etc.

The following conclusions were reached upon completing this task.

- Selecting an organic substrate should be based on effectiveness, cost, and availability.
- A mixture of substrates, with varying degrees of biodegradability, provides the best long-term bioreactor performance.
- Directly utilizable SRB substrates can be used to either initiate the SRB activity or restore the activity to spent organic media.
- The suitability of a substrate mixture for treating a particular AMD is best assessed empirically using laboratory tests.

As a result of the investigation conducted for Task I, a mixture of walnut shells and cow manure was selected as the optimum organic medium for the project. Cow manure is readily biodegradable, and the slow biodegradable walnut shells enhance long-term performance of the bioreactors and provide a structure for the organic medium to prevent it from settling.

Task II, development of PACTES, was completed. The PACTES consisted of a mixture of walnut shells and manure prepacked in plastic-net socks, approximately 1 cubic foot in volume. The mix consisted of 50% manure and 50% walnut shells by volume.

Task III was also advanced to the development of concepts for the RCS that currently includes a pattern of pipes filled with PACTES. The pipes will be placed in a container through which the AMD will flow in a vertical direction collinear with the axes of the pipes.

Initial work on Task IV identified an existing software, MINTEQAK, that was developed to simulate biochemical processes occurring in wetlands. This software must be modified to enable input of variables for the time and spatial coordinates.

Work on the project will continue into the end of fiscal 2002.

ACTIVITY III, PROJECT 25 PASSIVE ARSENIC REMOVAL DEMONSTRATION PROJECT

Project Overview

The objective of this project is to evaluate bench-scale, innovative, passive arsenic removal technologies with applicability to remote mine sites. By conducting this demonstration, the Mine Waste Technology Program (MWTP) will illustrate the functional and operational requirements of passive arsenic technologies and how these technologies can be used to alleviate the environmental problems associated with acidic, metal-laden mine drainage.

Technology Description

This project will evaluate passive technologies capable of removing arsenic from mine drainage. The most effective conventional arsenic treatment technologies are ferric hydroxide and magnesium hydroxide adsorption/precipitation. However, these methods are not adaptable to remote locations due to their chemical process nature. Technologies capable of passively removing arsenic from mine drainage include using various fine-grain sands such as manganese-dioxide-coated sand and granular ferric hydroxide in gravity-fed reactors.

Status

The first phase of this project identified passive arsenic treatment technologies. Several media were selected for laboratory column testing (see Figure 17). These media were manganese-dioxide-coated sand (Greensand), granular activated alumina, granular ferric hydroxide, iron filings, limestone, apatite, granular sulfide, and granular activated carbon. Silica sand was selected as the control media.

Water from the Susie/Valley Forge Mine in Rimini, Montana, was used for testing. Through 500 pour volumes, all test media, with the exception of apatite, removed over 99% of the arsenic (see Table 2). The next poorest treatment was the activated carbon column.

Since the dissolved iron to arsenic ratio of the Susie/Valley Forge Mine water was notably high, some of the arsenic removal may have been attributed directly to pH adjustment and the resulting ferric hydride/arsenic coprecipitation. Water with a lower iron to arsenic ratio was not tested; therefore, the efficiency of the tested arsenic treatment technologies is unknown for these types of waters.

Table 2. Results of laboratory column testing.

Pour Volumes	Magnesium Dioxide	Ferric Hydroxide	Activated Alumna	Limestone	Sulfide	Iron	Activated Carbon	Apatite
100	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.4%	96.7%
200	99.5%	100.0%	100.0%	99.7%	100.0%	100.0%	97.9%	96.0%
300	99.5%	100.0%	99.7%	100.0%	100.0%	100.0%	99.2%	97.9%
400	100.0%	100.0%	100.0%	100.0%	99.7%	100.0%	99.7%	91.4%
500	100.0%	100.0%	100.0%	99.7%	100.0%	100.0%	99.4%	97.5%

Figure 17. Laboratory column testing of media at the MSE Testing Facility in Butte, Montana.

ACTIVITY III, PROJECT 26 PREVENTION OF ACID MINE DRAINAGE GENERATION FROM OPEN-PIT MINE HIGHWALLS

Project Overview

Exposed, open-pit mine highwalls contribute significantly to the production of acid mine drainage (AMD) and can be problematic upon closure of an operating mine. Four innovative technologies were evaluated under the Mine Waste Technology (MWTP), *Prevention of AMD Generation from Open-Pit Highwalls Demonstration Project*. The objective of the field demonstration was to evaluate technologies for their ability to decrease or eliminate acid generation from treated areas of the highwall, compared to untreated highwall areas.

Technology Description

Generation of AMD from open-pit mine highwalls has been addressed in a limited manner, and little information is available on the subject. Most likely, this is due to the difficulty and danger of physically working on or near the face of the highwall. Other areas of concern such as mine tailings, underground workings and other above ground waste rock piles can usually be dealt with by physical means to control the generation of AMD, i.e., removal or application of a permanent impermeable cover. However, highwall generated AMD will continue to be produced for indefinite periods of time as weathering occurs and the flushing action of atmospheric precipitation and/or groundwater infiltration through the highwall takes place.

The main purpose of this project is to research technologies applicable to controlling or eliminating AMD generated from open-pit mine highwalls and then apply and monitor the potential technologies under actual field conditions. For this demonstration, four technologies having potential to passivate the AMD from a highwall were selected. The application methods required to apply each technology varied along with the application time and the materials.

The demonstration consists of three phases: 1) extensive site characterization and gathering background information; 2) technology identification and field application; and 3) long-term field monitoring and laboratory testing for confirmation of field results.

Site characterization in Phase I will include core drilling the highwall to determine geology, hydrogeology, and extent and depth of acid generation (i.e. geochemical analysis), and performing background sampling at all of the sampling ports placed on the highwall.

The third phase of the project involves monitoring the technologies using ASTMD 5744-96, Accelerated Weathering of Solid Materials using a Modified Humidity Cells, residual wall rinse samples from the treated highwall plots, microscopy, and other methods.

Status

The field demonstration was performed at the Golden Sunlight Mine (GSM), a subsidiary of Placer Dome, an operating gold mine located near Whitehall, Montana. The ore body at GSM is sulfidic, and the exposed highwall provides an AMD source.

Phase one, site characterization, was competed in September 2001.

Phase two, included selecting four technologies, was completed by May 2001. Placement of the technologies is scheduled for early FY02.

ACTIVITY III, PROJECT 27 REMEDIATING SOIL AND GROUNDWATER WITH ORGANIC APATITE

Project Overview

Apatite remediation of heavy metals is an emerging technology that addresses the need to remediate metals in wastes, contaminated groundwater, sediments and soils, including agricultural soils. Metals readily leach from contaminated soils and sediments serving as a constant source of metal contamination to surface waters, underlying groundwater zones, and ingestion pathways of the biota. Efforts to mobilize and remove metals from the subsurface to below regulatory or risk-based limits have been unsuccessful due to the various intermediate solubilities and sorption properties that each metal and suite of metals exhibits under most environmental conditions. Total removal of the contaminated material for disposal elsewhere is not feasible, as it exceeds all landfill space presently available. Alternatively, metals can be stabilized in place to prevent them from migrating or leaching into groundwater or accumulating in the ecosystem. Many materials have been proposed for this purpose, but the technology described here is particularly effective for nonredox-sensitive metals for which no adequate, cost-effective alternatives exist, e.g., lead, cadmium and uranium. This technology stabilizes metals by chemically binding them into new stable phosphate phases (apatite minerals) and other relatively insoluble phases in the soil, sediment, or in a permeable reactive groundwater barrier. Metals most effectively stabilized by this treatment are lead, uranium, zinc, copper, cadmium, nickel, barium, cesium, strontium, plutonium, thorium, and other lanthanides and actinides. Because of its high toxicity, lead has been the focus of some previous studies by other investigators. In addition to lead, this study will focus on other contaminants of concern frequently associated with mining derived wastes such as arsenic, cadmium, copper, mercury, and zinc.

Technology Description

The objective of the project is to determine the efficacy of metal cation removal by Apatite II from contaminated soil and groundwater. The technical information will be summarized in a final report, which represents the complete product of the project.

Technical objectives include:

- demonstrating that statistically significant metal cation removal can be achieved with Apatite II amendments to the soil or treating the groundwater;
- evaluating the long-term stability of the removed reaction products of cations with Apatite II;
- determining if field-scale studies with the material are warranted; and
- verifying that the technology is applicable at field scale.

Status

During FY-01 the project was initiated with preparation of the Work Plan and selection of sites for soil collection to use in the first phase of laboratory treatability studies.

- Batch reactor tests have been completed. These first two sets of samples were from areas along Silver Bow Creek near Butte, Montana, impacted by acid mine drainage and mill tailings. One area exhibited mercury and uranium levels above background as well as high levels of copper and zinc. The third and fourth sets of samples are from the Mammoth tailings near Mammoth, Montana. The fifth set is from the Joplin, Missouri, lead district. Apatite to soil concentrations that were initially tested for all sample sets are 1, 5, and 10 percent. Preliminary results indicated that the optimum apatite to soil ratio is between 1 and 5 percent. Therefore, an additional 1-week batch reactor test was performed with an apatite to soil ratio of 3 percent.

- The laboratory data is being evaluated before initiating the humidity cell tests. The humidity cells have been fabricated. The test equipment will simulate vadose zone soil conditions.

ACTIVITY III, PROJECT 29 REMEDIATION TECHNOLOGY EVALUATION AT THE GILT EDGE MINE

Project Overview

The objective of this project is to generate performance and cost data for promising new technologies for preventing the oxidation of sulfide waste rock, which may be applicable to many mine waste sites. The new technologies will be compared to the presumptive remedy of lime treatment as well as to controls in which no treatment is performed. The technology demonstration will be performed at the Gilt Edge Mine, a 270-acre, open-pit cyanide heap leach gold mine located about 5 miles southeast of Lead, South Dakota. The immediate area was the site of sporadic mining activity for over 100 years. The Gilt Edge Mine was operated by Brohm Mining Corporation, a wholly owned subsidiary of Dakota Mining Cooperation from February 1986 until July 1999. Brohm's activities included developing several open pits, crushing and placing the ore on a heap leach pad for gold leaching by cyanidation, and Merrill-Crowe gold recovery in an on-site mill. In July 1999, the mine's owners (Dakota Mining Corporation) declared bankruptcy, resulting in the Gilt Edge site being returned to the State of South Dakota for management. After incurring significant costs for water treatment to ensure no discharge of acidic mine water to the environment occurred, the State of South Dakota requested that EPA Region VIII take over the site and list it on the National Priorities List (NPL) as a Superfund site. The Gilt Edge Mine site presents an opportunity to evaluate emerging acid mine drainage (AMD)-treatment technologies while gathering data leading to a Record of Decision (ROD) for the site.

This project is a collaboration between EPA Region VIII and the EPA Mine Waste Technology Program (MWTP). The objective of Region VIII is to conduct a treatability study as part of the remedial investigation/feasibility study process for the site—providing data to help make decisions supporting the ROD for the site. The technical and economic information will be summarized in a final report.

The project involves constructing test cells, which will be loaded with sulfide-bearing waste rock from the Gilt Edge Mine site. EPA Region VIII (or its contractors), assisted by the U.S. Bureau of Reclamation will design and construct the test cells, as well as load the waste rock. Three technology providers will each install its respective technology for reducing AMD generated by the waste rock. The project will take place west of the Anchor Hill Pit at the Gilt Edge Mine. The test cells will receive ambient precipitation, and an irrigation system will apply additional simulated precipitation to the test cells. A system for managing and sampling leachate quality designed by EPA Region VIII will be integrated into the cell design. Twelve test cells are planned. Two cells are dedicated to each of the three technologies to show performance repeatability. Three control cells containing only waste rock (with no additional treatment) and three cells representing the presumptive remedy of blending lime with the waste rock will also be constructed. The performance of the installed technologies will be judged primarily by comparing leachate water quality from the installed technology cells with that of the control and presumptive remedy cells. The test cells will be constructed and loaded in September 2000. EPA Region VIII will monitor for 1 year; thereafter, the monitoring responsibility will be transferred to MWTP, while EPA Region VIII uses the generated data in preparing the site ROD. Monitoring will continue for at least 1 additional year, with following years added if budget allows and if observed results make it advisable to do so.

Technology Description

The three technologies to be demonstrated are:

- Silica microencapsulation [Klean Earth Environmental Company (KEECO)];
- Envirobond [Metals Treatment Technologies (MTT)]; and
- Passivation technology [Mackay School of Mines, University of Nevada, Reno (UNR)]

KEECO has developed a treatment technology for treating and preventing metals-contaminated waters, soils, and possibly sulfidic waste rock called silica microencapsulation (SME). This technology encapsulates metals in an impervious microscopic silica matrix (essentially locking them up in very small sand-like particles) that prevents the metals from leaching and migrating. Its chemical components react when introduced to water, creating an initial pH adjustment and electrokinetic reaction. The electrokinetic reaction serves to facilitate electrokinetic transport of metal particles toward the reactive components of the SME product, enhancing its efficiency. Metal hydroxyl formation follows; next, silica encapsulation of the metals occurs, forming a dense, stable coating. Contrary to conventional treatment process where sludges typically degrade over time, the SME silica matrix appears to continue to strengthen and tighten, providing for long-term isolation of contaminants from the environment. Silica microencapsulation has been applied to wastewater, sediment, sludge, soil, mine tailings, and other complex media but has never been applied and tested directly on sulfidic mine waste rock materials.

The Envirobond (Metals Treatment Technologies) technology is similar to the KEECO technology except that it involves phosphate stabilization chemistry rather than silicates. The technology has been applied at mining sites, firing ranges, sediment removal sites, and others to produce a solid treatment material meeting Toxicity Characteristic Leaching Procedure criteria. The technology can be adapted for a variety of wastestreams and soil conditions.

Over the past few years, DuPont developed a novel coating method known as a passivation technology. Recently, the technology was donated to UNR for further development and commercialization. The passivation process essentially creates an inert layer on the sulfide phase by contacting the sulfide with a basic permanganate solution to produce an inert manganese-iron oxide layer. This layer prevents contact with atmospheric oxygen during weathering of the sulfide rock, thus, preventing sulfuric acid generation. Another critical element of the process is the addition of trace amounts of magnesium oxide during pH adjustment. Magnesium oxide addition enhances the coating strength.

Status

The treatment cells were loaded and treated by the technology vendors in November 2000. Treatment monitoring started in May 2001 and continued through October 2001, when the cells froze. Monitoring will resume in the spring of 2002 when the cells thaw and will continue into the fall of 2002. Data from 2001 is still in the validation process; however, preliminary results show all treatment technologies reduced most metals concentrations and raised the pH of the cell effluent. Figures 18 and 19 illustrate the copper and pH trends for the treatment technologies through October 2001.

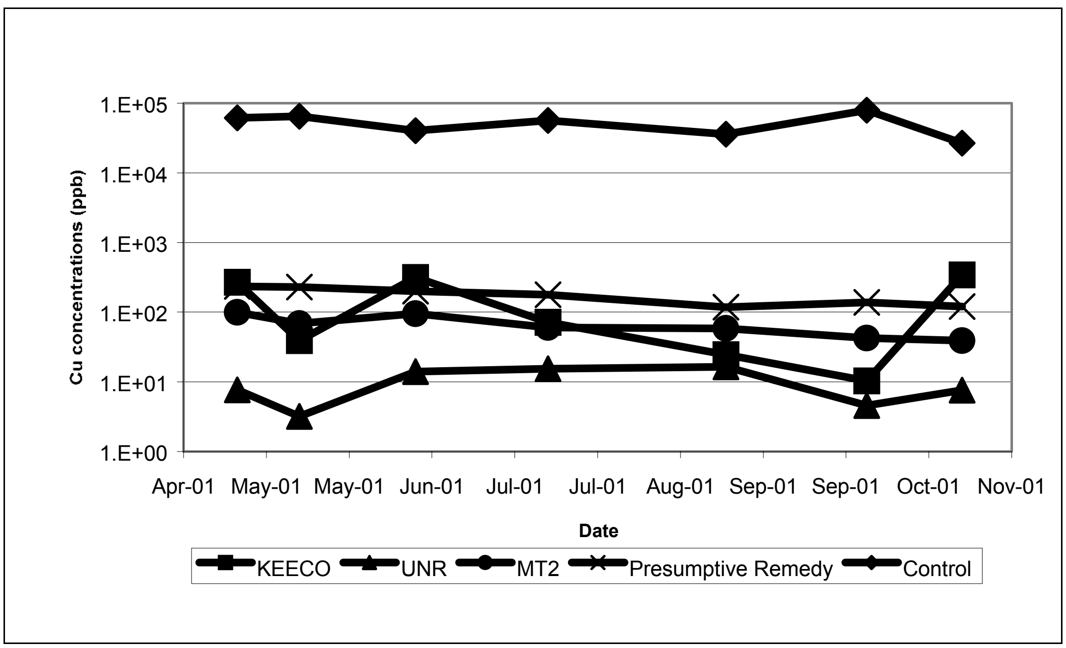


Figure 18. Copper trends.

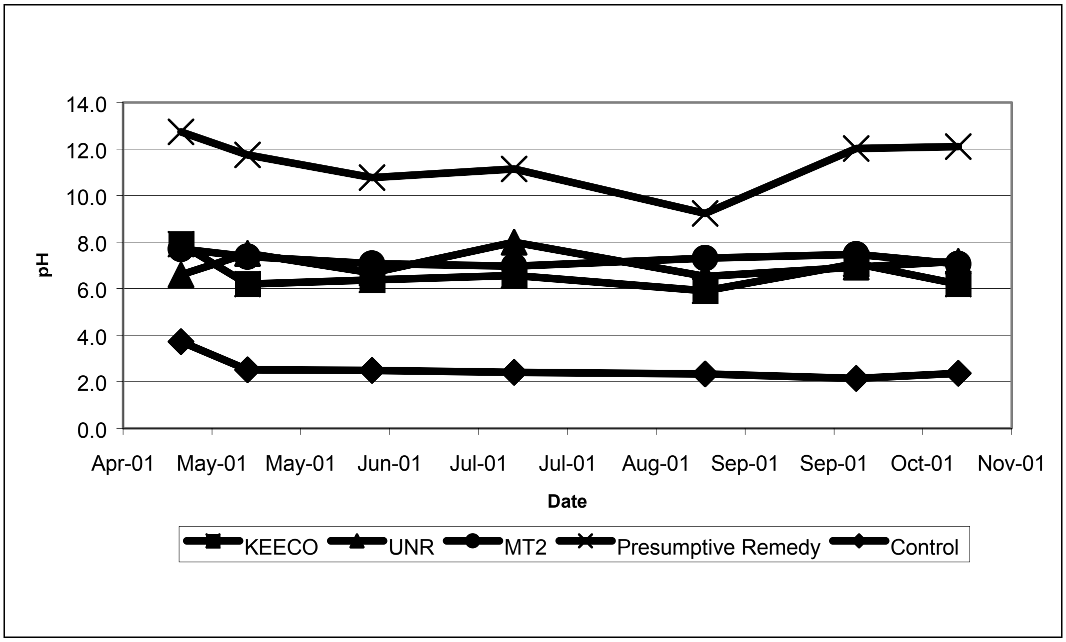


Figure 19. pH trends.

ACTIVITY III, PROJECT 30 ACIDIC/HEAVY METAL-TOLERANT PLANT CULTIVARS DEMONSTRATION, ANACONDA SMELTER SUPERFUND SITE

Project Overview

Presently, grass, forb, and shrub species commercially available for reclaiming acidic/heavy metals-contaminated (A/M) soils often come from outside the Northern Rocky Mountain region. These cultivated varieties may not tolerate the climatic-edaphic stresses (in addition to A/M stresses) as well as would A/M ecotypes indigenous to the region. Over the past several years, plant populations exhibiting A/M tolerance potential have been collected from the Anaconda Smelter Superfund Site and evaluated in laboratory, greenhouse, and preliminary field trial studies. The results indicate that self-sustaining plant communities comprised of native A/M tolerant ecotypes are possible. Thus, the goal of this project is to formally compare the performance of local seed mixes against comparable mixes now commercially available. If the local ecotypes (of the given grass/forb species) are indeed best performing, they would be made available for full-scale reclamation of hardrock mine/mill/smelter sites in the region.

Technology Description

The team comprised of the Deer Lodge Valley Conservation District (DLVCD), USDA/Bridger Plant Materials Center (BPMC), and MSE Technology Applications, Inc., will select and evaluate the most promising grass/forb accessions at two test sites in the Anaconda area over the 2002–2004 growing seasons. Shrub species will be evaluated at a third site that is not formally part of the Mine Waste Technology Program funded study. Four grass/forb mixtures from southwestern Montana will be compared against four very similar mixtures of commercially available cultivars. Four replications of each mixture will be at both the upland (Stucky Ridge) and lowland (Mill Creek) test sites. The laboratory and field data gathered during the three seasons will be statistically analyzed to determine whether any of the local seed mixes outperforms their commercial counterparts.

Status

The following project planning documents were completed in fiscal 2001: work plan, quality assurance project plan; NEPA compliance/site access agreements; health and safety plan; and subcontract with DLVCD-BPMC. The following activities continued: collection and laboratory analysis of plant and soil samples from the Anaconda area; greenhouse and field evaluations of plant performance; and production of seeds (at BPMC) from the most promising grass/forb accessions. The two test sites were prepared for planting (in fiscal 2002), and baseline soil samples were collected for target heavy metals levels analysis. The laboratory results (in Table 3) indicate the general suitability of these sites as a test bed for this project.

Table 3. Development of Acid/Metal Tolerant Cultivars Project: Baseline Soils Data Summary[a]

A. Upland/Stucky Ridge Plot

	As	Cd	Cu	Pb	Zn	pH / Eh
DLVCD-BPMC	131	2	502	44	133	5.5 / 380
MSE	178	1.8	779	66	161	4.7 / 302

B. Lowland/Mill Creek Plot

	As	Cd	Cu	Pb	Zn	pH / Eh
DLVCD-BPMC	386	8	676	174	464	6.2 / 323
MSE	493	10	858	212	650	5.8 / 262

Notes: [a] Acid-extractable metals in mg/kg; pH in S.U. and Eh in mv
[b] values are ≥ threshold of concern levels, from QAPP; level for Pb is > 400 mg/kg

ACTIVITY III, PROJECT 31 REMOTE AUTONOMOUS MINE MONITOR

Project Overview

Monitoring groundwater in the vicinity of mines for heavy metal contamination can be problematic in remote locations, especially when extreme weather conditions exist. One solution to this difficulty is an autonomous system capable of monitoring mine waters at remote locations for the presence of heavy metals. Typical metals concentrations that might be expected are shown in Table 4. Thus, an autonomous system should be able to measure metals at subparts per million (submilligrams per liter (mg/L) levels to be effective. The objective of this project is to test and evaluate a monitor for heavy metals in a controlled laboratory setting.

The project is divided into three phases:

- Phase I–Optimize Buffer Formulations/Determine Appropriate Detector;
- Phase II–Prototype Development/Laboratory Demonstration; and
- Phase III–Field Installation and Demonstration.

During FY 2001, Phase I was partially completed.

Technology Description

The remote mine monitor has three main subsystems: a capillary electrophoresis analyzer; a single board computer; and a satellite telemetry link. The electrophoresis system will be based on an automated system developed and tested for NASA space applications. The NASA system measures a number of components of astronaut urine. The NASA system is fully automated. Some alterations in the system must be made to accommodate the remote mine monitoring application.

Figure 20 shows a rear view of the NASA automated system. The mine monitor would remain essentially the same. The only modifications envisioned include: enlarging the buffer and sodium hydroxide tanks to accommodate long deployment times and adding a pump to draw well water samples to deliver to the nanoliter syringe pump that delivers the sample to the electrophoresis device. This pump will also need to be incorporated into the control system. Both of these changes are relatively minor engineering changes. Once these changes have been made, further laboratory testing will establish how many analyses can be run on a single capillary tube before replacement is required. This information is essential to examining sample rate versus unattended deployment time issues.

Power consumption issues are important. At this time, it is assumed that a battery bank will be used to power the field deployable monitor. The type and charging method for such a battery bank would be site dependent and will not be considered as part of this proof-of-principle project.

Status

During FY 2001, the Johns Hopkins University Applied Physics Laboratory (JHU/APL) optimized the buffer formulations for the metals of interest. The optimum separation buffer was 2 mM 8-hydroxyquinoline-5-sulfonic acid (HQS), 10 mM phosphate, and 6 mM borate adjusted to pH 8.0 with sodium hydroxide. Work in FY 2002 will specify the detector that will be used on the prototype instrument. The final products of Phase I work will be the optimal buffer and design specifications for the detector, which will be included in a summary report drafted by JHU/APL.

If Phase I of the testing program is promising, JHU/APL may be funded to assemble a prototype instrument based upon component subsystems developed or under development at JHU/APL that is capable of meeting the requirements articulated above. JHU/APL would assemble and laboratory test the prototype as a of proof-of-principle exercise during Phase II. MSE Technology Applications, Inc., would serve as the verification entity and support the laboratory testing portion of the project. If the laboratory testing phase is successful (i.e., the mine monitor could accurately and precisely detect the metals of interest), a field test of the mine monitor system may be funded as Phase III of the project.

Table 4. Sample mine metal concentrations.

	Concentration (mg/l)			
	Calliope	**Peerless**	**Lilly Orphan Boy**	**Crystal**
Al	14.1	2.08	3.11	22.0
Cu	3.08	0.873	0.142	25.7
Fe	7.2	0.237	5.82	105.0
Mn	3.7	14.6	6.05	13.7
Zn	11.1	6.36	15.70	80.6

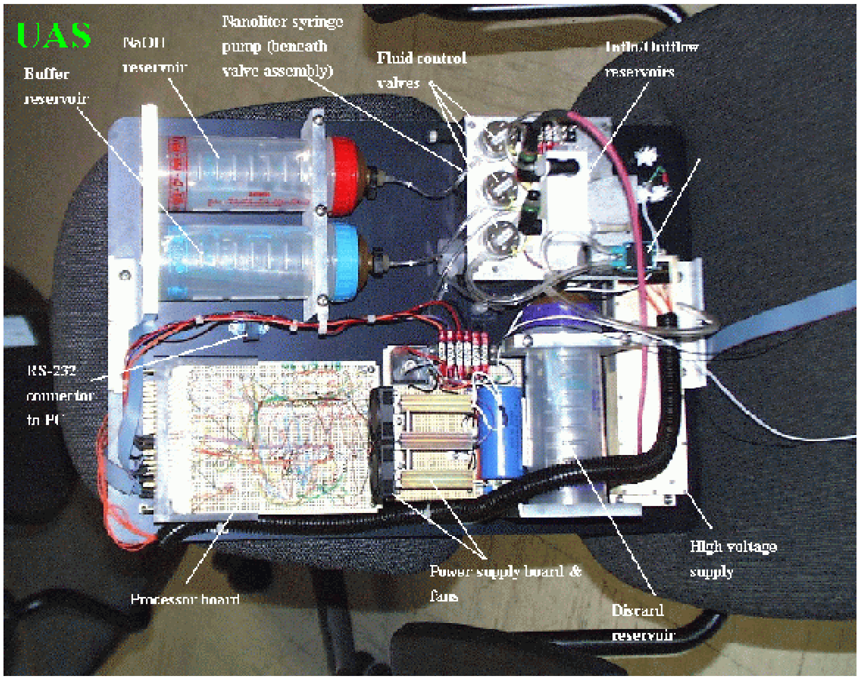


Figure 20. Rear view of the NASA monitor system

ACTIVITY III, PROJECT 33 MICROENCAPSULATION TO PREVENT ACID MINE DRAINAGE

Project Overview

This project is a laboratory-scale demonstration project and is being conducted on a cost share basis with the Minnesota Department of Natural Resources. The objective of the project is to evaluate the potential field application success of commercial microencapsulation products to prevent acid mine drainage on a mine waste material. This demonstration serves as an evaluation of the effectiveness of the technology approach and will also be used to estimate field application requirements.

Technology Description

Two technologies, Klean Earth Environmental Company (KEECO) and Envirobond, are being evaluated in comparative laboratory studies using modified humidity cells. The KEECO KB-SEA process employs a silica microencapsulation treatment that acts to encapsulate solid media particles. The materials become stabilized as this silica coating helps to control future acid generation. The Envirobond process works to prevent the leaching of metal contaminates by creating an impenetrable chemical bond.

Status

Cell testing started in May 2001. All treatment reagents were supplied and applied by the technology vendors. The test cells are scheduled for 16 months or until treatment is no longer effective. Initial effluent pH results of the first weeks of testing as compared to a control are presented in Figure 21. Generally, the data shows that both technologies offer some ability to prevent the generation of an acidic leachate. A full report with test data and materials characterization results will be issued at the completion of the project.

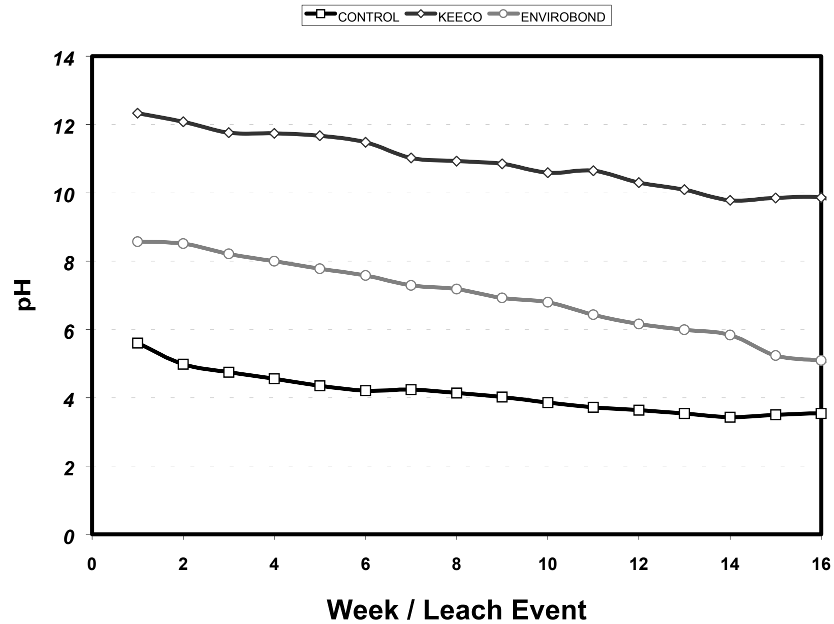


Figure 21. Initial microencapsulation cell test results.

ACTIVITY III, PROJECT 34 BIOREMEDIATION OF PIT LAKES (GILT EDGE MINE)

Project Overview

This project is being conducted at the Gilt Edge Mine Superfund site near Deadwood, South Dakota. The project is a collaboration between the Mine Waste Technology Program (MWTP) and the EPA Region VIII Superfund office. MWTP is taking the prime role in this project with support from EPA Region VIII. EPA Region VIII's interest is to conduct a treatability study as part of the site Remedial Investigation/ Feasibility Study (RI/FS) process, while MWTP's interest is to develop data applicable to other similar sites. An in situ treatment of the Anchor Hill Pit, an open pit at the Gilt Edge site containing approximately 70 million gallons of acidic water containing high levels of metals, sulfate, and nitrate, will be performed. The treatment will consist of an initial neutralization step followed by a biological treatment to further improve water quality and create a long-term, stable system. After the two-step treatment, the project will enter a monitoring mode where the pit lake will be physically and chemically characterized on a quarterly basis for several years. The monitoring will show how well the treatments work and how stable the pit lake water becomes, e.g., if metal sulfides are produced, does the system reoxidize and remobilize those metals.

Technology Description

After initial chemical/physical characterization of the pit lake, the neutralization step will be implemented by Shepherd-Miller, Inc. (SMI) of Fort Collins, Colorado, under subcontract to MSE Technology Applications, Inc. (MSE). SMI will use a Neutra-Mill fed with lime (CaO). The Neutra-Mill is simply a floating platform containing an apparatus to mix a reagent in with the water it is floating on (see Figure 22). The Neutra-Mill was developed by Earth System, Pty. of Australia; SMI holds the United States license to apply the technology. MSE and SMI will take the lead in carrying out the neutralization with assistance from EPA Region VIII and its contractors.

After neutralization, the pit will be allowed to sit undisturbed for several weeks to allow precipitated solids to settle and the system to stabilize. After stabilization, the pit lake will once again be characterized. Thereafter, material consisting of methanol, molasses, and phosphoric acid will be added to the pit lake. This mixture has been patented by Green World Science, Inc., of Boise, Idaho. The purpose of the organic carbon addition is to produce reducing conditions in the water and stimulate the activity of indigenous bacteria. This should have the effect of reducing or eliminating nitrate/nitrite and selenium, and polishing toxic metals concentrations to very low levels by precipitating them as sulfides (produced by reducing some sulfate to sulfide by sulfate-reducing bacteria activity), and adding bicarbonate alkalinity to the water to provide buffering capacity.

Status

Project accomplishments in FY 2001 included developing a project work plan; initiating subcontracts with the technology providers (Shepherd-Miller, Inc. and Green World Science, Inc.); developing a quality assurance project plan; initial sampling of the Anchor Hill Pit water and sediment; neutralizing the Pit using the Neutra-Mill and lime (CaO); additional sampling of the Pit water and sediment; dosing with methanol, molasses, and phosphoric acid to initiate biological treatment (see Figures 23 and 24); and initiating quarterly monitoring of the Pit water after organic dosage.

Water samples are being collected quarterly at two depths at each of two lateral locations. Sediment samples are being collected annually at the two lateral locations.

Neutralizing the Anchor Hill Pit consumed approximately 290 tons of lime. Based on the initial acidity of the water and neutralization potential of the lime, this represents an efficiency of approximately 70%, as compared with a performance goal of 85% set by SMI. However, it should be noted that the excess lime settled to the bottom of the Pit and will serve as an additional alkalinity source in the future. Initial results from sampling after adding nutrients to the Pit indicate that the biological treatment was proceeding slowly. The nitrate/nitrite concentrations were decreasing, and selenium concentrations were decreasing. No sulfate reduction had yet occurred; however, no sulfate reduction is expected until denitrification is complete.

Figure 22. Neutra-Mill and feed hopper.

Figure 23. Molasses addition.

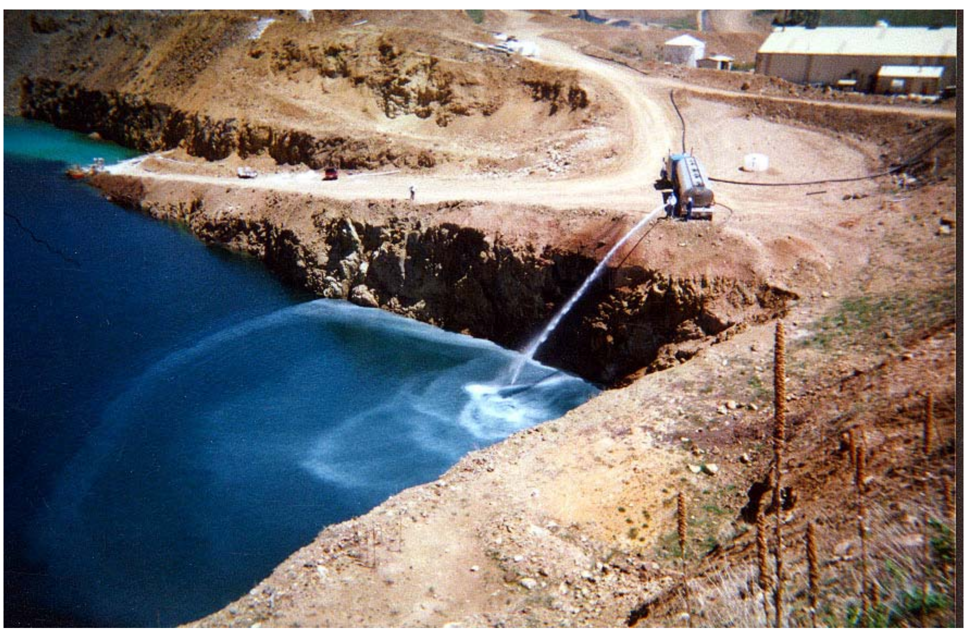


Figure 24. Methanol addition.

ACTIVITY III, PROJECT 35 BIOLOGICAL PREVENTION OF ACID MINE DRAINAGE (GILT EDGE MINE)

Project Overview

This project is a collaboration between the U.S. Environmental Protection Agency (EPA) Region VIII and EPA Office of Research and Development's (ORD) Mine Waste Technology Program (MWTP). The goal of this project is to evaluate the Shepherd-Miller, Inc. (SMI) Redox-Mediated Biotransformation (RMB) technology and determine cost, performance, and long-term stability for SMI's RMB technology. MWTP is responsible to provide a subcontract to SMI, while EPA Region VIII will conduct the technology demonstration. The technology will be demonstrated at the Gilt Edge Mine, a 270-acre open-pit cyanide heap leach gold mine located about 5 miles southeast of Lead, South Dakota. The immediate area was the site of sporadic mining activity for over 100 years. The Gilt Edge Mine was operated by Brohm Mining Corporation, a wholly owned subsidiary of Dakota Mining Cooperation from February 1986 until July 1999. Brohm's activities included developing several open pits, crushing, and placing ore on a heap leach pad for gold leaching by cyanidation, and Merrill-Crowe gold recovery in an on-site mill. In July 1999, the mine's owners (Dakota Mining Corporation) declared bankruptcy, resulting in the Gilt Edge site being returned to the State of South Dakota for management. After incurring significant costs for water treatment to ensure no discharge of acidic mine water to the environment occurred, the State of South Dakota requested that EPA Region VIII take over the site and list it on the National Priorities List (NPL) as a Superfund site. The Gilt Edge Mine site presents an opportunity to evaluate emerging acid mine drainage treatment technologies while gathering data leading to a Record of Decision for the site.

The RMB technology will be implemented in Gilt Edge's high-density polyethylene (HPDE)-lined neutralization pond. The pond's base footprint is approximately 80 feet wide by 80 feet long and 15 feet deep with 2 to 1 sloped walls. The pond will contain between 5,000 to 8,000 cubic yards of sulfide waste rock obtained from the Ruby Waste Rock Dump. Approximately 25,000 gallons of water will be placed in the pond containing the waste rock to mimic a backfilled pit lake. The Oro Fino shaft will provide the groundwater used to fill waste rock interstial voids.

Technology Description

The RMB technology is an in situ biological treatment technology designed to reductively remove nitrate, sulfate, metals, and metalloids from mine wastewater. This reduction process forms precipitates such as elemental selenium, metal sulfides, and elemental sulfur. The transformation of aqueous constituents to the solid phase improves the water quality in the pond and the stability of these precipitates can be maintained for long periods if proper reducing conditions are maintained in the pond. The RMB technology was developed by Green World Science, Inc., and is covered by patents granted (U.S. patents 5,632,715 and 5,710,361) and others pending.

The RMB technology involves adding a proprietary mixture developed by Green World Science, Inc., containing organic carbon (primarily sugars and alcohols) material and biological nutrients to the pond water. Adding organic carbon materials will create reducing conditions within the pond and stimulate activity of indigenous sulfate- and iron-reducing bacteria. These bacteria will oxidize the carbon to bicarbonate and reduce sulfate to the sulfide form. This, in turn, will improve water quality within the pond—bicarbonate will provide alkalinity and buffering capacity while the sulfide produced will facilitate removing metals via the formation of stable metal-sulfide precipitates.

The pond water will be characterized physically and chemically before organic dosage. After organic dosage, EPA Region VIII will monitor the pond for at least 1 year to assess the long-term stability of the system set up by the RMB technology. Untreated wasterock will be isolated in 4-foot-diameter tanks to isolate the wasterock and serve as a background for comparing the technology.

Status

The pond was loaded and treated by Green World Science in June 2001. EPA Region VIII monitored the water levels, and it was evident by July 2001 the pond had a leak. EPA Region VIII made an effort to remedy the problem by refilling the pond using water from the secondary containment; however, the pond still leaked, and new water had to be added several times. Due to the constant fluctuation and flux of water through the pond, the RMB technology could not be evaluated accurately. As a result, MWTP discontinued the evaluation of this project.

ACTIVITY III, PROJECT 36: CERAMIC MICROFILTRATION SYSTEM DEMONSTRATION

Project Overview

The purpose of this project is to evaluate the performance of the BASX Systems, LLC Ceramic Microfiltration System (CMS) to effectively remove copper, iron, manganese, and zinc from a selected acid mine drainage (AMD). The project is divided into three phases: bench-scale scoping tests of two to four pretreatment technologies to determine those most effective in precipitating the target metals; 1-gallon per minute (gpm) pilot-scale testing of these technologies under field conditions; and designing a 300-gpm treatment plant.

Table 5 summarizes the heavy metal contamination problems currently observed at the Gregory Incline outfall.

Although nickel does not currently exceed the discharge standard for Clear Creek, it will be monitored throughout the study because it is possible that the discharge limit may be lowered if a full-scale production facility was implemented. All the metals listed above were the only regulated heavy metals that can be quantified in the Gregory Incline AMD.

The AMD from Gregory Incline has been chosen for this project; however, the results of this study can be applied to other sites with similar water quality and heavy metal contamination,

Technology Description

The CMS consists of two unit operations: precipitation and solid liquid separation. Chemical/physical precipitation is not unique in treating AMD; however, when coupled with the ceramic microfilter, the BASX CMS has the potential for both technical and economic improvement in the overall handling of heavy metal precipitates. The ceramic microfilter performs the work of a conventional clarifier. As shown in Figure 25, slurry from the precipitation stage is pumped through the ceramic filter bundle. The pore size of the filters is such that water can pass through tangentially (see Figure 26) to the direction of flow; the precipitate cannot pass through tangentially and exits the end of the filter as a concentrated metal stream.

In the bench-scale phase of this project, several precipitation steps will be tested for their ability to remove the targeted metals from AMD and their compatibility with the ceramic microfilter. These technologies include chemical precipitation using sodium hydroxide, magnesium hydroxide, and physical precipitation by electrocoagulation with aluminum and carbon electrodes.

In the pilot-scale phase, the most effective precipitation step(s) will be tested onsite in Black Hawk, Colorado, in a continuous 1-gpm plant. This phase will prove the CSM at a higher flow rate than the bench-scale tests and will provide operating parameters for designing the 300-gpm plant, which is Phase III of the Project.

Status

Project 36 began in August 2001. Project planning and issue of a subcontract to BASX Systems LLC were completed by the end of fiscal year 2001.

Table 5. Gregory incline water quality contamination.

Parameter	Concentration	Colorado Standard for Clear Creek
Cadmium	0.012	0.007
Copper	0.78 (± 0.06)	0.064
Iron	153 (± 3)	5.4
Manganese	30.8 (± 0.6)	1.0
Nickel	0.20 (± 0.01)	0.56
Zinc	6.9 (± 0.2)	0.74

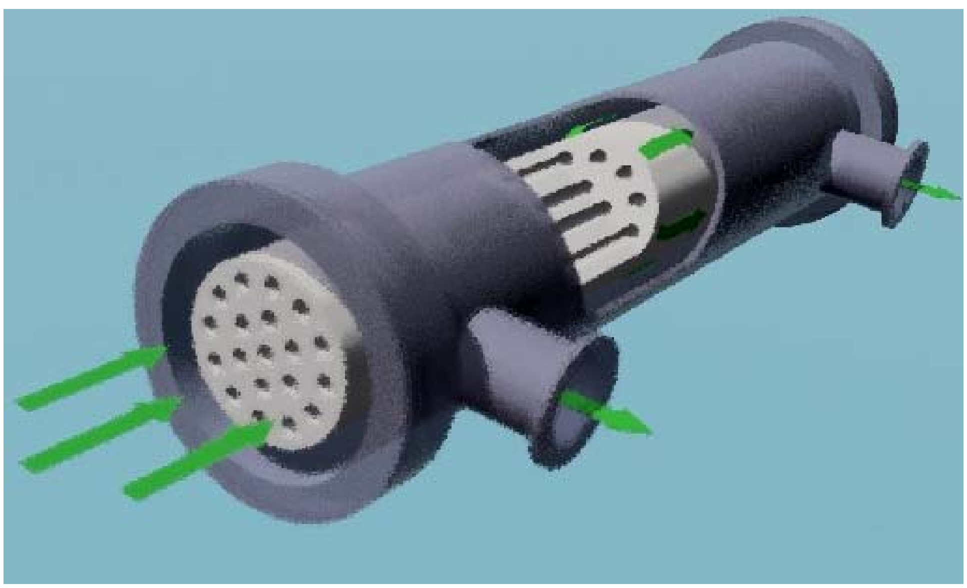


Figure 25. Ceramic microfilter bundled.

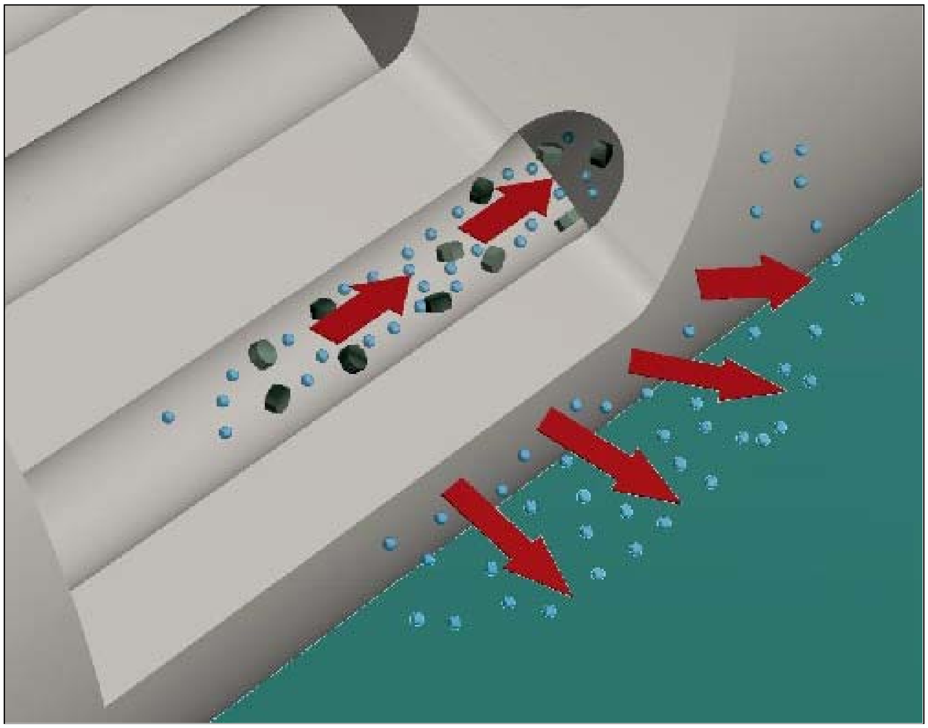


Figure 26. Cutaway view of ceramic microfilter bundle.

ACTIVITY IV OVERVIEW

The objective of this activity is to develop, qualify, and screen techniques that show promise for cost-effective remediation of mine waste. The most promising and innovative techniques will undergo bench- or pilot-scale evaluations and applicability studies to provide an important first step to full-scale field demonstrations. Each experiment is assigned as an approved project with specific goals, budget, schedule, and principal team members.

ACTIVITY IV, PROJECT 13: SULFIDE COMPLEXES FORMED FROM MILL TAILINGS PROJECT

Project Overview

A general belief is that any metal oxides that are mobilized in the upper oxidized zone will be reprecipitated as sulfides in the lower reducing zones of the tailings. Numerous metal sulfides exist and may be formed in this reducing zone of the tailings. These complexes may be mobilized as the reduction-oxidation (redox) potential changes within the tailings. In the case of the Berkeley Pit, if tailings are deposited into the Pit lake, and the system's redox potential changes over time, any metal sulfide complexes could be mobilized and enter the deep aquifer surrounding the Berkeley Pit. The main goal of this project was to determine the leachability of the tailings produced by Montana Resources during their operation. This research was very timely since Montana Resources, ARCO, and the EPA are presently considering depositing the tailings produced by Montana Resources into the Berkeley Pit Lake.

Status

The following summarizes the data generated during this project.

The initial conditions of the components of the experiment are as follows:

- Berkeley Pit water: pH 2.2, E_h 258 mV (measured), 756 µg/L dissolved arsenic, 182 mg/L dissolved copper, 1072 mg/L dissolved iron, and 8400 mg/L sulfate.

- Unlimed Tailings Slurry: pH 6.9, E_h 12.7 mV (measured), 5.9 µg/L dissolved arsenic, 10 µg/L dissolved copper, no dissolved iron, and 1580 mg/L sulfate.

- Limed Tailings Slurry: pH 9.7, E_h 139 mV (measured), 16.3 µg/L dissolved arsenic, 10 µg/L dissolved copper, 6.2 µg/L dissolved iron, and 990 mg/L sulfate.

- Distilled Water: pH 9.1, E_h 108 mV (measured), no dissolved arsenic, 2.4 µg/L dissolved copper, 12.3 µg/L dissolved iron, and no sulfate.

Using a mass balance approach, the total metals leached out of the tailings material was determined. Tailings slurry with lime added deposited in Berkeley Pit water showed a 10% increase in dissolved copper, an 18% increase in dissolved iron, a 65% increase in sulfate, and a 16% decrease in dissolved arsenic. Tailings slurry without lime added deposited in Berkeley Pit water showed a 2% decrease in dissolved copper, a 10% increase in dissolved iron, a 30% increase in sulfate and a 3% decrease in dissolved arsenic. Unlimed tailings were also mixed with distilled water; but because of the low concentrations present, only qualitative statements can be made. Significant increases in dissolved copper, iron, and sulfate can be determined, but the actual percentage of the increase would not be relevant. The pH of the limed tailings/Berkeley Pit water mixture ranged from 4.0 standard units near the top of the column to 3.7 standard units at the bottom. The pH of the unlimed tailings/Berkeley Pit water mixture ranged from 4.5 standard units near the top of the column to 3.7 standard units at the bottom. The pH of the unlimed tailings/distilled water mixture was fairly constant at about 7.0 standard units throughout the column.

The Final report will be completed in FY02.

ACTIVITY IV, PROJECT 14 ARTIFICIAL NEURAL NETWORKS AS AN ANALYSIS TOOL FOR GEOCHEMICAL DATA

Project Overview

The Montana Bureau of Mines and Geology provided inductively coupled plasma (ICP) water quality analysis data from the Berkeley Pit that were used in a neural network approach to modeling Berkeley Pit water chemistry. The available Berkeley Pit data comprise a relatively small data set for neural network analysis and results, though encouraging, are not reliable for substantive predictive modeling.

Artificial neural networks comprise a relatively new approach to modeling complex nonlinear systems. Due to the inherent structure of neural networks, they have the desirable characteristics of being tolerant of noise in data and, more importantly, of not requiring a priority model for parameter prediction. Instead, neural networks learn relationships from data examples.

Neural networks are generally grouped into two main categories: supervised and unsupervised. Supervised neural networks use known data examples consisting of input/desired output pairs and adjust themselves to learn the relationship between input/output data. Unsupervised neural networks use only input data with no known output pairs. Unsupervised neural networks work by detecting clusters and trends in the data with minimal user input. As such, unsupervised neural networks can provide a powerful, unbiased approach to data analysis. Both neural network approaches excel in analyzing large, complex, multidimensional data sets.

Two neural network approaches were used to analyze the available Berkeley Pit data. First, the data matrix was used as input to an unsupervised neural network to determine if any previously unidentified data clusters or trends could be determined. For this sparse data set, this classification or data-mining approach was unsuccessful. Secondly, supervised neural networks were constructed and trained to investigate relationships between the various chemical species, depth, pH, and specific conductivity. Various testing combinations were analyzed and results are encouraging to pursue this approach with a more complete data set.

Status

Results were not verified with a comprehensive testing data set; but because they were validated with small data subsets, indications are that neural networks can analyze sparse, geochemical data with good reliability. In each case, the successful results were repeatable, which is a good indicator of reliability. More data is needed, and the intention of this project is to recommend a good sampling program over the next few years. If complete data were to be collected, a neural network could determine data relationships in a fraction of the time.

The final report will be completed in FY02.

ACTIVITY IV, PROJECT 16 PIT LAKE SYSTEM CHARACTERIZATION AND REMEDIATION FOR BERKELEY PIT—PHASE III

Project Overview

This research project is designed to study and characterize several aspects of the Berkeley Pit lake system to gain a better understanding of the pit lake systems. The information obtained from the Berkeley Pit lake research will be used to predict future qualities of the water, to evaluate the potential for natural remediation, to determine if partial in-situ remediation may be practical prior to pump and treat remediation, to develop new or improved remediation technologies, and to predict water quality for similar bodies of water in the United States. The following areas of research and testing for the Berkeley Pit lake have been determined: Humic Remediation Potential; Algal Remediation of Berkeley Pit Water; Berkeley Pit Aquifer Modeling; and Remediation by Photocatalysis.

Technology Description

Humic Remediation Potential

Humic substances have widely varying chemical compositions and molecular weights. These substances are generally acidic and are considered to be polymeric in structure. Humic materials are produced by the biological and chemical degradation of plant and animal matter and are often operationally separated into two water-soluble fractions, fulvic acids, and humic acids. The distinction between these two groups is a result of different molecular-weight ranges, solubilities, and the separation procedure used. The fulvic acid group has the lower molecular-weight range and higher water solubility. Chemical analyses of humic materials has consistently demonstrated the presence of a large fraction of aromatic material and carboxylic acid and phenolic functional groups. These oxygenated functional groups are responsible for the strong binding of the humic materials to mineral surfaces and the binding of metal ions in aqueous solutions.

Algal Remediation of Berkeley Pit Water

Ongoing research is beginning to help us understand the microbial ecology of the Berkeley Pit Lake System, with ever increasing information becoming available regarding the diversity of algae, protistans, fungi, and bacteria that inhabit this mine waste site. Defining the baseline community structure has been the first step not only toward understanding the interactions of the different groups of organisms but also toward assessing any improvement in biodiversity within the biotic community. Now that this first step has begun, this research will investigate how some of these extremophiles, specifically algae, that have been isolated from the Berkeley Pit Lake System may be used as a potential solution for bioremediation. The primary goal of this study is to determine the potential utilization of algae for bioremediation of the Berkeley Pit Lake System.

Berkeley Pit Aquifer Modeling

The water level in the Berkeley pit has risen a little more than 1 foot per month for the last several years. There are several sources of groundwater and a range of ground-water qualities entering the pit: a) contaminated groundwater from the underground workings in the bedrock aquifer west of the pit; b) uncontaminated groundwater from the bedrock aquifer east and southeast of the pit; and c) contaminated alluvial groundwater from east and south of the pit. At a water-depth of 850 feet, the rising water in the pit is presently not in contact with the alluvial aquifer, but rather, seepage faces have formed along the rim of the pit near the bedrock-alluvium contact. The rising water level in the pit will reach a depth of about 1,150 feet (100 feet above the bedrock-alluvial contact) before controls will be implemented.

Presently, a ground-water divide exists roughly coincident with Continental Drive between the Berkeley Pit and the Butte valley. Groundwater and surface water north of the divide flow into the pit while groundwater and surface water south of the divide flow into the Metro Storm Drain and ultimately into Silver Bow Creek. As the pit water level rises above the bedrock-alluvium contact, the ground-water gradient toward the pit will decrease, possibly shifting the ground-water divide south of the pit, thereby, diverting a portion of the groundwater now flowing into the pit to the Butte valley. This would manifest itself as an increase in water levels throughout the residential area south of the pit and a flow increase in the metro storm drain.

Remediation by Photocatalysis

Numerous technologies are available for remediating acid rock drainage. These technologies include biosorption, mineral/resin adsorption, chemical precipitation, ion exchange, freeze crystallization, evaporation, and a host of others. Several of these technologies have been tested over the past decade on Berkeley Pit Lake water. Lime precipitation became recognized as the U.S. Environmental Protection Agency's Best-Determined Available Technology for remediating the Berkeley Pit water. However, the conventional process had to be modified to meet discharge standards regarding pH and manganese and aluminum concentrations. The resulting two-stage process required an intermediate filtration step to remove precipitates that would redissolve upon continued lime addition.

In a previous study funded by the Mine Waste Technology Program, a process was developed for remediating Berkeley Pit water while simultaneously recovering the copper and zinc and producing other marketable products. This process uses a combination of the technologies listed above but has a novel approach for using ultraviolet radiation to meet the objectives. As indicated, the process uses five stages to selectively remove various metal constituents in the water by precipitation. Solid/liquid separations between the individual stages allows for the precipitates to be recovered and eventually marketed. Furthermore, the process also meets the discharge requirements of the metals including that of arsenic.

Status

Humic Remediation Potential

The results from the experiments demonstrated that organic amendments can have a positive effect on the remediation of the water in the Berkeley Pit. Of the four organic amendments tested (sawdust, aspen leaves, lawn clippings, and treated sewage sludge), the treated sewage sludge was the most effective at removing the high concentration metal ions from the water and raising the pH of the acidic water. The experimental variables of light versus dark and readily available room air versus exclusion of room air had minimal differences in the sequestering of most metals. Iron was the major exception to this observation.

Algal Remediation of Berkeley Pit Water

In general, *Chromulina freiburgensis* did not remove metals over a long-term experiment through absorption or adsorption from Berkeley Pit water. Removal was not observed for aluminum, cadmium, chromium, copper, magnesium, manganese, sulfur, and zinc. Significant removal was detected for calcium (12.8%), iron (12.7%), nickel (8.4%), and silicon (56.2%).

Metal removal was not observed, possibly because of the long experimentation time of 90 days. In this time, cultures of *Chromulina freiburgensis* could have become nutrient starved and formed cysts. It is possible that the metals were adsorbed initially, and rereleased when the cells became stressed. Further discussion is provided in the final report.

Berkeley Pit Aquifer Modeling

Since water-level data for the alluvial wells and the Berkeley Pit continue to be collected, it is possible to continue the calibration process for several years. In 1995, water levels in the alluvial aquifer south of the pit had increased by 1 to 3 feet compared to 1991 water levels; by 1998, water-level rise ranged from 5 to 9 feet compared to 1991 data. In addition to the continued water-level rise in the pit, this period coincides with greater-than-normal precipitation in the area. Thus, calibration in the strictest sense becomes ambiguous: the relative contribution of the pit water-level rise and the increased recharge cannot be determined. Through modeling, however, the increased recharge can be eliminated; modeling can demonstrate if the pit is contributing to the water-level change in the alluvium.

Remediation by Photocatalysis

In summary, iron removal (Stage I) was successful and fairly selective with ultraviolet photo-oxidation in the presence of hydrogen peroxide; was best under high oxidation conditions with 254-nm radiation within the 2-hour time examined; and was essential in this photochemical treatment process (as noted in most other industrial selective-metal recovery processes).

Removal of arsenic (Stage I) was successful and principally followed the ANSTO UV-Process. Manganese removal could be accomplished with photo-oxidation but requires further research to prove. In this regard, it had to be accomplished by permanganate addition resulting in Stage Two. Because permanganate can increase manganese concentrations, other oxidants should be tested. Sulfide precipitation of copper (Stage III) and cadmium (Stage IV) were successful. Zinc removal (Stage IV) appeared to follow wurtzite solubility; thus, ZnS precipitation did not meet the drinking water standard. However, sphalerite seeding of the stage could prove worthy and needs further study. Aluminum precipitation (Stage V) as a hydroxide also nearly met the drinking water standard and could feasibly benefit from seeding as well.

Based on the results and discussions of this study, it is clear that the manganese, zinc, and aluminum removal stages could be improved. As discussed previously, this may simply involve seeding the zinc and aluminum precipitation stages with more stable solids or studying further the manganese photo-oxidation process. Of course, other possibilities could be explored and may involve kinetics and temperature effects. Likewise, all stages in the selective metal recovery process could be improved kinetically, thermally, and/or chemically by using better compounds.

The final report will be completed in FY02.

ACTIVITY IV, PROJECT 17: MINE DUMP RECLAMATION USING TICKLE GRASS PROJECT

Project Overview

Experiments were conducted to test the reclamation potential of tickle grass in the greenhouse at Montana Tech and on three reciprocal transplant sites with the hypothesis that the Badger Mine (BM) tickle grass population is an ecotype within the species suitable for the reclamation of mine dump materials. *Agrostis hiemalis*, tickle grass, grows on the dump consisting of acid generating rock and tailings formed about 25 years ago. Tests indicate that this site has a pH of 3.1, and the *soil* material has high concentrations of heavy metals such as arsenic, copper, iron, lead, nickel, and zinc. The area is located near the Badger Mine site, northeast of Walkerville in Silver Bow County, Montana.

The performance of the BM tickle grass population was compared to populations of tickle grass from the Beaver Pond (BP) site and Yellowstone National Park (YN) growing at the Bridger Plant Material Center in Bridger, Montana. Data analysis was conducted for height, basal area, biomass, vigor, plant appearance, and state of the flower head to determine whether BM tickle grass population is an ecotype adapted to harsh conditions.

Status

The results of height and basal area from the greenhouse study partially validated the hypothesis of the BM tickle grass population being an ecotype within the species, where as the hypothesis of the BM tickle grass population being more suitable to the mine dump material was not completely satisfied. The results of the transplant garden study partially supported the hypothesis of the BM tickle grass population being suitable for the reclamation of mine dump material as compared to the BP and the YN population. Soil characterization of the Badger Mine dump material verified the assumption of the BM tickle grass population surviving harsh conditions of low pH, low nutrient levels, and high concentrations of heavy metals such as arsenic, copper, iron, lead, nickel, and zinc. An on-site reclamation option was favored for the Badger Mine site.

The final report will be completed in FY02.

ACTIVITY IV, PROJECT 18: INVESTIGATION OF NATURAL WETLANDS NEAR ABANDONED MINE SITES

Project Overview

The main objective of this project was to determine how and to what extent metals are being attenuated by natural wetlands at two remote locations in Montana. Sites selected for fieldwork included the Copper Gulch wetland (near Jefferson City, Montana), and the Fisher Creek wetland (near Cooke City, Montana). At both sites, representative samples of soil, groundwater, and surface water were collected for metal analysis. The hydrogeology of each wetland was characterized, with the help of shallow piezometers to monitor water level and to collect groundwater samples. Each site was visited several times throughout the year to determine seasonal changes in hydrology or metal removal efficiency.

Status

At Copper Gulch, discharging groundwater initially had low pH (3.5 to 4) and elevated concentrations of metals, including aluminum, iron, copper, manganese, and zinc. By the time water reached the outlet of the sedge wetland, pH rose to > 5, and concentrations of aluminum, iron, and copper were decreased. Most of the copper appeared to be scavenged by the subsurface wetland soils; whereas, aluminum and iron were precipitated within the surface drainage of the wetland. At Fisher Creek, influent springs were weakly acidic, very dilute, but contained elevated copper concentrations. Although a quantitative water and copper mass balance was not possible, it appeared that most of the influent copper passed through or around the wetland, with only localized attenuation. Nonetheless, copper concentrations in humic wetland soils at this site were extremely high (> 1 wt %), indicating that metal removal, although inefficient, can result in impressive accumulations over very long periods of time.

If natural wetlands are to be used for treating metals or acidity near abandoned mine sites, steps should be taken to create the largest water retention time possible, which may entail enlarging a preexisting wetland or eliminating channeled flow. The potential for metal-rich wetlands to become a source, rather than a sink, for contaminants should also be considered.

The final report will be completed in FY02.

ACTIVITY IV, PROJECT 19: REMOVING OXYANIONS OF ARSENIC AND SELENIUM FROM MINE WASTEWATERS USING GALVANICALLY ENHANCED CEMENTATION TECHNOLOGY

Project Overview

Many solution species can be effectively removed from mine water by electrochemical reduction of the aqueous species, to a solid elemental species on the surface of a metal (called cementation), e.g., aqueous solution species of copper, arsenic, selenium can be reduced to the solid elemental state on an iron surface. Presently, the industrial use of cementation has been limited to copper recovery. It was proposed that the rate of reduction of arsenic (arsenate, arsenite) and selenium (selenate, selenite) could be increased dramatically by using galvanically coupled substrates (instead of iron).

Galvanically coupled substrates provide greatly enhanced active metal dissolution rates. The enhanced metal dissolution rates (called anodic dissolution) are accompanied by the production of electrons in the substrate (iron). The available electrons in the substrate metal (iron) must be discharged at cathodic sites on the more noble metal surface. The consumption of electrons is characterized as reduction reactions, i.e., reduction of aqueous species in the solution phase to the elemental state on the nobler cathodic surface. Therefore, if the metal dissolution rate is enhanced (increased) then the reduction rate of oxyanions (arsenic and selenium) will also be increased.

Two major experimental studies were conducted during the present investigation, i.e., electrochemical characterization of iron and galvanic couple surfaces and application of iron and galvanic couples for selenium/arsenic removal from synthetic and real solutions. The conclusions drawn from each of the major studies are briefly presented below.

Status

Electrochemical Characteristics of Iron and Galvanic Couple Surfaces

Selenate. The conclusions drawn from the electrochemical studies included:

- The selenate reduction reaction proceeded rapidly on an iron substrate.

- The selenate reduction reaction rate was enhanced by using galvanically coupling. Coupling of iron with copper approximately doubles the selenate reduction rate (for equal surface areas of iron and copper in the presence of 2 mg/L selenium at pH 7). Coupling of iron with nickel increased the selenate reduction rate by a factor of approximately 25 (for equal surface areas of iron and nickel in the presence of 2 mg/L selenium at pH 7).

- If the electrochemically-measured rates are applied to a kettle reactor environment, it is predicted that selenate removal could be accomplished very rapidly.

Arsenate. The conclusions drawn from the electrochemical studies included:

- The arsenate reduction reaction proceeded rapidly on an iron substrate.

- The hydrogen ion reduction reaction rate was increased by using galvanically coupling. Coupling of iron with copper increased the hydrogen ion reduction rate by a factor of 18 times (for equal surface areas of iron and copper at pH ~7).

- The effect of the presence of arsenate in the iron/copper/arsenic system was to decrease the rate of the hydrogen ion reduction reaction. This effect was opposite to the effect of the presence of arsenate in the iron/arsenic system, e.g., the presence of arsenate in the iron/arsenic system increased the overall rate. The reasons for the noted effect are presently unknown.

- Insufficient data were generated to make a final conclusion concerning the effect of galvanic coupling on arsenate removal. It is recommended that further studies be conducted to evaluate the use of other couples, such as iron/nickel, iron/palladium, and magnesium/aluminum couples.

Application of Iron and Galvanic Couples for Selenium/Arsenic Removal

Kettle Reactor Test Work. The conclusions drawn from the kettle treatment test work using synthetic water and industrial water included:

- Iron particulate was an excellent reductant for reducing selenate or arsenate. The same result was achieved in synthetic water and industrial water, except a lower pH was required for the industrial water.

- Iron/copper galvanic couples showed mixed results but in all cases the enhancement by the galvanic couple, where it occurred, was not very significant.

- The rate of arsenic and selenium removal at a nominal pH of 4 showed the same general trend for the various substrates, i.e., the rate of removal of arsenic and selenium was greater for the uncoupled iron than for the iron/copper galvanic couples. At higher copper contents, the arsenic and selenium removal rate decreased.

- The electrochemical study results suggest that galvanic couples should show a major enhancement in the selenate reduction rate. The kettle test results showed relatively poor enhancement by the iron/copper galvanic couples compared to uncoupled iron for both arsenate and selenate.

The final report will be completed in FY02.

ACTIVITY IV, PROJECT 20: ALGAL BIOREMEDIATION OF BERKELEY PIT WATER, PHASE II

Project Overview

The Berkeley Pit Lake System is one of the largest contaminated sites in North America and is located near the headwaters of the largest superfund site in the United States. The Pit Lake is more than 542 meters deep with a lateral extent of approximately 1.8 by 1.4 kilometers across the rim. The only larger pit mine in the United States is the Bingham Pit in Salt Lake City, Utah. The Berkeley Pit has a water depth of approximately 275 meters and is rising at a rate of about 8 meters per year. This represents roughly 1,140 billion liters of metal laden, contaminated water, with a pH of 2.7, that has been designated a Superfund project for cleanup. The goal of the Mine Waste Technology Program, Activity IV Project, was to continue to gain an understanding of the microbial ecology of the Berkeley Pit Lake System, which will ultimately provide necessary data for bioremediation studies that may apply to other contaminated pit lakes worldwide.

Status

Preliminary lab experiments showed that even getting algae to grow to very eutrophic levels did not significantly remove metals from the water. The only metal that was significantly removed was aluminum, and the final concentration of aluminum under optimal removal in the experiments was 150 mg/L.

Furthermore, under optimal experimental metal removal, the pit water still contained high levels of metals and would need to be treated with lime precipitation as stated in the record of decision. Since the solubility product of $Al(OH)_3$ is 3.8×10^{-9} compared to the solubility product of $Cu(OH)_2$ of 3.5×10^{-7}, the aluminum would precipitate before the copper. Therefore, aluminum removal by the algae would not significantly reduce the treatment cost for Berkeley Pit water or significantly reduce the amount of sludge generated.

The final report will be completed in FY02.

ACTIVITY V OVERVIEW TECHNOLOGY TRANSFER

This activity consists of making technical information developed during Mine Waste Technology Program (MWTP) activities available to industry, academia, and government agencies. Tasks include preparing and distributing MWTP reports, presenting information about MWTP to various groups, publications in journals and magazines, holding Technical Integration Committee meetings, sponsoring mine waste conferences, and working to commercialize treatment technologies.

Fiscal Year Highlights

- The MWTP Annual Report was published summarizing fiscal year accomplishments. A similar report will be published each year.

- Several MWTP professionals appeared at varied meetings to discuss the Program with interested parties. Many mine waste conferences, as well as mining industry meetings, were attended.

ACTIVITY VI OVERVIEW TRAINING AND EDUCATION

Through its education and training programs, the Mine Waste Technology Program (MWTP) continues to educate professionals and the general public about the latest information regarding mine and mineral waste cleanup methods and research.

As a result of rapid technology and regulatory changes, professionals working in the mine- and mineral-waste areas often encounter difficulties in upgrading their knowledge and skills in these fields. In recent years, the environmental issues related to the mining and mineral industries have received widespread public, industry, and political attention. While knowledge of current research and technology is vital for dealing with mine and mineral wastes, time and costs may prevent companies from sending employees back to the college classroom.

Through short courses, workshops, conferences, and video outreach, Activity VI of MWTP educates professionals and the general public and brings the specific information being generated by bench-scale research and pilot-scale technologies to those who work in mine- and mineral-waste remediation.

Fiscal 2001 Highlights

- The *Mine Design, Operations, and Closure Conference 2001,* conducted in April 2001 continued last year's interagency cooperation. The 5-day event was cosponsored by the U.S. Forest Service; U.S. Bureau of Land Management; Montana Department of State Lands; MSE Technology Applications, Inc.; Haskell Environmental Research Studies Center; several other private companies; and Montana Tech. During the conference, experts presented overviews on such topics as predictive chemical modeling for acid mine drainage, mine water quality source control, state-of-the-art containment technologies, and innovative pit reclamation. Over 130 mine operators, consultants, and professionals from the private and public sectors attended the conference.

- The Mine and Mineral Waste Emphasis Program has an enrollment of 10 students with all of them receiving funding from MWTP. This is an interdisciplinary graduate program that allows students to major in their choice of a wide variety of technical disciplines while maintaining an emphasis in mining and mineral waste.

- A group of Mine and Mineral Waste Emphasis graduate students attended the Mine Design, Operations, and Closure Conference 2001.

- A cooperative agreement is in place for work with the Haskell Environmental Research Studies Center at Haskell Indian Nations University.

- Graduate students in the Mine and Mineral Waste Emphasis Program are working on projects in Activities IV.

- As part of the Native American Initiative, Montana Tech presented five short courses: Mining and the Environment at Fort Belknap, and Acid Rock Drainage at both Fort Belknap and Salish Kootenai College. An environmental learning community was set up to house the short courses and Web courses to make them accessible to Native American communities around the country. One Web course, *Environmental Planning for Small Communities*, is on-line.

Future Activities

The following training and educational activities are scheduled for 2002:

- MWTP Training and Educational activities will offer the Mine Design, Operations, and Closure Conference 2002 in April 2002.

- MWTP is working on a cooperative education package for the Montana Department of Environmental Quality.

- All funded Mine and Mineral Waste Emphasis Program graduate students will work on mine waste-oriented projects as a part of their funding requirements.

FINANCIAL SUMMARY

Total expenditures during the period October 1, 2000, through September 30, 2001, were $3,687,532, including both labor and nonlabor expense categories. Individual activity accounts are depicted on the performance graph in Figure 27.

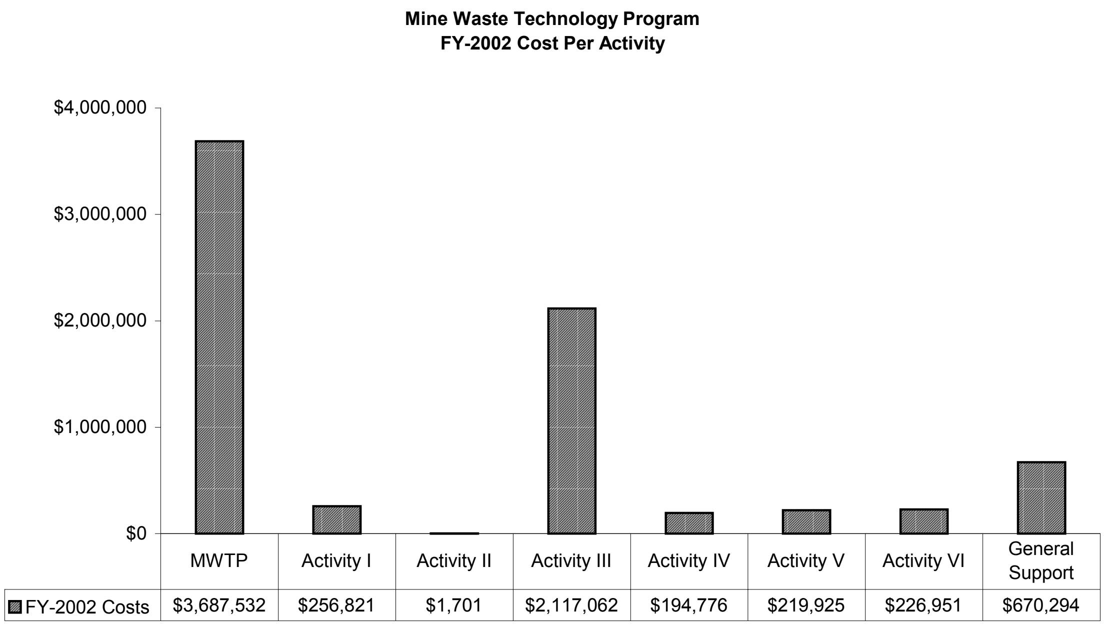


Figure 27. Mine Waste Technology Program fiscal 2001 performance graph, costs per activity.

COMPLETED ACTIVITIES

For information on the following completed Mine Waste Technology Program activities, refer to the web site: http://www.epa.gov/ORD/NRMRL/std/mtb/mwtphome.html.

Activity III

Project 1	Remote Mine Site Demonstration
Project 2	Clay-Based Grouting Demonstration
Project 4	Nitrate Removal Demonstration
Project 5	Biocyanide Demonstration
Project 6	Pollutant Magnet
Project 7	Arsenic Oxidation
Project 9	Arsenic Removal
Project 10	Surface Waste Piles—Source Control
Project 11	Cyanide Heap Biological Detoxification Demonstration
Project 12A	Calliope Mine Internet Monitoring System
Project 13	Hydrostatic Bulkhead with Sulfate-Reducing Bacteria
Project 17	Lead Abatement Demonstration
Project 18	Gas-Fed Sulfate-Reducing Bacteria Berkeley Pit Water Treatment
Project 20	Selenium Removal/Treatment Alternatives

Activity IV

Project 1	Berkeley Pit Water Treatment
Project 2	Sludge Stabilization
Project 3	Photoassisted Electron Transfer Reactions Research
Project 3A	Photoassisted Electron Transfer Reactions for Metal-Complexed Cyanide
Project 3B	Photoassisted Electron Transfer Reactions for Berkeley Pit Water
Project 4	Metal Ion Removal from Acid Mine Wastewaters by Neutral Chelating Polymers
Project 5	Removal of Arsenic as Storable Stable Precipitates
Project 7	Berkeley Pit Innovative Technologies Project
Project 8	Pit Lake System—Characterization and Remediation for the Berkeley Pit
Project 9	Pit Lake System—Deep Water Sediment/Pore Water Characterization and Interactions
Project 10	Pit Lake System—Biological Survey of Berkeley Pit Water
Project 11	Pit Lake System Characterization and Remediation for Berkeley Pit—Phase II
Project 12	An Investigation to Develop a Technology for Removing Thallium from Mine Wastewaters

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