United States
Environmental Protection
Agency

SITE Technology Capsule

Compost-Free Bioreactor Treatment of Acid Rock Drainage

Abstract

As part of the Superfund Innovative Technology Evaluation (SITE) program, an evaluation of the compost-free bioreactor treatment of acid rock drainage (ARD) from the Aspen Seep was conducted at the Leviathan Mine Superfund site located in a remote, high altitude area of Alpine County, California. The evaluation was performed by U.S. Environmental Protection Agency (EPA) National Risk Management Research Laboratory (NRMRL), in cooperation with EPA Region IX, the state of California, and Atlantic Richfield Company (ARCO), and the University of Nevada-Reno (UNR). The primary target metals of concern in the ARD include aluminum, copper, iron, and nickel; secondary target metals include selenium and zinc.

Drs. Glenn Miller and Tim Tsukamoto of the UNR have developed a compost-free bioreactor technology in which sulfate-reducing bacteria are nurtured to generate sulfides which scavenge dissolved metals to form metal sulfide precipitates. Unlike compost bioreactors, this technology uses a liquid carbon source (ethanol) and a rock matrix rather than a compost or wood chip matrix which is consumed by bacteria and collapses over time. The benefits include better control of biological activity and improved hydraulic conductivity and precipitate flushing.

Evaluation of the compost-free bioreactor technology occurred between November 2003 and July 2005. The treatment system neutralized acidity and precipitated metal sulfides from ARD at flows up to 24 gallons per minute (gpm) on a year-round basis. Multiple sampling events were conducted during both gravity flow and recirculation modes of operation. During each sampling event, EPA collected chemical data from the system influent and effluent streams and documented metals removal and reduction in acidity between system components. Operational information pertinent to the evaluation of the treatment system was also recorded. The treatment system was evaluated based on removal efficiencies for primary and secondary target metals, on a comparison of effluent concentrations to EPA interim (pre-risk assessment and record of decision) discharge standards, and on the characteristics of and disposal requirements for the resulting metals-enriched solid wastes. Removal efficiencies of individual unit operations were also evaluated.

The compost-free bioreactor treatment system was shown to be extremely effective at neutralizing acidity and reducing the concentrations of the 4 of the 5 target metals to below EPA interim discharge standards. Pilot testing to determine optimal sodium hydroxide addition resulted in exceedance of discharge standards for iron. However, after base optimization during gravity flow operations effluent iron concentrations met discharge standards. Iron also exceeded discharge standards during recirculation operations when base addition was stopped due to equipment failure or lack of adequate base supply. Although the influent concentrations for the primary target metals were up to 580 fold above the EPA interim discharge standards, the treatment system was successful in reducing the concentrations of the primary target metals in the ARD to between 1 and 43 fold below the discharge standards. Removal efficiencies for the 5 primary target metals exceeded 85 percent; sulfate ion was reduced by 17 percent. The metal sulfide precipitates generated by this technology were not found to be hazardous or pose a threat to water quality and could be used as a soil amendment for site reclamation.

Based on the success of bioreactor treatment at the Leviathan Mine site, ARCO will continue to use this technology to treat ARD at the Aspen Seep.

Introduction

In 1980, the U.S. Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund. CERCLA is committed to protecting human health and the environment from uncontrolled hazardous waste sites. In 1986, CERCLA was amended by the Superfund Amendments and Reauthorization Act (SARA). These amendments emphasize the achievement of long-term effectiveness and permanence of remedies at Superfund sites. SARA mandates the use of permanent solutions, alternative treatment technologies, or resource recovery technologies, to the maximum extent possible, to clean up hazardous waste sites. State and Federal agencies, as well as private parties, have for several years now been exploring the growing number of innovative technologies for treating hazardous wastes. EPA has focused on policy, technical, and informational issues related to the exploring and applying new remediation technologies applicable to Superfund sites. One such initiative is EPA's SITE program, which was established to accelerate the development, demonstration, and use of innovative technologies for site cleanups. Technology Capsules summarize the latest information available on selected innovative treatment, site remediation technologies, and related issues. These capsules are designed to help EPA remedial project managers and on-scene coordinators, contractors, and other site cleanup managers understand the types of data and site characteristics needed to effectively evaluate a technology's applicability for cleaning up Superfund sites.

Compost-free bioreactor treatment systems are an improvement to current wood chip, compost, and manure based bioreactors in place at many facilities. This capsule provides information on new approaches to the use of compost-free bioreactors to reduce the concentration of toxic metals and acidity in ARD from the Aspen Seep at Leviathan Mine. The treatment system implemented by ARCO was specifically designed to treat low to moderate flow rates of ARD (pH of 3) containing hundreds of milligrams per liter (mg/L) of toxic metals that would otherwise be released to the environment. The mine site also poses operational challenges associated with its remote location and winter weather conditions that limit site access and operations from late fall through late spring. This capsule presents the following information that documents the evaluation of the treatment system:

- Project background
- Technology description
- Performance data
- Process residuals
- Technology applicability
- Technology limitations
- Site requirements
- Technology status
- Sources of further information

Project Background

Leviathan Mine is a former copper and sulfur mine located high on the eastern slopes of the Sierra Nevada Mountain range, near the California-Nevada border. The mine occupies approximately 253 acres on the northwestern flank of Leviathan Peak, at an elevation of about 7,800 feet. The mine site is drained by Leviathan and Aspen creeks, which combine with Mountaineer Creek 2.2 miles below the mine to form Bryant Creek, a tributary to the East Fork of the Carson River. Intermittent mining of copper sulfate, copper, and sulfur minerals since the mid 1860s has resulted in acid mine drainage (AMD) at Leviathan Mine. During the process of converting underground workings into an open pit mine in the 1950s, approximately 22 million tons of overburden and waste rock were removed from the open pit mine and placed in the Aspen Creek drainage, contributing ARD to the Aspen Seep. Oxidation of sulfur and sulfide minerals within the mine workings and waste rock forms sulfuric acid (H_2SO_4), liberating toxic metals discharged in the ARD.

Historically, the concentrations of four primary target metals, aluminum, copper, iron, and nickel in the ARD released from Aspen Seep have exceeded EPA interim discharge standards up to 580 fold. Release of these metals has contributed to fish and insect kills in Leviathan Creek, Bryant Creek, and the east fork of the Carson River. In 1984 the state of California significantly reduced the quantity of toxic metals discharging from the mine site by partially filling and grading the open pit, building retention ponds to contain the AMD, building a channel under-drain (CUD) system to capture ARD, and rerouting Leviathan Creek through a concrete diversion channel to reduce contact with waste rock. To further reduce the amount of toxic metals discharging from the mine site, the state of California initiated pilot-scale compost bioreactor studies in 1996 to treat ARD and constructed an active lime treatment system in 1999 to treat AMD that collects in the retention ponds. In 2001, ARCO constructed the semi-passive Alkaline Lagoon treatment system to treat ARD from the CUD. In 2003, ARCO in conjunction with UNR constructed the full-scale compost-free bioreactor treatment system to treat ARD from Aspen Seep.

Technology Description

Biological treatment of ARD relies on the biologically mediated reduction of sulfate to sulfide followed by metal sulfide precipitation. Biologically promoted sulfate-reduction has been attributed primarily a consortium of sulfate-reducing bacteria, which at Leviathan Mine utilizes ethanol as a carbon substrate to reduce sulfate to sulfide. This process generates hydrogen sulfide, elevates pH to about 7, and precipitates divalent metals as metal sulfides. The following general equations describe the sulfate-reduction and metal sulfide precipitation processes.

$$2CH_3CH_2OH + 3SO_4^{2-} \rightarrow 3HS^- + 3HCO_3^- + 3H_2O \quad (1)$$

$$2CH_3CH_2OH + SO_4^{2-} \rightarrow 2\ CH_3COO^- + HS^- + H_2O \quad (2)$$

$$HS^- + M^{2+} \rightarrow MS + 2H^+ \quad (3)$$

Here ethanol is the carbon source and SO_4^{2-} is the terminal electron acceptor in the electron transport chain of sulfate-reducing bacteria. Reaction No.1 causes an increase in alkalinity and a rise in pH, while reaction No.2 results in the generation of acetate rather than complete oxidation to carbonate. HS^- then reacts with a variety of divalent metals (M^{2+}), resulting in a metal sulfide (MS) precipitate.

The reduction of sulfate to sulfide requires 8 electrons:

$$H_2SO_4 + 8H^+ + 8e^- \rightarrow H_2S + 4H_2O \quad (4)$$

Ethanol contributes 12 electrons per molecule oxidized, assuming complete oxidation to carbon dioxide.

$$3H_2O + C_2H_5OH \rightarrow 12e^- + 2CO_2 + 12H^+ \quad (5)$$

However, incomplete oxidation of ethanol to acetate yields only 4 electrons per molecule oxidized.

$$H_2O + C_2H_5OH \rightarrow 4e^- + C_2H_3OOH + 4H^+ \quad (6)$$

The moles of ethanol consumed per mole of sulfate reduced in the bioreactors at Leviathan Mine suggest that incomplete oxidation of ethanol is the predominant reaction.

Compost-Free Bioreactor System Overview: At Leviathan Mine, the compost-free bioreactor treatment system consists of ethanol and sodium hydroxide feed stocks, a pretreatment pond, two bioreactors, a settling pond, a flushing pond, and an aeration channel. The system was designed to treat ARD by gravity flow through successive sulfate-reducing bioreactors and precipitation of metal sulfides in the bioreactors as well as in a continuous flow settling pond (Figure 1). During the demonstration, an alternative mode of operation (recirculation) was also evaluated, which involved the direct contact of ARD with sulfide rich water from the bioreactors and precipitation of the majority of the metal sulfides in the settling pond. A portion of the pond supernatant containing excess sulfate is then pumped to the head of the bioreactor system to generate additional sulfides (Figure 2).

The heart of the treatment system is the two compost-free, sulfate-reducing bioreactors. The bioreactors are ponds lined with 60 mil high density polyethylene (HDPE) and filled with 8- to 16-inch river rock (Figure 2 and 3). River rock was selected because of the stability of the matrix and the ease at which metal sulfide precipitates can be flushed from the matrix to the flushing pond. Each bioreactor consists of three 4-inch diameter influent distribution lines and three 4-inch effluent collection lines. The distribution and collection lines are located near the top, in the middle, and just above the bottom of the bioreactor to precisely control flow within the bioreactor media. ARD water can be drawn upward or downward through the aggregate to one of three effluent collection lines located at the opposite end of each bioreactor (Figures 2 and 3).

Compost-Free Bioreactor Operation: Influent to the treatment system consists of ARD discharged from Aspen Seep. In gravity flow mode (Figure 1), influent ARD from Aspen Seep passes through a flow control weir at flow rates ranging from 6.4 to 21.9 gpm, where a 25 percent sodium hydroxide solution (0.26 [ml/L] milliliter per liter or 83 mg/L) is added to adjust the pH from 3.1 to approximately 4 to maintain a favorable environment for sulfate-reducing bacteria and ethanol (0.43 ml/L or 339 mg/L) is added to provide a carbon source for reducing equivalents for the sulfate-reducing bacteria. The dosed influent discharges into a pretreatment pond (1,000 ft^3 [cubic foot], 4 hour hydraulic residence time [HRT] at 30 gpm) to allow sufficient time for reagent contact and to stabilize the flow to the head of Bioreactor No.1. A small volume of metal precipitation also occurs within the pretreatment pond. ARD from the pretreatment pond then flows through Bioreactor No.1 (12,500 ft^3 total volume, 5,300 ft^3 active volume, 22 hour HRT at 30 gpm) and Bioreactor No.2 (7,000 ft^3 total volume, 3,000 ft^3 active volume, 13 hour HRT at 30 gpm) to reduce sulfate to sulfide. Excess sulfide generated in the first bioreactor is passed, along with partially treated ARD water, through to the second bioreactor for additional metals removal. Effluent from the second bioreactor discharges to a continuous flow pond (16,400 ft^3, 68 hour HRT at 30 gpm) for extended settling of metal sulfide precipitates. A twenty-five percent sodium hydroxide solution (0.85 ml/L or 270 mg/L) is added to the bioreactor effluent prior to the continuous flow settling pond to consume remaining mineral acidity, convert bisulfide to sulfide which is necessary for metal sulfide precipitation, and provide a source of hydroxide ion for metals that do not form precipitates with sulfide.

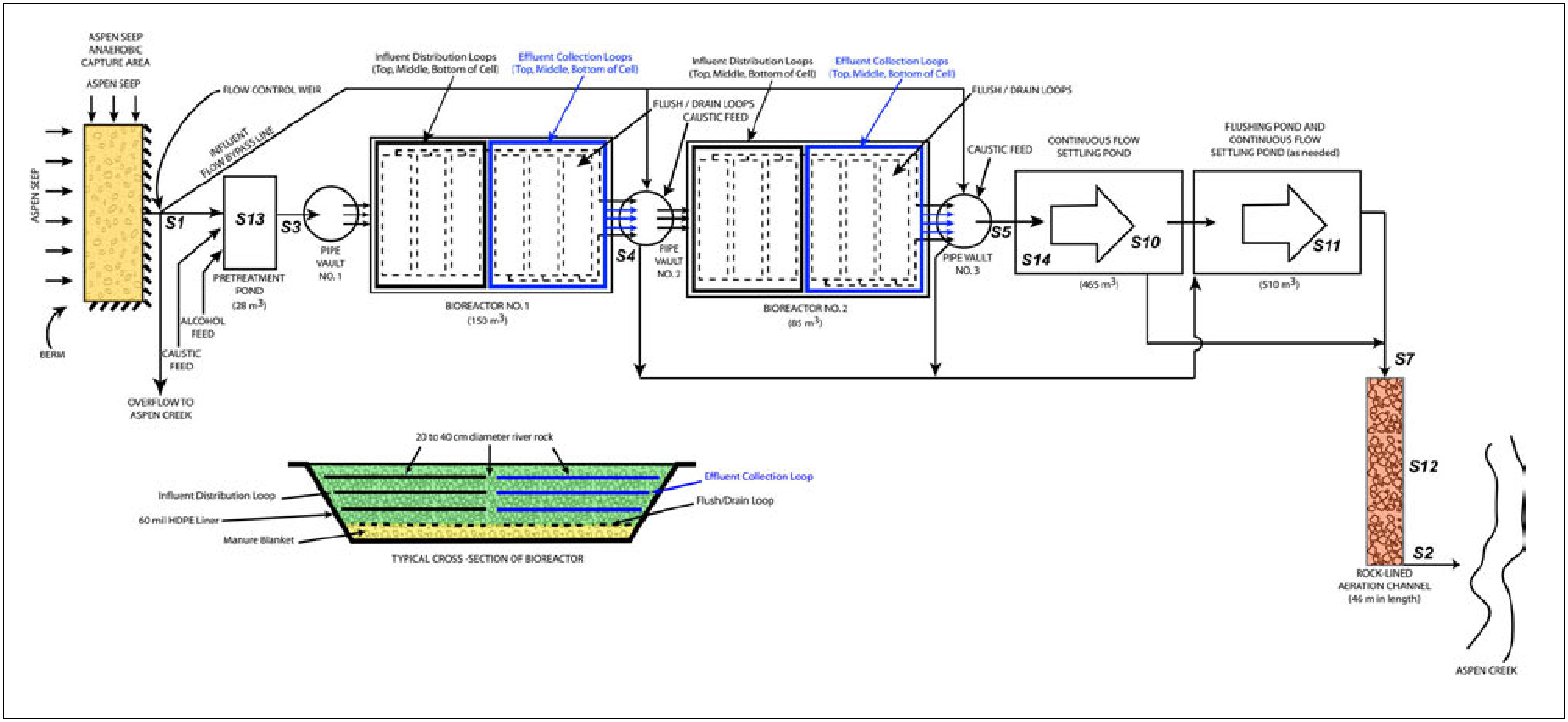

Figure 1-1. Bioreactor Treatment System, Gravity Flow Configuration Schematic

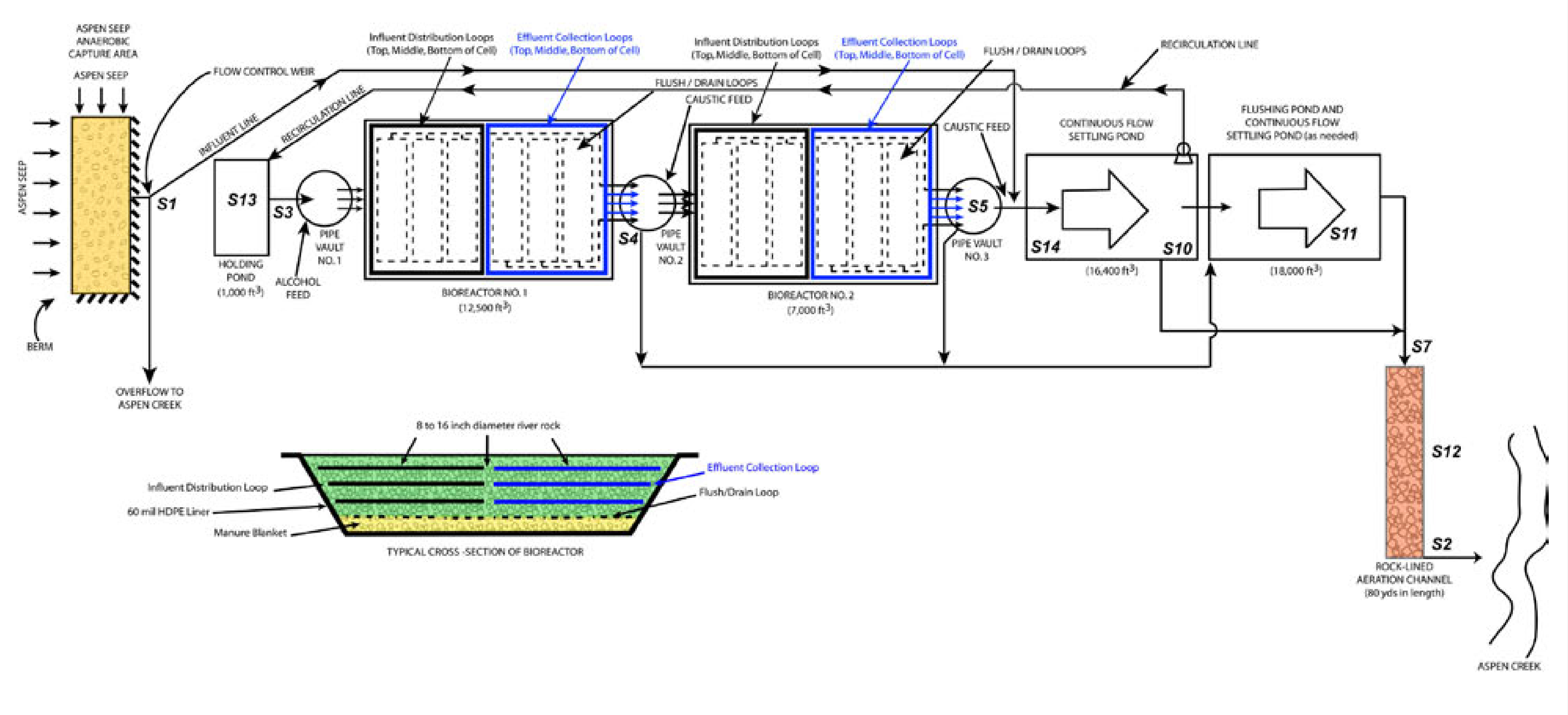

Figure 1-2. Bioreactor Treatment System, Recirculation Configuration Schematic

Operated in recirculation mode (Figure 2), metal-rich ARD influent from Aspen Seep passes through a flow control weir at which point the ARD flow is routed around the two bioreactors to a flow control vault at the head of the continuous flow settling pond. The untreated ARD is mixed with sulfide rich water discharging from bioreactor No.2 and a 25 percent sodium hydroxide solution (0.5 ml/L or 159 mg/L) and is then discharged to the settling pond. The combination of a neutral pH condition and high sulfide concentrations promotes rapid precipitation of metal sulfides in the settling pond rather than in the two bioreactors. Precipitation of a majority of the metal sulfides downstream of the two bioreactors reduces precipitate formation in the bioreactors and the need for flushing and the associated stress on the two bioreactors. A portion of the pond supernatant containing excess sulfate is then pumped to a holding pond at flow rates ranging from 30 to 60 gpm (influent to recirculation ratio of 1:2 to 1:6). Ethanol (0.50ml/L or 395 mg/L) is added to the discharge from the holding pond, just prior to the head of bioreactor No.1. Sulfate-rich and metal poor water from the holding pond then flows through the two bioreactors to promote additional sulfate reduction to sulfide. The pH of the supernatant recirculated through the bioreactors is near neutral, providing optimal conditions for sulfate-reducing bacteria growth. The system operated in recirculation mode requires about 49 percent less sodium hydroxide and 14 percent more ethanol than the gravity flow mode of operation.

In both modes of operation, the effluent from the continuous flow settling pond then flows through a rock lined aeration channel (150 feet long by 2 feet wide) to promote gas exchange (eliminate hydrogen sulfide and introduce oxygen) prior to effluent discharge. Precipitate slurry is periodically flushed from the two bioreactors to prevent plugging of the river rock matrix. The slurry is sent to a flushing pond (18,000 ft^3, 75 hour HRT at 30 gpm) for extended settling. The flushing pond can also be used for extended settling of the continuous flow settling pond effluent in the event of a system upset. Settled solids are periodically pumped out of the settling and flushing ponds and dewatered using 10- by 15-foot spun fabric bag filters. The bag filtration process relies on the build up of filter cake on the inside of each bag to remove progressively smaller particles. Effluent from the bag filters, including soluble metals and particles too small to be captured, flows by gravity back into the settling pond. Metals in bag filter solids are not hazardous under Federal or California standards and can be disposed of on- or off-site. The total system HRT is 107 hours at maximum design flow of 30 gpm, and 352 hours at an average flow rate of 10 gpm during the demonstration.

Performance Data

The evaluation of the compost-free bioreactor treatment systems at Leviathan Mine was conducted between November 2003 and July 2005; focusing on two primary objectives. The first objective was to determine the removal efficiencies for the primary target metals of concern and the secondary target metals. The second objective was to determine whether the concentrations of the primary target metals in the effluent from the bioreactor treatment system were below EPA interim discharge standards, as presented in Table 1.

The data evaluation was designed to address both primary objectives and included both descriptive and inferential statistics. Descriptive summary statistics of the data were calculated to screen the sample data for possible outliers; these statistics included the mean, median, range, variance, and standard deviation. To successfully calculate removal efficiencies for each metal, influent concentrations must be significantly different than effluent concentrations. A paired t-test was applied to the data collected during each sampling event to determine if the influent and effluent concentrations were statistically different. Where influent and effluent concentrations for a particular metal were not statistically different, removal efficiencies were not calculated for that metal. In addition, removal efficiencies were not calculated for individual influent/effluent data pairs when both concentrations for a metal were not detected.

Tables 2 and 3 present the average and range of removal efficiencies for filtered influent and effluent samples collected from the treatment system during both gravity flow and recirculation modes of operation. A summary of the average influent and effluent metals concentrations for each mode of operation is also presented. The results of a comparison of the average effluent concentration for each metal to the EPA interim discharge standards is also presented; where a “Y” indicates that either the maximum concentration (based on a daily composite of three grab samples) and/or the average concentration (based on four consecutive sampling events) was exceeded; and an “N” indicates that neither discharge standard was exceeded.

Although the influent concentrations for the primary target metals were up to 580 fold above EPA interim discharge standards, both modes of treatment system operation were successful in reducing the concentrations of the primary target metals in the ARD to between 1 and 43 fold below the discharge standards. Internal trials run to refine base addition requirements and to evaluate various sources of base addition lead to significant excursions of effluent iron concentrations

Table 1. EPA Interim Discharge Standards for Metals of Concern at Leviathan Mine

Target Metals	Maximum (a) (µg/L)	Average (b) (µg/L)
Primary Target Metals		
Aluminum	4,000	2,000
Arsenic	340	150
Copper	26	16
Iron	2,000	1,000
Nickel	840	94
Secondary Target Metals		
Cadmium	9.0	4.0
Chromium	970	310
Lead	136	5.0
Selenium	No Standard	5.0
Zinc	210	210

(a) Maximum concentration based on a daily composite of three grab samples
(b) Average concentration based on four consecutive sampling events
µg/L = microgram per liter

Table 2. Bioreactor Treatment System Removal Efficiencies: Gravity Flow Configuration

Target Metal	Number of Sampling Events	Average Filtered Influent Concentration (µg/L)	Standard Deviation	Average Filtered Effluent Concentration (µg/L)	Standard Deviation	Exceeds Discharge Standard (Y/N)	Average Removal Efficiency (%)	Range of Removal Efficiencies (%)
Primary Target Metals								
Aluminum	6	37,467	2,011	103	78.8	N	99.7	99.5 to 99.9
Arsenic	6	2.1	0.64	4.7	4.0	N	NC	NC
Copper	6	691	51.2	4.8	1.6	N	99.3	99.1 to 99.7
Iron	6	117,167	6,242	4,885	4,771	Y	95.8	65.6 to 99.9
Nickel	6	487	33.5	65.5	36	N	86.6	72.1 to 92.6
Secondary Target Metals								
Cadmium	6	0.61	0.27	<0.21	0.07	N	65.3	42.5 to 79
Chromium	6	12.2	8.9	7.8	6.6	N	NC	NC
Lead	6	3.6	2.5	4.7	2.9	N	NC	NC
Selenium	6	13.9	3.1	11.2	2.6	Y	NC	NC
Zinc	6	715	47.1	15.8	6.8	N	97.8	95.9 to 98.6

NC = Not calculated as influent and effluent concentrations were not statistically different
µg/L = Microgram per liter

Table 3. Bioreactor Treatment System Removal Efficiencies: Recirculation Configuration

Target Metal	Number of Sampling Events	Average Filtered Influent Concentration (µg/L)	Standard Deviation	Average Filtered Effluent Concentration (µg/L)	Standard Deviation	Exceeds Discharge Standard (Y/N)	Average Removal Efficiency (%)	Range of Removal Efficiencies (%)
Primary Target Metals								
Aluminum	7	40,029	4,837	52.7	25.7	N	99.9	99.7 to 99.9
Arsenic	7	7.4	6.5	6.5	4.9	N	NC	NC
Copper	7	795	187	4.6	3.2	N	99.4	98.8 to 99.8
Iron	7	115,785	13,509	2,704	3,000	Y	97.7	92.8 to 99.7
Nickel	7	529	34.1	69.7	44.2	N	86.8	71.0 to 96.4
Secondary Target Metals								
Cadmium	7	0.60	0.50	<0.20	0.09	N	NC	NC
Chromium	7	11.1	6.3	6.4	5.2	N	42.5	21.2 to 84.8
Lead	7	4.2	2.3	2.5	1.6	N	41.5	22.0 to 57.1
Selenium	7	11.5	5.1	8.5	3.6	Y	NC	NC
Zinc	7	776	51.7	8.9	7.4	N	98.9	97.7 to 99.8

NC = Not calculated as influent and effluent concentrations were not statistically different
µg/L = Microgram per liter

above the EPA interim discharge standards during a portion of the evaluation. However, after base optimization during gravity flow operations, effluent iron concentrations met discharge standards. Iron also exceed discharge standards during recirculation operations when base addition was stopped due to equipment failure or lack of adequate base supply. In addition, the concentrations of the secondary target metals, with the exception of selenium, were reduced to below the discharge standards.

The bioreactor treatment system operated in gravity flow mode from November 2003 through mid-May 2004 treating 2.44 million gallons of ARD using 2,440 gallons of sodium hydroxide and 1,180 gallons of ethanol. The bioreactor treatment system operated in the recirculation mode from mid-May 2004 through July 2005 treating 5.81 million gallons of ARD using 5,820 gallons of sodium hydroxide and 2,805 gallons of ethanol.

For the gravity flow mode of treatment system operation, the average removal efficiency for the primary target metals was 95 percent over 6 sampling events. For the recirculation mode of treatment system operation, the average removal efficiency for the primary target metals was 96 percent over 7 sampling events. Removal efficiencies for arsenic were not calculated because the influent and effluent metals concentrations were not statistically different. In addition, the concentration of arsenic in system influent was well below discharge standards.

Average removal efficiencies for secondary target metals ranged from 40 to 99 percent in both modes of operation; however, removal efficiencies were not calculated for chromium, lead, and selenium as the influent and effluent concentrations were not statistically different. In the case of arsenic, cadmium, chromium, and lead in the ARD, concentrations were near or below the EPA interim discharge standards in the influent; therefore, the treatment system was not optimized for removal of these metals. Sulfate reduction averaged 17 percent, decreasing from an average influent concentration of 1,567 mg/L to an average effluent concentration of 1,295 mg/L. There was on average a 9 percent increase in sulfate removal during the recirculation mode of treatment system operation.

The bioreactor treatment system is extremely effective at neutralizing acidity and reducing metals content in ARD, with resulting effluent streams that meet EPA interim discharge standards for the primary target metals and the secondary target metals. Based on the success of treatment system at the site, ARCO will continue to treat ARD at the site using the bioreactor treatment system in recirculation mode.

A more detailed evaluation of the compost-free bioreactor treatment technology, including discussion of secondary project objectives, will be presented in the forthcoming Innovative Technology Evaluation Report (ITER) that is anticipated in the spring of 2006.

Process Residuals

There is one process residual associated with bioreactor treatment of ARD. The process produces a relatively small quantity of metal sulfide sludge. During operation from November 2003 through July 2005, the bioreactor generated about 14.2 dry tons (49 cubic meters at 80 percent moisture content) of sludge consisting mainly of iron sulfide. This equals 1.7 dry tons of sludge per million gallons of ARD treated. The volume of sludge generated is small in comparison to that generated by lime treatment of ARD.

The solid waste residuals produced by the treatment system were analyzed for hazardous waste characteristics. Total metals and leachable metals analyses were performed on the solid wastes for comparison to California and Federal hazardous waste classification criteria. To determine whether the residuals are California hazardous waste, total metals results were compared to Total Threshold Limit Concentration (TTLC) criteria. To determine whether the residuals pose a threat to water quality, metals concentrations in Waste Extraction Test (WET) leachate samples were compared to Soluble Threshold Limit Concentration (STLC) criteria. To determine if the residuals are a Resource Conservation and Recovery Act (RCRA) waste, Toxicity Characteristic Leaching Procedure (TCLP) results were compared to TCLP limits. The waste characteristics determined for the solid waste stream are presented in Table 4. None of the solid wastes were found to be hazardous or a threat to

Table 4. Determination of Hazardous Waste Characteristics for Bioreactor Solid Waste Streams

Treatment System	Solid Waste Stream	Total Solid Waste Generated	TTLC Pass or Fail	STLC Pass or Fail	TCLP Pass or Fail	Waste Handling Status
Bioreactor Treatment System	Dewatered Sludge	4.3 dry tons	**P**	**P**	**P**	Off-site Disposal
	Pretreatment Pond	Moved into Flushing Pond	**P**	**P**	**P**	Moved into Flushing Pond
	Settling Pond	10 dry tons (estimated)	**P**	**P**	**P**	Pending Filtration
	Flushing Pond	4.3 dry tons (estimated)	**P**	**P**	**P**	Pending Filtration

STLC = Soluble limit threshold concentration
TTLC = Total threshold limit concentration
TCLP = Toxicity characteristic leaching procedure

water quality; however, the solids were disposed of off site pending designation of an on-site disposal area.

Technology Applicability

Bioreactor treatment of ARD at Leviathan Mine was evaluated based on nine criteria used for decision making in the Superfund feasibility study process. Results of the evaluation are summarized in Table 5. The bioreactor treatment system evaluated was specifically designed to treat ARD at the mine site to meet EPA interim discharge standards. In addition to the five primary target metals of concern, EPA identified the following metals as secondary target metals: cadmium, chromium, lead, selenium, and zinc. The bioreactor treatment system implemented at Leviathan Mine was also successful at reducing concentrations of these metals in the ARD, with the exception of selenium, to below EPA interim discharge standards. The bioreactor treatment system can be modified to treat a higher flow rate and ARD with varying metals concentrations and acidity.

Technology Limitations

In general, the limitations of the bioreactor treatment system implemented at Leviathan Mine were not related to the applicability of the technology, but rather to operational issues due to weather conditions, maintenance problems, and the remoteness of the site. The technology is not limited by the sub-freezing temperatures encountered in the high Sierra Nevada during the winter months. However, biological activity did slow resulting in decreased sulfate reduction to sulfide. Effluent discharge standards continued to be met during winter months as the flow of ARD entering the bioreactor treatment system also decreased during the winter. When designing systems for extremely cold winters, consideration should be given to constructing bioreactors of sufficient size to meet winter HRT requirements and depth to buffer freezing temperatures near the ground surface. In addition, adjustable standpipes in below grade vaults should be used to control the flow of water rather than mechanical valves, which are subject freezing during the winter.

During extended operation of the bioreactor treatment system, reagent metering and water recirculation pumps and the generator that provided power to these pumps were susceptible to failure. In addition, aboveground influent ARD transfer and recirculation pipelines were susceptible to breakage. These limitations are currently being mitigated by 1) developing wind, solar, and hydroelectric power sources, 2) installing redundant pumps, and 3) placing transfer lines below grade.

Overall, the bioreactor treatment system required minimal maintenance (once a week) in comparison to maintenance intensive lime treatment systems.

The remoteness of the site also created logistical challenges in maintaining operation of the bioreactor treatment system. A winter snow pack from November through May prevents site access to all delivery vehicles except for snowmobiles. Consumable materials, such as sodium hydroxide, ethanol, and diesel fuel (to power a generator) must be transported to and stored in bulk at the site during the summer. Sludge transfer from the settling ponds, dewatering, and on- or off-site disposal must also be performed during the summer months to provide sufficient settling pond capacity during the following winter months. Careful planning is essential to maintain supplies of consumable materials and replacement equipment at a remote site such as Leviathan Mine.

Site Requirements

To conduct full-scale bioreactor treatment of ARD, the main site requirement at the Leviathan Mine site was developing adequate space for the treatment system, staging areas, and support facilities. Space is needed for reagent storage tanks, a pretreatment pond, bioreactor ponds, settling ponds, an aeration channel, and bag filters. Additional space was required adjacent to the treatment system for storage of spare parts and equipment, for loading and unloading equipment, supplies, and reagents, and for placement of operating facilities such eye wash stations, fuel storage tank, and power generating equipment. Overall, the space requirement for the bioreactor treatment of ARD at a flow rate of 30 gpm at Leviathan Mine is about 0.75 acre.

The main utility requirement for the bioreactor treatment system is electricity, which is used to operate reagent delivery pumps, a water recirculation pump, and sludge transfer pumps, and site work lighting. The bioreactor treatment system, operated in recirculation mode, requires less than 0.6 kilowatt (KW) hour of electricity for continuous operation. Power for recirculation mode of operation is provided by a 6 KW-hour diesel generator. Diesel fuel for the generator is stored in a 1,000 gallon above ground tank. The bioreactor treatment system, operated in gravity flow mode, requires less than 0.1 KW hour of electricity for continuous operation as a recirculation pump is not required. Power for the gravity flow mode of operation is provided by a solar panel and storage batteries. Satellite phone service is also required due to the remoteness of the site.

Table 5. Feasibility Study Criteria Evaluation for Compost-Free Bioreactor Treatment System at Leviathan Mine

Criteria	**Technology Performance**
Overall Protection of Human Health and the Environment	Bioreactor treatment has been proven to be extremely effective at reducing concentrations of aluminum, copper, iron, nickel, zinc, and other dissolved metals which can significantly degrade the quality of surface water receiving ARD at the Leviathan Mine site. The bioreactor treatment system evaluated at Leviathan Mine is effective at reducing the concentrations of toxic metals in ARD that was historically released to Aspen Creek, to below EPA interim discharge standards, which were established to protect water quality and the ecosystem in Aspen Creek and down-stream receiving waters. Resulting metals-enriched wastes were not determined to be hazardous based on State or Federal criteria or a threat to water quality and can be disposed of on- or off-site.
Compliance with Applicable or Relevant and Appropriate Requirements (ARAR)	The bioreactor treatment system is generally compliant with EPA interim discharge standards for the Leviathan Mine site. However, the effluent from the treatment system did not always meet the EPA interim (pre-risk assessment and record of decision) discharge standards for the site or the secondary maximum contaminant limit for iron, which could easily be met with additional sodium hydroxide dosing. No hazardous process residuals are generated by the treatment system.
Long-term Effectiveness and Performance	A bioreactor treatment system has been in operation at Leviathan Mine since 1996. The current full-scale compost-free bioreactor treatment system has been in operation since the summer of 2003. By the fall of 2003, the entire ARD flow from Aspen Seep was being treated by the full-scale system. The treatment system has consistently met EPA interim discharge standards, with the exception of iron, since the fall of 2003. The treatment system operates year round; therefore, discharge of metals-laden ARD has not occurred from the mine site since initiation of treatment. The treatment system continues to be operated by UNR and ARCO. Long-term optimization of the treatment system will likely refine sodium hydroxide dosage necessary for iron polishing, optimize recirculation rates for sulfide generation, and demonstrate whether wind, solar, or a water turbine can meet the power required for chemical dosage and recirculation pumps.
Reduction of Toxicity, Mobility, or Volume through Treatment	Bioreactor treatment significantly reduces the mobility and volume of toxic metals from ARD at Leviathan Mine. The dissolved toxic metals are precipitated from solution, concentrated, and dewatered removing toxic levels of metals from the ARD. The bioreactor treatment does produce a solid waste; however, the waste generated has been determined to be non-hazardous and can be disposed of on- or off-site.
Short-term Effectiveness	The resulting effluent from the bioreactor treatment system does not pose any risks to human health. The sodium hydroxide solution, ethanol feedstock, and biologically-generated hydrogen sulfide gas, each having potentially hazardous chemical properties, may pose a risk to site workers during treatment system operation. Exposure to these hazardous chemicals must be mitigated through engineering controls and proper health and safety protocols.
Implementability	The bioreactor treatment technology relies on a relatively simple biologically-mediated sulfate reduction and metal sulfide precipitation process and can be constructed using readily available equipment and materials. The technology is not proprietary, nor does it require proprietary equipment or reagents. Once installed, the system can be optimized and maintained indefinitely. System startup and biological acclimation can take up to three months, depending on target metal concentrations and weather conditions. Routine maintenance is required, involving a weekly visit by an operator to ensure reagent and recirculation pumps are operational, replenish reagents as needed, and handle settled metal sulfides as needed. The remoteness of the site also necessitates organized, advanced planning for manpower, consumables, and replacement equipment and supplies.
Cost	Total first year cost for the construction and operation of the bioreactor treatment system operated in gravity flow mode was $941,248 and $962,471 operated in recirculation mode. The operation and maintenance costs associated with the treatment system ranged from $15.28 (recirculation) to $16.54 (gravity flow) per 1,000 gallons at an average ARD flow rate of 9.45 gallons per minute. The operational costs were incurred during a research mode of operation. Once the system is optimized an operations mode will be implemented which will reduce operational labor and reagent costs. Costs for construction and O&M of the treatment system are dependent on local material, equipment, consumable, and labor costs, required discharge standards, and hazardous waste classification requirements and disposal costs (if necessary).
Community Acceptance	The bioreactor treatment technology presents minimal to no risk to the public since all system components are located at and treatment occurs on the Leviathan Mine site, which is a remote, secluded site. Hazardous chemicals used in the treatment system include sodium hydroxide, ethanol, and for the short term diesel fuel. These chemicals pose the highest risk to the public during transportation to the site by truck. The diesel generator creates the most noise and air emissions at the site; again, because of the remoteness of the site, the public is not impacted. Alternative sources of power are being pilot tested at the site to eliminate the need for the diesel powered generator.
State Acceptance	ARCO, in concurrence with the State, selected, constructed, and is currently operating a full-scale bioreactor treatment system at Leviathan Mine, which indicates the State's acceptance of the technology to treat ARD. The bioreactor treatment system is the only technology operating year round at the mine site. All other treatment systems at the mine site shutdown for the winter, requiring long-term storage or discharge of ARD and AMD.

Technology Status

The technology associated with the compost-free bioreactor treatment system is not proprietary, nor are proprietary reagents or equipment required for system operation. The system has been demonstrated at full-scale and is currently operational at Leviathan Mine. The treatment system is undergoing continuous refinement and optimization to reduce the quantity of alcohol and caustic chemicals required for system operation. The power required for recirculation of water to the head of the system is currently provided by a generator. In 2006, alternative methods of power generation will be investigated. Based on the success of bioreactor treatment at the Leviathan Mine site, ARCO will continue to use this technology to treat ARD at the Aspen Seep. Application of the technology to other ARD-impacted sites does not require a pilot-scale system because the uncertainties related to carbon availability and sulfate reduction efficiency, matrix compaction, and solids flushing associated with compost and wood chip matrices are essentially eliminated. A simple bench test can be used to optimize the ethanol dose necessary to reduce sulfate, to optimize the base type and dose required to neutralize acidity, and to estimate the volume of precipitate that will be generated.

Sources of Further Information

The ITER for compost-free bioreactor treatment of ARD at Leviathan Mine is being prepared along with this Technology Capsule report. The ITER is anticipated to be available in the spring of 2006. The ITER provides more detailed information on the treatment technology, a detailed discussion of capital and operation and maintenance costs, and a more thorough discussion of the evaluation results.

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