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Compost-Free Bioreactor Treatment of Acid Rock Drainage Leviathan Mine, California

Innovative Technology Evaluation Report

**National Risk Management Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268**

Notice

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Foreword

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The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

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Sally C. Gutierrez, Director
National Risk Management Research Laboratory

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, and Atlantic Richfield Company (ARCO), the state of California, 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 continuous liquid carbon source 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 91 liters per minute (24 gallons per minute) 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, documented metals removal and reduction in acidity between the bioreactors, settling ponds, and aeration channel, and recorded operational information pertinent to the evaluation of the treatment system. The treatment system was evaluated independently, based on removal efficiencies for primary and secondary target metals, 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 4 of the 5 target metals in ARD flows at Leviathan Mine to below EPA interim discharge standards. During the demonstration, 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 treat ARD at the Aspen Seep. The state of California and ARCO are also evaluating the potential effectiveness, implementability, and costs for treatment of other ARD sources at the mine site.

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Acronyms, Abbreviations, and Symbols

$\mu\text{g/L}$	Microgram per liter
$\mu\text{mhos/cm}$	Micromhos per centimeter
$^{\circ}\text{C}$	Degree Celsius
ACQR	Air quality control region
AMD	Acid mine drainage
AQMD	Air quality management district
ARAR	Applicable or relevant and appropriate requirements
ARCO	Atlantic Richfield Company
ARD	Acid rock drainage
CAA	Clean Air Act
CERCLA	Comprehensive Emergency Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
cm	Centimeter
CUD	Channel under drain
CWA	Clean Water Act
DI	Deionized water
DO	Dissolved oxygen
DOT	Department of Transportation
EE/CA	Engineering evaluation cost analysis
EPA	U.S. Environmental Protection Agency
HDPE	High density polyethylene
HRT	Hydraulic residence time
ICP	Inductively coupled plasma
ITER	Innovative Technology Evaluation Report
kg	Kilogram
kg/day	Kilogram per day
kW	Kilowatt
L	Liter
L/min	Liter per minute
m^3	Cubic meter
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
MD	Matrix duplicate
mg/kg	Milligram per kilogram

Acronyms, Abbreviations, and Symbols (continued)

mg/L	Milligrams per liter
mL	Milliliter
ml/L	Milliliter per liter
ml/min	Milliliter per minute
MS	Matrix spike
mV	Millivolt
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NPDES	National Pollutant Discharge and Elimination System
NRMRL	National Risk Management Research Laboratory
O&M	Operation and maintenance
ORP	Oxidation reduction potential
OSHA	Occupational Safety and Health Administration
PARCC	Precision, accuracy, representativeness, completeness, and comparability
pH	Negative logarithm of the hydrogen ion concentration
POTW	Publicly-owned treatment works
PPE	Personal protection equipment
PQL	Practical quantitation limit
PUD	Pit under drain
QA/QC	Quality assurance/quality control
RCRA	Resource Conservation and Recovery Act
RPD	Relative percent difference
RWQCB	California Regional Water Quality Control Board – Lahontan Region
SARA	Superfund Amendment and Reauthorization Act
SCADA	Supervisory Control and Data Acquisition
SDG	Sample delivery group
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SPLP	Synthetic precipitation and leaching procedure
STLC	Soluble threshold limit concentration
TCLP	Toxicity characteristic leaching procedure
TDS	Total dissolved solids
TEP/QAPP	Technology Evaluation Plan/Quality Assurance Project Plan
Tetra Tech	Tetra Tech EM Inc.
TOM	Task order manager
TSD	Treatment, storage, and disposal
TSS	Total suspended solids
TTLC	Total threshold limit concentration
UNR	University of Nevada Reno
USACE	US Army Corp of Engineers
WET	Waste extraction test

Conversion Factors

	<i>To Convert From</i>	<i>To</i>	<i>Multiply By</i>
Length:	Centimeter	Inch	0.3937
	Meter	Foot	3.281
	Kilometer	Mile	0.6214
Area:	Square Meter	Square Foot	10.76
Volume:	Liter	Gallon	0.2642
	Cubic Meter	Cubic Foot	35.31
	Cubic Meter	Cubic Yard	1.308
Flow:	Liter per minute	Gallon per minute	0.2642
Mass:	Kilogram	Pound	2.2046
	Metric Ton	Short Ton	1.1025
Energy:	Kilowatt-hour	British Thermal Unit	3413
Power:	Kilowatt	Horsepower	1.34
Temperature:	°Celsius	(°Fahrenheit + 32)	1.8

Acknowledgements

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This project consisted of the demonstration of an innovative technology under the SITE program to evaluate the compost-free bioreactor treatment system developed by Drs. Glenn Miller and Tim Tsukamoto of the University of Nevada Reno. The technology demonstration was conducted on acid rock drainage at the Leviathan Mine Superfund site in Alpine County, California. The technology is currently being used as an interim action at the site, pending completion of a remedial investigation, feasibility study, and record of decision. This Innovative Technology Evaluation Report (ITER) interprets the data that were collected during the two-year demonstration period and discusses the potential applicability of the technology to other mine sites.

The cooperation of the following people during the technology demonstration and review of this report are gratefully acknowledged: Mr. Scott Jacobs and Ms. Diana Bless of NRMRL, Drs. Glenn Miller and Tim Tsukamoto of the University of Nevada Reno, Mr. Roy Thun and Mr. John Pantano of ARCO, and Mr. Chris Stetler and Mr. Doug Carey of the California Regional Water Quality Control Board-Lahontan Region.

SECTION 1 INTRODUCTION

This section provides background information about the Superfund Innovative Technology Evaluation (SITE) Program and the SITE demonstration that was conducted at a mine site in Alpine County, California, discusses the purpose of this Innovative Technology Evaluation Report (ITER), and briefly describes the technology that was evaluated. Key contacts are listed at the end of this section for inquiries regarding additional information about the SITE Program, the evaluated technology, and the demonstration site.

1.1 Project Background

The U.S. Environmental Protection Agency (EPA), the states, and the Federal Land Management Agencies all need better tools to manage acid rock drainage (ARD) at abandoned mine sites. Over a 21-month period during 2003 and 2005, EPA evaluated the use of compost-free bioreactors for removal of high concentrations of metals from ARD generated at Leviathan Mine, located northwest of Monitor Pass in northeastern Alpine County, California (Figure 1-1). The compost-free bioreactor treatment SITE demonstration was conducted by EPA under the SITE Program, which is administered by EPA's National Risk Management Research Laboratory (NRMRL), Office of Research and Development. The SITE demonstration was conducted by EPA in cooperation with EPA Region IX, the state of California, and Atlantic Richfield Company (ARCO).

The compost-free bioreactor treatment system in operation at Leviathan Mine is an improvement to current wood chip, compost, and manure based bioreactors in place at many facilities. The treatment system was installed by the University of Nevada Reno (UNR) and ARCO from fall 2002 through the spring 2003. The bioreactor treatment system was specifically designed by UNR to treat moderate flow rates of ARD containing hundreds of milligrams per liter (mg/L) of metals at a pH as low as 3.0. Without treatment, the ARD from the mine would otherwise be released to the environment. The SITE demonstration consisted of monthly sampling events of the bioreactor treatment system with

periods of extended inaccessibility due to winter snowfall. Throughout the SITE demonstration, EPA collected chemical data on the system's influent and effluent streams, documented metals removal and reduction in acidity within the system's unit operations, and recorded operational information pertinent to the evaluation of the treatment system. EPA evaluated the treatment system based on removal efficiencies for primary and secondary target metals, comparison of effluent concentrations to interim discharge standards (pre-risk assessment and record of decision) mandated by EPA in 2002 and on the characteristics of resulting metals-enriched solid wastes. Removal efficiencies of individual unit operations were also evaluated. A summary of the SITE demonstration and the results of the bioreactor treatment technology evaluation are presented in Sections 2 through 5 of this report.

1.2 The SITE Demonstration Program and Reports

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

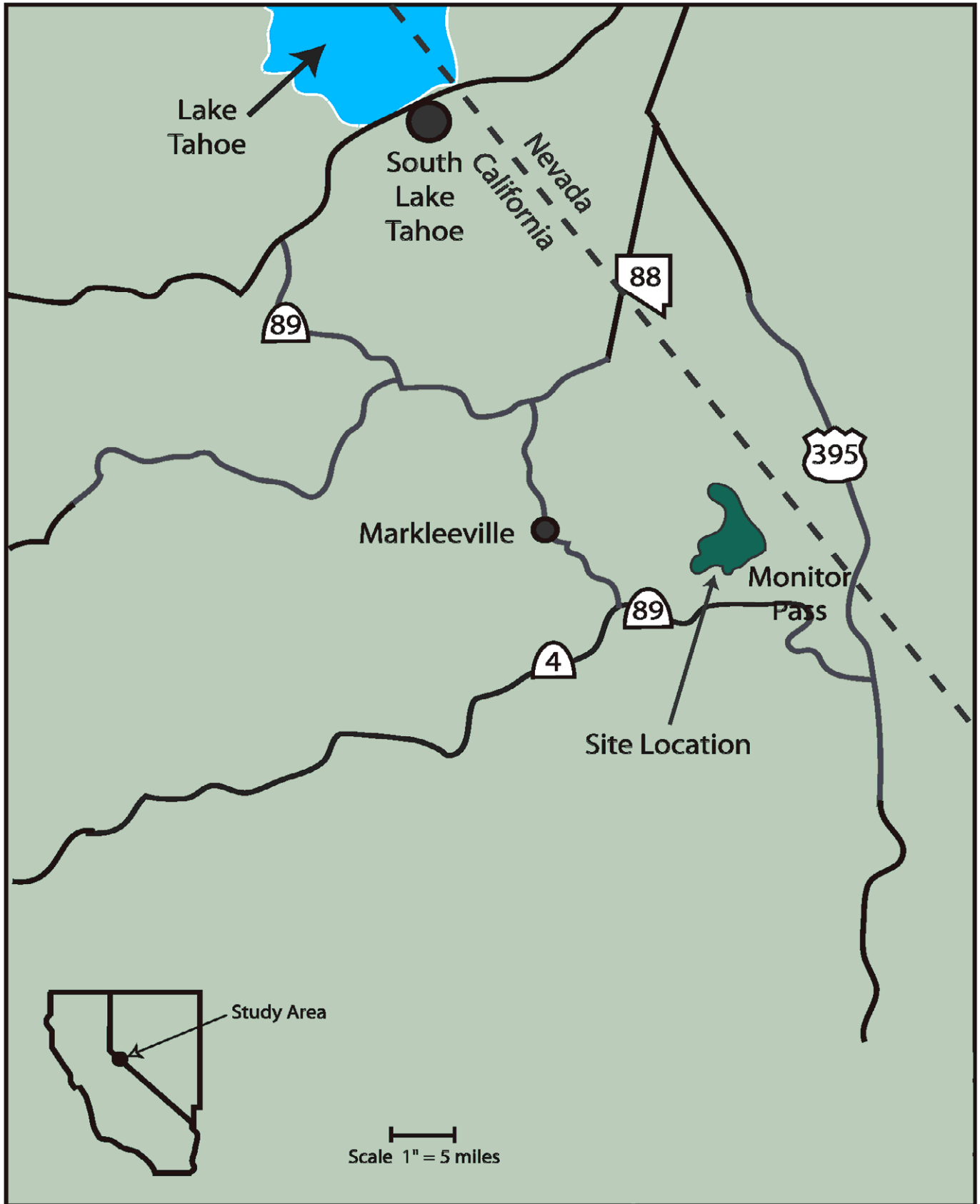


Figure 1-1. Site Location Map

accelerate the development, demonstration, and use of innovative technologies for site cleanups. The SITE Program's primary purpose is to maximize the use of alternatives in cleaning hazardous waste sites by encouraging the development and demonstration of new, innovative treatment and monitoring technologies. It consists of three major elements: the Demonstration Program, the Consortium for Site Characterization Technologies, and the Technology Transfer Program.

The objective of the Demonstration Program is to develop reliable performance and cost data on innovative technologies so that potential users can assess the technology's site-specific applicability. Technologies evaluated are either available commercially or are close to being available for full-scale remediation of Superfund sites. SITE demonstrations usually are conducted at hazardous waste sites under conditions that closely simulate full-scale remediation conditions, thus assuring the usefulness and reliability of the information collected. Data collected are used to assess: (1) the performance of the technology; (2) the potential need for pre- and post treatment of wastes; (3) potential operating problems; and (4) the approximate costs. The demonstration also provides opportunities to evaluate the long term risks and limitations of a technology.

At the conclusion of a SITE demonstration, EPA prepares a Demonstration Bulletin, Technology Capsule, and an ITER. These reports evaluate all available information on the technology and analyze its overall applicability to other potential sites characteristics, waste types, and waste matrices. Testing procedures, performance and cost data, and quality assurance and quality standards are also presented. The Technology Bulletin consists of a one to two page summary of the SITE demonstration and is prepared as a mailer for public notice. The Technology Bulletin provides a general overview of the technology demonstrated, results of the demonstration, and telephone numbers and e-mail address for the EPA project manager in charge of the SITE evaluation. In addition, references to other related documents and reports are provided. The Technology Capsule consists of a more in-depth summary of the SITE demonstration and is usually about 10 pages in length. The Technology Capsule presents information and summary data on various aspects of the technology including applicability, site requirements, performance, process residuals, limitations, and current status of the technology. The Technology Capsule is 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 the technology's applicability for cleaning Superfund sites. The final SITE document produced is the ITER. The ITER consists of an in-depth evaluation of the SITE demonstration including details on field activities and operations, performance data and statistical evaluations, economic analysis, applicability, and effectiveness, as discussed in the following section.

1.3 Purpose of the Innovative Technology Evaluation Report

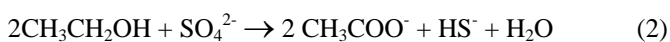
The ITER is designed to aid decision-makers in evaluating specific technologies for further consideration as applicable options in a particular cleanup operation. The ITER should include a comprehensive description of the SITE demonstration and its results, and is intended for use by EPA remedial project managers, EPA on-scene coordinators, contractors, and other decision-makers carrying out specific remedial actions.

To encourage the general use of demonstrated technologies, EPA provides information regarding the applicability of each technology to specific sites and wastes. The ITER includes information on cost and desirable site-specific characteristics. It also discusses advantages, disadvantages, and limitations of the technology. However, each SITE demonstration evaluates the performance of a technology in treating a specific waste matrix at a specific site. The characteristics of other wastes and other sites may differ from the characteristics at the demonstration site. Therefore, a successful field demonstration of a technology at one site does not necessarily ensure that it will be applicable at other sites. Data from the field demonstration may require extrapolation for estimating the operating ranges in which the technology will perform satisfactorily. Only limited conclusions can be drawn from a single field demonstration.

This ITER provides information on new approaches to the use of a compost-free bioreactor treatment system to reduce the concentration of toxic metals and acidity in ARD at Leviathan Mine, and is a critical step in the development and commercialization of compost-free bioreactor treatment systems for use at other applicable mine sites.

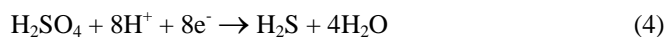
1.4 Technology Description

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.



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.

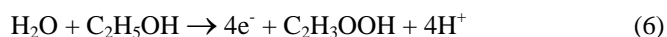
The reduction of sulfate to sulfide requires 8 electrons:



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



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



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 heart of the treatment system is the two compost-free, sulfate-reducing bioreactors. A blanket of manure was added to the base of each bioreactor to support the startup of each bioreactor. The bioreactors are lined ponds filled with river rock (Figures 1-2 and 1-3). 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 influent distribution loops and three effluent collection loops 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 1-2 and 1-3).

The system was designed to treat ARD by gravity flow through successive sulfate-reducing bioreactors and precipitation of metal sulfides in a continuous flow settling pond (Figure 1-2). During the demonstration, an alternative mode of operation (recirculation) was also evaluated, which involved the direct contact of influent ARD with sulfide rich water from the bioreactors and precipitation of 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 1-3).

Compost-Free Bioreactor Operation: Operated in gravity flow mode (Figure 1-2), influent ARD passes through a flow control weir at flow rates ranging from 25 to 47 liters per minute (L/min), where sodium hydroxide is added to adjust the pH to approximately 4 to maintain a favorable environment for sulfate-reducing bacteria and ethanol is added to provide a carbon source for reducing equivalents for the sulfate-reducing bacteria. Precipitates that are formed at this state are settled out in the pretreatment pond. ARD flows through Bioreactor No.1 and Bioreactor No.2 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 for extended settling of metal sulfide precipitates. Sodium hydroxide is added to the bioreactor effluent to consume mineral acidity and convert bisulfide to sulfide, which is necessary to precipitate iron as iron sulfide in the settling pond.

Operated in recirculation mode (Figure 1-3), metal-rich ARD 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 sodium hydroxide and sulfide rich water from bioreactor No.2, and is then discharged to the settling pond. The combination of a neutral pH condition and high sulfide concentration promotes rapid generation and precipitation of metal sulfides in the settling pond rather than in the two bioreactors. Precipitation of metal sulfides downstream of the two bioreactors greatly reduces precipitation 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 bioreactor No.1 at flow rates ranging from 114 to 227 L/min (influent to recirculation ratio of 1:2 to 1:6). Ethanol is added to the influent vault at 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 addition 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 flows through a rock lined aeration channel to promote gas exchange prior to effluent discharge. Metal sulfide 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 for extended settling. Metal sulfide precipitates are periodically pumped out of the settling and flushing ponds and dewatered using bag filters. Metals in bag filter solids did not exceed Federal or state of California standards for characterization as a hazardous waste.

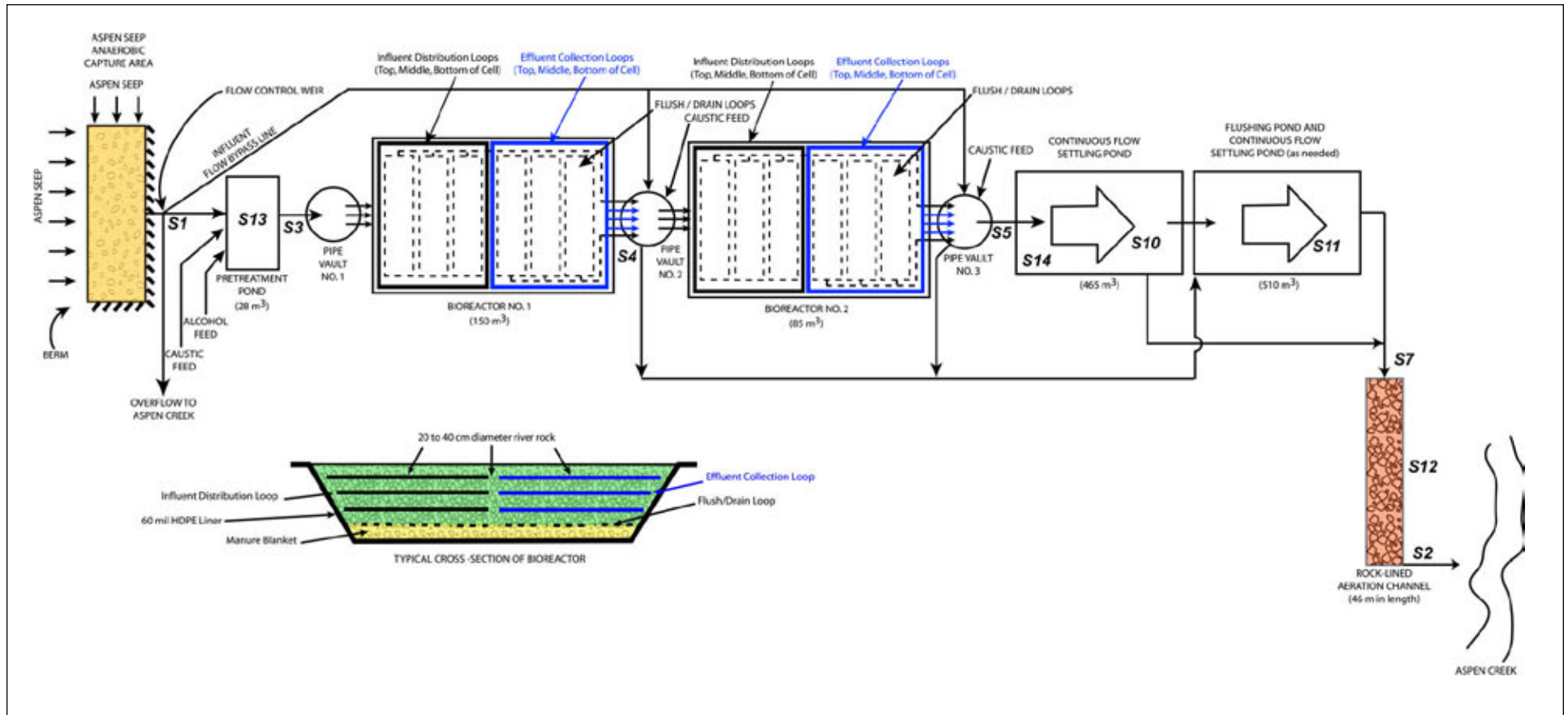


Figure 1-2. Bioreactor Treatment System, Gravity Flow Configuration Schematic

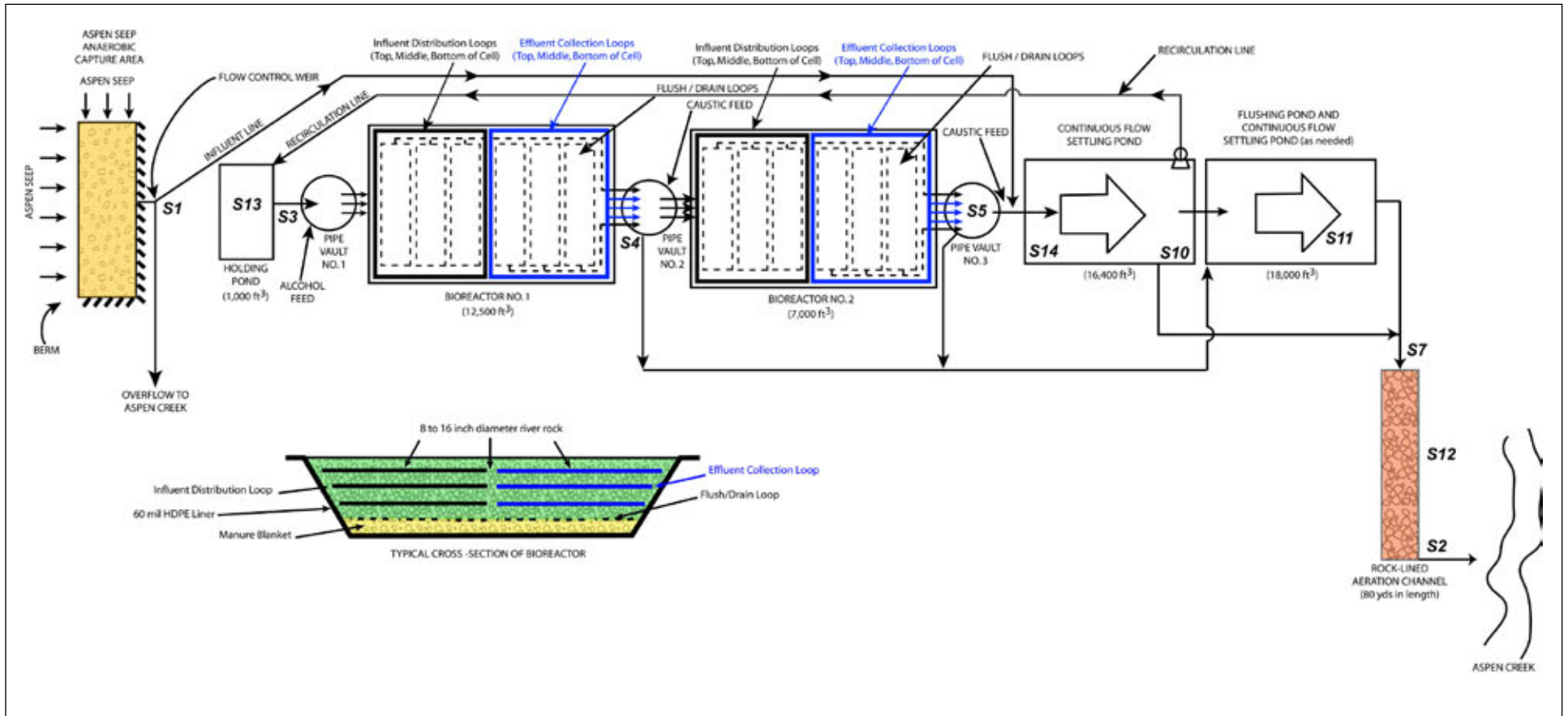


Figure 1-3. Bioreactor Treatment System, Recirculation Configuration Schematic

1.5 Key Findings

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. The bioreactor treatment system operated in gravity flow mode from November 2003 through mid-May 2004 treating 9.24 million liters (2.44 million gallons) of ARD using 9,236 liters (L) of sodium hydroxide and 4,466 L of ethanol. The bioreactor treatment system operated in the recirculation mode from mid-May 2004 through July 2005 treating 22.1 million liters (5.81 million gallons) of ARD using 22,029 L of sodium hydroxide and 10,617 L of ethanol.

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 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 exceeded 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. For the gravity flow mode of treatment system operation, the average removal efficiency for the primary target metals was 94 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 (p-value exceeded 0.05). In addition, the concentration of arsenic in system influent was well below discharge standards.

Average removal efficiencies for secondary target metals ranged from 41 to 99 percent in both modes of operation; however, removal efficiencies were not calculated for arsenic, cadmium, chromium, lead, and selenium as the influent and effluent concentrations were not statistically different (p-value exceeded 0.05). In the case of arsenic, cadmium, chromium, lead, and selenium 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 resulting in lower removal efficiencies. Removal efficiencies for sulfate ranged from 8 to 35 percent with an average reduction in sulfate of 17 percent. There was on average a 9 percent increase in sulfate removal during

recirculation operations when compared to gravity flow operations.

Tables 1-1 and 1-2 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 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 daily composite samples) was exceeded; and an “N” indicates that neither discharge standard was exceeded.

The bioreactor treatment system produced a relatively small quantity of metal sulfide sludge. During operation from November 2003 through July 2005, the bioreactor generated about 14.2 dry tons (12,900 kilograms [kg]) of sludge consisting mainly of iron sulfide. This equals about 1.7 dry tons (1,550 kg) of sludge per million gallons (0.45 dry ton [410 kg] per million liters) of ARD treated. The solid waste residuals produced by the treatment system were analyzed for potential hazardous waste characteristics. Total and leachable metals analyses were performed on the solid wastes for comparison to California and federal hazardous waste classification criteria. The characteristics of the solid waste stream are presented in Table 1-3. None of the solid wastes were found to be hazardous or a threat to water quality; however, the solids were disposed of off site pending designation of an on-site disposal area.

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 (extreme cold and winter snow pack), maintenance problems (recirculation pump failures and reagent delivery), and the remoteness of the site (power supply, maintaining adequate supplies of consumables and replacement equipment). 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 were generally met as the flow of ARD entering the bioreactor treatment system also decreased during the winter.

1.6 Key Contacts

Additional information on this technology, the SITE Program, and the evaluation site can be obtained from the following sources:

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Table 1-1. 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 ⁽¹⁾ (%)	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	4.73	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	35.9	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	7.83	6.6	N	NC	NC
Lead	6	3.64	2.5	4.69	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
(1) Average removal efficiency calculated using the average influent and average effluent concentration data. NC = Not calculated as influent and effluent concentrations were not statistically different µg/L = Microgram per liter								

Table 1-2. 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 ⁽¹⁾ (%)	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	7.43	6.5	6.51	4.9	N	NC	NC
Copper	7	795	187	4.59	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	6.38	5.2	N	42.5	21.2 to 84.8
Lead	7	4.17	2.3	2.45	1.6	N	41.3	22.0 to 57.1
Selenium	7	11.5	5.1	8.49	3.6	Y	NC	NC
Zinc	7	776	51.7	8.91	7.4	N	98.9	97.7 to 99.8
(1) Average removal efficiency calculated using the average influent and average effluent concentration data. NC = Not calculated as influent and effluent concentrations were not statistically different µg/L = Microgram per liter								

Table 1-3. Determination of Hazardous Waste Characteristics for Bioreactor Solid Waste Streams

Treatment System	Solid Waste Stream	Total Solid Waste Generated	TTLC	STLC	TCLP	Waste Handling Status
			Pass or Fail	Pass or Fail	Pass or Fail	
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			1 dry ton = 907 kilograms			

SECTION 2 TECHNOLOGY EFFECTIVENESS

The following sections discuss the effectiveness of the compost-free bioreactor treatment technology demonstrated at the Leviathan Mine site. The discussion includes a background summary of the site, description of the technology process and the evaluation approach, a summary of field activities, and results of the evaluation.

2.1 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. Intermittent mining of copper sulfate, copper, and sulfur minerals since the mid-1860s resulted in extensive acid mine drainage (AMD) and ARD 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), which liberates toxic metals from the mine wastes creating AMD and ARD. AMD and ARD at Leviathan Mine contain high concentrations of toxic metals and historically flowed directly to Leviathan Creek without capture or treatment.

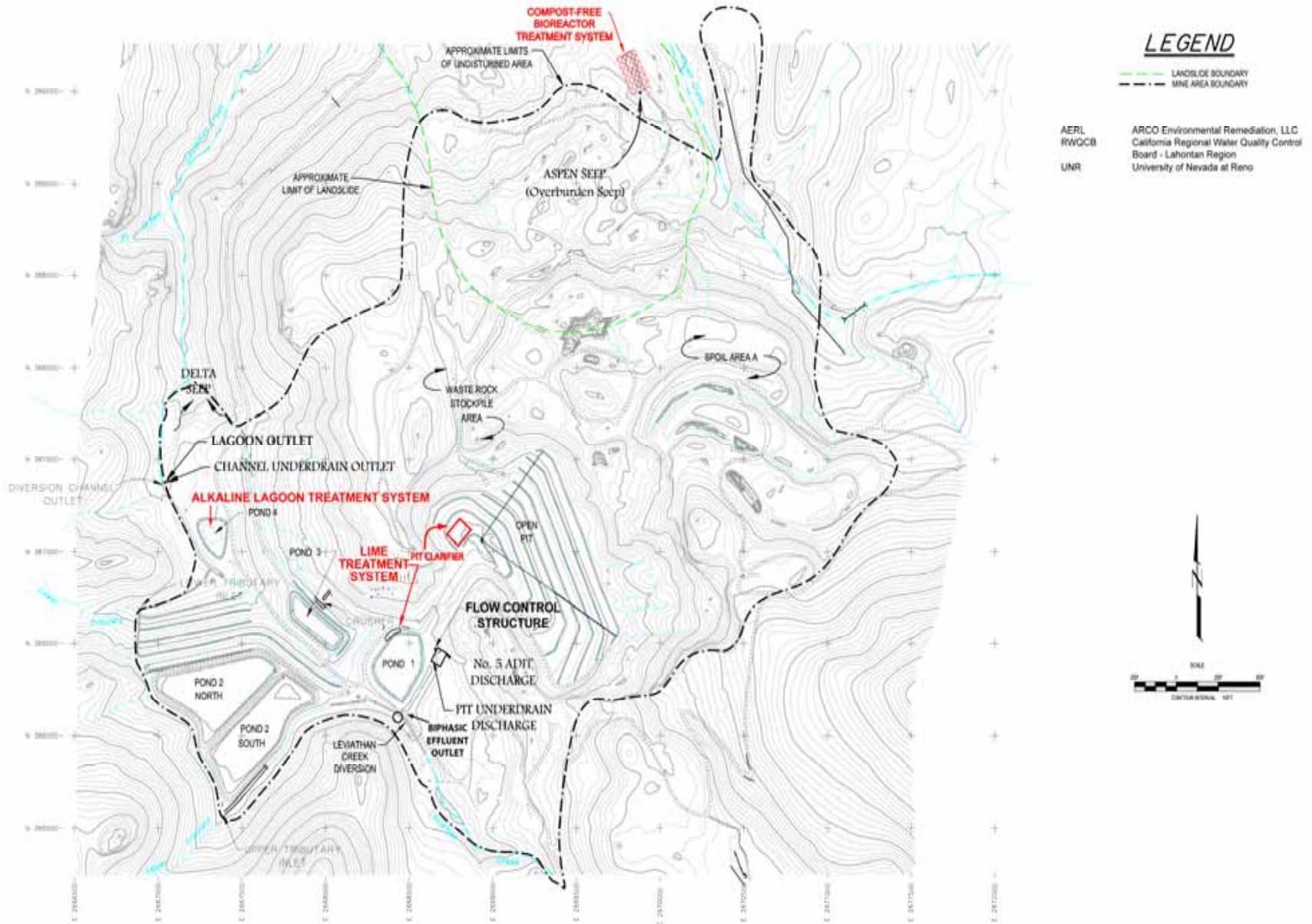
2.1.1 Site Description

The Leviathan Mine property occupies approximately 102 hectares in the Leviathan Creek basin, which is located on the northwestern flank of Leviathan Peak at an elevation ranging from 2,134 to 2,378 meters (7,000 to 7,800 feet) above mean sea level. Access to the mine site is provided by unpaved roads (United States Forest Service Road 52) from State Highway 89 on the southeast and from US Highway 395 south of Gardnerville, Nevada, on the northeast. Of the total property, approximately 1 million square meters (247 acres) are disturbed by mine-related activities. With the exception of approximately 85 thousand square meters on Forest Service lands, mine-related workings are located on property owned

by the State of California. Figure 2-1 presents a map showing the layout of the Leviathan Mine site.

The mine site lies within the Bryant Creek watershed and is drained by Leviathan and Aspen creeks, which combine with Mountaineer Creek 3.5 kilometers below the mine to form Bryant Creek, a tributary to the East Fork of the Carson River. The terrain in the Leviathan Creek basin includes rugged mountains and high meadowlands. The area has a climate typical of the eastern slope of the Sierra Nevada range characterized by warm dry summers with the bulk of the precipitation occurring as winter snow. Vegetation at the site is representative of the high Sierra Nevada floristic province, with scattered stands of mixed conifers or Jeffery pine on north-facing slopes. Aspen groves border parts of Leviathan and Aspen creeks, while shrub communities dominate flats and south facing slopes.

Precipitation in the area around Leviathan Mine varies with elevation and distance from the crest of the Sierra Nevada mountain range. The heaviest precipitation is from November through April. Annual precipitation on western slopes of the Sierra Nevada averages about 140 centimeters (cm), varying from a low of about 51 cm to highs estimated in the range of 165 to 178 cm in some of the more remote mountain areas near the easterly boundary of Leviathan Creek basin. There is little precipitation data for the mine site; therefore, a mean annual precipitation was estimated at 70.6 cm per year using local weather monitoring stations provided by the U.S. Geological Survey (EMC² 2004a). A large percentage of the precipitation which falls during the winter months occurs as snow. Snow pack accumulates from about November through March, with the maximum accumulation generally occurring about April 1. The average April 1 snow line is below an elevation of 1,525 meters. The snow pack generally begins to melt during March, but the period of major snowmelt activity is typically April through July. Winter snow pack is the source of about 50 percent of annual runoff.



SOURCE: AERL Early Response Action Work Plan

Figure 2-1. Site Layout

2.1.2 History of Contaminant Release

Prior to 1984, the various sources of AMD and ARD discharging from the Leviathan Mine site included AMD from the floor of the mine pit flowing west into Leviathan Creek; AMD from Adit No. 5, located below the mine pit, flowing west into Leviathan Creek; ARD from the Delta Area (also known as Delta Seep), located adjacent to Leviathan Creek along the western edge of the mine area, flowing northwest into Leviathan Creek; and ARD from Aspen Seep, located along the northern portion of the site within the overburden piles, flowing north into Aspen Creek. Historically, the concentrations of five primary target metals, aluminum, arsenic, copper, iron, and nickel in the AMD and ARD released to Leviathan and Aspen creeks have exceeded EPA interim (pre-risk assessment and record of decision) discharge standards up to 3,000 fold. Historical concentrations for each source of AMD and ARD are presented in Table 2-1.

When AMD was inadvertently released in large quantities from the Leviathan Mine site in the 1950s, elevated concentrations of toxic metals resulted in fish and insect kills in Leviathan Creek, Bryant Creek, and the east fork of the Carson River. The absence of trout among the fish killed in Bryant Creek and in the east fork of the Carson River immediately downstream from Bryant Creek indicated that continuous discharges from mining operations had eliminated the more sensitive trout fisheries that existed prior to open-pit operations. Various efforts were made between 1954 and 1975 to characterize the impacts of Leviathan Mine on water quality at and below the site during and after open-pit mining operations (California Regional Water Quality Control Board – Lahontan Region [RWQCB] 1995).

2.1.3 Previous Actions

The Leviathan Mine Pollution Abatement Project was initiated by the state of California in 1979 with the preparation of a feasibility study. In 1982, the State contracted the design of the Pollution Abatement Program, which was then implemented in 1984 with physical actions that significantly reduced the quantity of toxic metals discharging from the mine site. Work conducted at the site included regrading overburden piles to prevent impounding and infiltration of precipitation and promote surface runoff; partially filling and grading the open pit; constructing a surface water collection system within the reworked mine pit to redirect uncontaminated surface water to Leviathan Creek; constructing a pit under drain (PUD) system beneath the pit (prior to filling and grading) to collect and divert surface water seeping into the pit floor; construction of five storage/evaporation ponds to collect discharge from the PUD and Adit No. 5; and rerouting Leviathan Creek by way of a concrete diversion channel to minimize contact of creek water with waste rock piles. During pond construction, previously unrecognized springs were encountered. To capture the

subsurface flow from these springs, a channel under drain (CUD) was constructed beneath Leviathan Creek (RWQCB 1995). Discharges of ARD to Aspen Creek were not addressed as a part of the project. Figure 2-1 presents a detailed site map of the mine site as it exists in 2004, after implementation physical work conducted at the mine site.

Starting in 1996, pilot studies were conducted by UNR in coordination with the state of California to precipitate metals in ARD discharging from Aspen Seep using sulfate-reducing bacteria. The pilot studies evaluated wood chip and rock substrates, base addition, and a solids collection and removal strategies. The information developed during the pilot studies resulted in the design and construction of a full-scale compost-free bioreactor treatment system in the fall of 2002 through the summer of 2003.

Starting in 1997, EPA initiated enforcement actions at the Leviathan Mine site to further mitigate potential releases of AMD and ARD from the various sources. In response to EPA's 1997 action memorandum, the state of California implemented the active lime treatment system in 1999 to treat AMD that collects in the retention ponds. Since the installation of the active lime treatment system in 1999, no releases of AMD have occurred from the retention ponds to Leviathan Creek. In response to EPA's July 21, 2001, action memorandum, ARCO implemented a semi-passive alkaline lagoon treatment system to treat ARD from the CUD. Figure 2-1 presents a detailed site map of the mine site after construction of the lime and bioreactor treatment systems.

In 2002, EPA prepared an additional action memorandum setting interim discharge standards for the five primary target metals and five secondary water quality indicator metals for discharge of treated water from the treatment systems to Leviathan Creek (EPA 2002). Discharge standards for the five primary metals of concern are presented in Table 2-1. The maximum daily standard equals the highest concentration of a target metal to which aquatic life can be exposed for a short period of time without deleterious effects. The four-day average standard equals the highest concentration of a target metal to which aquatic life can be exposed for an extended period of time (4 days) without deleterious effects.

2.2 Process Description

The bioreactor treatment system evaluated at Leviathan Mine was set up to treat ARD captured from Aspen Seep at the mine site. The treatment system consists of one 7,600 L ethanol and three 3,800 L sodium hydroxide feed stock tanks, 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 a continuous flow settling pond (Figure 1-2). System design flow is 114 L/min. During the demonstration, an alternative mode of

Table 2-1. Summary of Historical Metals of Concern

Analyte	Number of Samples	Detection Percentage	Minimum Concentration (mg/L)	Maximum Concentration (mg/L)	Mean (mg/L)	Standard Deviation (mg/L)	Discharge Standards	
							Maximum (a) (mg/L)	Average (b) (mg/L)
Aspen Seep								
Aluminum	34	100	0.073	65	51	14.2	4.0	2.0
Arsenic	34	97.1	0	0.1	0.03	0.03	0.34	0.15
Copper	21	95.2	0	1.8	1.3	0.55	0.026	0.016
Iron	34	100	0.11	580	124	113	2.0	1.0
Nickel	34	97.1	0	0.75	0.55	0.18	0.84	0.094
Adit No. 5								
Aluminum	46	100	220	430	310	63.6	4.0	2.0
Arsenic	45	100	8.6	28	16.2	5.5	0.34	0.15
Copper	28	100	0.88	4.2	1.5	0.97	0.026	0.016
Iron	45	100	120	2,400	815	369	2.0	1.0
Nickel	46	100	4.4	10	6.1	1.6	0.84	0.094
Combination of Ponds 1, 2 North, and 2 South								
Aluminum	29	100	3	4,900	1,199	1,036	4.0	2.0
Arsenic	27	100	0.192	92	27.1	19.9	0.34	0.15
Copper	9	100	2.4	35	8.1	10.2	0.026	0.016
Iron	32	100	4	6,600	1,734	1,450	2.0	1.0
Nickel	27	100	1.2	61	17.5	12	0.84	0.094
Channel Under Drain								
Aluminum	60	100	29	68	48	10.6	4.0	2.0
Arsenic	61	100	0.091	0.80	0.45	0.19	0.34	0.15
Copper	37	97.3	0	0.13	0.026	0.035	0.026	0.016
Iron	61	100	270	460	367	59.2	2.0	1.0
Nickel	61	100	0.21	3.4	1.95	0.79	0.84	0.094
Delta Seep								
Aluminum	18	100	0.89	4.7	1.68	0.88	4.0	2.0
Arsenic	19	84.2	0.052	0.094	0.067	0.012	0.34	0.15
Copper	17	35.3	0.0018	0.14	0.032	0.054	0.026	0.016
Iron	19	100	18.0	33.0	21.5	3.9	2.0	1.0
Nickel	18	100	0.41	0.563	0.49	0.05	0.84	0.094
(a) Based on a daily composite of three grab samples (b) Based on the average of four daily composite samples mg/L = Milligram per liter								

operation (recirculation) was also evaluated, which involved the direct contact of ARD with sulfide rich water from the bioreactors and precipitation of metal sulfides in the settling pond. A portion of the settling pond supernatant containing excess sulfate is then pumped to the head of the bioreactor system to generate additional sulfides (Figure 1-3).

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 20 to 40 cm river rock. River rock was selected because of the ease at which precipitates can be flushed through the matrix and the stability of the matrix. A blanket of manure was

added to the base of each bioreactor to support the startup of each bioreactor. Each bioreactor consists of three 10 cm diameter influent distribution lines and three 10 cm 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 1-2 and 1-3).

Influent to the treatment system consists of ARD discharged from Aspen Seep. In gravity flow mode (Figure 1-2), influent

ARD from Aspen Seep passes through a flow control weir at flow rates ranging from 25 to 91 L/min, 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 (28 m³ [cubic meter], 4 hour hydraulic residence time [HRT] at 114 L/min) 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 (354 m³ total volume, 150 m³ active volume) and Bioreactor No.2 (200 m³ total volume, 85 m³ active volume) to reduce sulfate to sulfide. The HRT for the two bioreactors are 22 hours for Bioreactor No.1 and 13 hours for Bioreactor No.2 at a design flow rate of 114 L/min. 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 (465 m³ volume, 68 hour HRT at 114 L/min) 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 reduce acidity, raise the pH to 7, and enhance metal sulfide precipitation.

Operated in recirculation mode (Figure 1-3), 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 the sulfide-rich water from bioreactor No.2 followed by 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 bacteria in the two bioreactors. A portion of the pond supernatant containing excess sulfate is then pumped to a holding pond at flow rates ranging from 114 to 227 L/min. Ethanol (0.5 ml/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 (Tsukamoto 2005a). 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.

During both modes of operation, the effluent from the continuous flow settling pond then flows through a rock lined aeration channel (46 meter long by 0.6 meter wide) to promote gas exchange 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 (510 m³ volume, 75 hour HRT at 114 L/min) 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 3 meter by 4.6 meter 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 flushing pond. Metals in bag filter solids did not exceed Federal or state of California standards for characterization as a hazardous waste. The total system HRT is 107 hours at maximum design flow of 114 L/min, and 352 hours at an average flow rate of 37.9 L/min during the demonstration.

2.3 Evaluation Approach

Evaluation of the bioreactor treatment technology occurred between November 2003 and July 2005 on a year round basis. During the evaluation period, multiple sampling events of the treatment system were conducted in accordance with the 2003 Technology Evaluation Plan/Quality Assurance Project Plan (TEP/QAPP) (Tetra Tech EM Inc [Tetra Tech] 2003). During each sampling event, EPA collected chemical data from the systems' influent and effluent streams, documented metals removal and reduction in acidity within the systems' unit operations, and recorded operational information pertinent to the evaluation of the treatment system. The treatment system was evaluated based on removal efficiencies for primary and secondary target metals, comparison of effluent concentrations to EPA interim 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 following sections describe in more detail the project objectives and sampling program.

2.3.1 Project Objectives

As discussed in the TEP/QAPP (Tetra Tech 2003), two primary objectives identified for the SITE demonstration were considered critical to the success of the bioreactor treatment technology evaluation. Seven secondary objectives were identified to provide additional information that is useful, but not critical to the technology evaluation. The primary objectives of the technology evaluations were to:

- Determine the removal efficiencies for primary target metals over the evaluation period
- Determine if the concentrations of the primary target metals in the treated effluent are below the interim (pre-risk assessment and record of decision) discharge standards mandated in 2002 Action Memorandum for Early Actions at Leviathan Mine (EPA 2002)

The following secondary objectives also were identified:

- Document operating parameters and assess critical operating conditions necessary to optimize system performance
- Monitor the general chemical characteristics of the ARD water as it passes through the treatment system
- Evaluate operational performance and efficiency of solids separation systems
- Document solids transfer, dewatering, and disposal operations
- Determine capital and operation and maintenance (O&M) costs
- Document winter operating procedures and effectiveness
- Determine the volume and type of metal precipitate generated in the bioreactors and the optimal frequency and duration of bioreactor flushing

2.3.2 Sampling Program

Over the duration of the demonstration, EPA collected pretreatment, process, and post-treatment water samples from the treatment system. These samples were used to evaluate the primary and secondary objectives, as identified in the TEP/QAPP (Tetra Tech 2003). Sludge samples also were collected to document the physical and chemical characteristics of the sludge and to estimate the volume and rate of sludge generation. Summary tables documenting the water and sludge samples collected and the analyses performed for each mode of treatment system operation are presented in Appendix A. In addition to chemical analyses performed on the samples collected, observations were recorded on many aspects of the operations of each treatment system. The sampling program is summarized below by objective.

Primary Objective 1: Determine the removal efficiency for each metal of concern over the demonstration period.

To achieve this objective, influent and effluent samples from the treatment system were collected from strategic locations within the treatment system. The samples were filtered, preserved, and then analyzed for primary target metals: aluminum, arsenic, copper, iron, and nickel and secondary

water quality indicator metals: cadmium, chromium, lead, selenium, and zinc. From the influent and effluent data collected, overall average removal efficiencies were calculated for each target metal over the period of the demonstration. The results of the removal efficiency calculations are summarized in Section 2.5.1.

Primary Objective 2: Determine if the concentration of each target metal in the treated effluent is below the EPA interim discharge standard.

Results from effluent samples collected to meet Primary Objective 1 were used to meet this objective. The sampling schedule was designed so that a composite of three grab samples were collected on each sampling day. Results from daily composite samples were compared against EPA's daily maximum discharge standards (EPA 2002). In addition, 4-day running averages were calculated for each target metal for comparison against EPA's four-day average discharge standards. To determine if the discharge standards were met, the effluent data were compared directly to the applicable standards as specified in Table 2-1. In addition, a statistical analysis was performed to determine whether or not statistically the results were below the discharge standards. The results of the comparison of effluent data to discharge standards are summarized in Section 2.5.2.

Secondary Objective 1: Document operating parameters and assess critical operating conditions necessary to optimize system performance.

To achieve this objective, system flow and recirculation rate data, ethanol and sodium hydroxide dosing data, and HRT data were recorded by the system operator and the SITE demonstration sampling team. The performance of individual unit operations was assessed by determining the reduction in target metal concentrations along the treatment system flow path. A description of system operating parameters and discussion of metals reduction within individual unit operations are presented in Section 2.5.3.

Secondary Objective 2: Monitor the general chemical characteristics of the ARD water as it passes through the treatment system.

To achieve this objective, the influent and effluent samples collected to meet Primary Objectives 1 and 2 were analyzed for total iron, sulfate, total suspended solids (TSS), total dissolved solids (TDS), and total and bicarbonate alkalinity. Field measurements were also collected for ferrous iron, sulfide, pH, dissolved oxygen (DO), temperature, oxidation-reduction potential (ORP), and conductivity. Organic analysis for residual ethanol or metabolites was not conducted as a part of the sampling program. A discussion of these data and associated reaction chemistry are presented in Section 2.5.3.

Secondary Objective 3: Evaluate operational performance and efficiency of solids separation systems.

To achieve this objective, influent and effluent samples were collected from the bioreactors and settling ponds and were analyzed for

filtered and unfiltered metals, TSS, and TDS to assess target metal removal efficiencies, solids removal rates and efficiencies, HRT, and residual levels of solids in the effluent streams. The results of this evaluation are presented in Section 2.5.3.

Secondary Objective 4: Document solids transfer, dewatering, and disposal operations. To achieve this objective, the system operator maintained a log of the volume and rate of solids transferred from the settling ponds for dewatering and disposal. Solids samples were collected after dewatering and analyzed for residual moisture content and total and leachable metals to determine waste characteristics necessary for waste classification prior to disposal. Leachable metals were evaluated using the California Waste Extraction Test (WET) (State of California 2004), the Method 1311: Toxicity Characteristic Leaching Procedure (TCLP) (EPA 1997), and Method 1312: Synthetic Precipitation and Leaching Procedure (SPLP) (EPA 1997). An evaluation of solids handling is presented in Section 2.5.4.

Secondary Objective 6: Document winter operating procedures and effectiveness. To achieve this objective, winter O&M activities were documented by the system operator. The system operator logged changes to system configuration; changes in influent flow and chemical dosing rates; changes in activity of sulfate-reducing bacteria; changes in solids settling efficiencies; operational problems and system down time; frequency of site visits and access difficulties; and consumables and equipment change out. Samples were also collected as specified in secondary objective No. 1, 2, 3, and 4 to document the effect of winter conditions on the anaerobic wetland treatment system. The results of this evaluation are presented in Section 2.5.3.

Secondary Objective SAW1: Determine the volume and type of metal precipitate generated in the bioreactors and the optimal frequency and duration of bioreactor flushing. To achieve this objective, the system operator documented the volume of metal precipitate flushed from each bioreactor and the overall rate and volume of metal precipitate accumulation in the flushing pond. Solids samples were collected from the flushing pond and analyzed for total metals to determine the type of metal precipitates formed. An evaluation of solids handling is presented in Sections 2.5.3 and 2.5.4.

2.4 Field Evaluation Activities

The following sections discuss activities required to conduct a technical evaluation of each mode of the bioreactor treatment system operation at the Leviathan Mine site. The discussion includes a summary of mobilization activities, O&M activities, process modifications, evaluation monitoring activities, demobilization activities, and lessons learned.

2.4.1 Mobilization Activities

The bioreactor treatment system was constructed between the fall of 2002 and the summer of 2003 and required startup and acclimation prior to technology evaluation activities. Mobilization activities described below were based on weekly oversight visits under a separate contract and on information provided by UNR. Mobilization activities after initial system construction, including bioreactor acclimation, typically require a two to three month period and include the following:

- Delivery, positioning, and assembly of reagent storage tanks, reagent day tanks, reagent delivery pumps, reagent metering devices, and distribution lines
- Reagent delivery and storage
- Installation of solar panel and storage battery, layout of power lines for reagent delivery pumps (gravity flow operations)
- Initial filling of the bioreactors and one settling pond
- Monitoring of system influent, whole bioreactor influent and effluent, individual bioreactor effluent loops, and settling pond effluent for biological activity, sulfide generation, metals removal
- Adjustment of ethanol and sodium hydroxide dosage along with gradual increase in influent flow as biological activity increases
- Pipe and pump lay out and assembly for recirculation operations (recirculation flow operations)
- Fuel storage tank and secondary containment system delivery, setup, and fuel delivery (recirculation flow operations)
- Generator delivery and setup, layout of power lines for recirculation pumps (recirculation flow operations)

2.4.2 Operation and Maintenance Activities

The following section discusses O&M activities documented during the evaluation of each mode of bioreactor treatment operation. The discussion includes a summary of system operational dates, treatment and discharge rates, problems encountered, quantity of waste treated, reagents consumed, process waste generated, and percentage of time the system was operational.

The bioreactor treatment system was operated in gravity flow mode from November 2003 through mid-May 2004, and in recirculation mode from mid-May 2004 through July 2005. A description of system O&M activities for each mode of operation is presented below.

Gravity Flow Operations. Bioreactor No.1 began receiving ARD during the first week on March 2003. On April 21, 2003 12 L/min of neutralized ARD (pH 8) and 700 mg/L ethanol was diverted into Bioreactor No.1 to begin the acclimation process. On May 30, 2003, the flow of neutralized ARD (pH 6 to 7) was reduced to 4 to 6 L/min. On June 24, 2003 effluent from Bioreactor No.1 was allowed to discharge to and begin acclimation of Bioreactor No.2. Between August 12 and October 22, 2003 influent ARD flow was slowly increased until the entire flow of Aspen Seep was being treated. Acclimation of the bioreactors was completed on November 12, 2003 at which point discharge from the treatment system was initiated. Following acclimation, treatment system discharge rates ranged from 25 to 47 L/min.

On November 13, 2003, the sodium hydroxide supply was consumed and base addition at the influent weir was suspended for one day pending delivery of sodium hydroxide. Influent pH to the bioreactor was not adjusted; however, given the long bioreactor HRT no impact was observed.

From November 25 through December 8, 2003, sodium hydroxide addition to system ARD influent was deliberately stopped to determine whether the bioreactors could treat the ARD without an initial pH adjustment. Starting on December 8, 2003 sodium hydroxide was added to the effluent from Bioreactor No.2 to raise the pH to near neutral in order to promote the precipitation of iron sulfide in the settling pond.

During the week of December 22, 2003 the solar system controller failure leading to a lack of base addition for up to three days. The cessation of sodium hydroxide addition reduced the pH in the pretreatment pond and Bioreactor No.1.

Treatment of ARD from Aspen Seep under gravity flow conditions was completed on May 11, 2004. During gravity flow operations from November 12, 2003 through May 11, 2004, the system treated 9.24 million liters of ARD using 9,235 L of 25 percent sodium hydroxide (average dosage of 317 mg/L) and 4,466 L of ethanol (average dosage of 381 mg/L) and generated about 4.2 dry tons (3,800 kg) of non-hazardous solids. The system was operational approximately 98 percent of the time during gravity flow operations. The system operated 24 hours per day and was maintained 1 to 2 days per week by an operator.

Recirculation Flow Operations. Treatment of ARD from Aspen Seep under recirculation flow conditions was initiated on May 12, 2004 and continued through the end of the technology evaluation period on July 13, 2005. Treatment rates ranged from 25 to 91 L/min. Recirculation rates from the settling pond to the head of Bioreactor No.1 ranged from 114 to 227 L/min. On average, approximately five parts sulfide-rich bioreactor effluent were mixed with one part influent ARD in the settling pond.

Twice during the week of July 12, 2004 the generator supply power for the recirculation pumps failed. Recirculation stopped and sulfide-rich water was not longer discharging from the bioreactors for up to two days. Influent ARD was treated by residual sulfide in the settling pond and the flushing pond.

On August 19, 2004, UNR reversed the flow direction in Bioreactor No.1 to minimize development of preferential flow paths. Influent enters the north end of the bioreactor and effluent discharges from the south end of the bioreactor. Effluent is piped around the bioreactor and enters Bioreactor No.2 in the typical south to north flow regime.

During the weeks of September 27 and October 4, 2004 sludge was transferred from Pond 3 to Pond 4 to provide the necessary sludge storage capacity in Pond 3 for winter operations.

Twice during the week of November 8, 2004 the generator supply power for the recirculation pumps failed due to water in the diesel fuel tank. Recirculation stopped and sulfide-rich water was not longer discharging from the bioreactors for up to two days. The solar panel battery also failed, which stopped the addition of sodium hydroxide to the settling pond for up to three days. The cessation of sodium hydroxide addition reduced the pH in the settling and flushing ponds. Influent ARD was being treated by residual sulfide in the settling pond and the flushing pond.

On November 25, 2004, the single large capacity recirculation pump was replaced with three smaller capacity pumps to provide redundancy in the event of a single pump failure. On December 3, 2004 the intakes on the three recirculation pumps were raised to reduce the intake of settled sludge from the settling pond and transfer of solids to the head of Bioreactor No.1. On February 3, 2005 the three smaller capacity pumps were replaced with a single large capacity recirculation pump due to reliability problems with the pump controller.

On March 17, 2005 the generator supply power for the recirculation pump failed. Recirculation stopped and sulfide-rich water was not longer discharging from the bioreactors for up to two days. Influent ARD was being treated by residual sulfide in the settling pond and the flushing pond.

During the week of June 28, 2005 settled solids were transferred from the settling pond to the flushing pond.

On July 13, 2005 the generator supply power for the recirculation pump failed. Recirculation stopped and sulfide-rich water was not longer discharging from the bioreactors for a one day period. Influent ARD was being treated by residual sulfide in the settling pond and the flushing pond.

On July 13, 2005 two solar powered recirculation pumps were installed at the settling pond. The combined flow of the two pumps was about 45 L/min, handling approximately one-quarter of the flow necessary for recirculation operations.

On August 30, 2005 the generator supply power for the recirculation pump failed. Recirculation stopped and sulfide-rich water was not longer discharging from the bioreactors for three days. Influent ARD was being treated by residual sulfide in the settling pond and the flushing pond.

From mid-August through mid-November 2005, approximately 200,000 L of sludge from the settling pond was dewatered using seven bag filters. Each bag required one day to build up a sufficient layer of cake to adequately concentrate solids within the bag. Approximately 4.3 dry tons (3,900 kg) of non-hazardous bag filter solids were generated and disposed of off-site. Approximately 10 dry tons (9,100 kg) of non-hazardous solids remain in the settling and flushing ponds.

During recirculation flow operations, the system treated 22.1 million liters of ARD using 22,029 L of 25 percent sodium hydroxide (average dosage of 316 mg/L) and 10,617 L of ethanol (average dosage of 379 mg/L) and generated about 10 dry tons (9,100 kg) of non-hazardous solids. The system was operational approximately 98 percent of the time during recirculation operations. The system operated 24 hours per day and was maintained 1 to 2 days per week by an operator.

2.4.3 Process Modifications

A number of modifications were made to the bioreactor treatment system to improve bioreactor performance, solids handling, and the type and rate of reagent consumption. The primary modification involved recirculation as an alternate mode of contact between ARD and sulfide-rich water and location for collection of metal sulfide precipitates.

- An alternate method and location of contact between the ARD and sulfide-rich bioreactor effluent was implemented. Influent ARD was combined with bioreactor effluent at the head of the settling pond to promote precipitation and settling of metal sulfides in the pond rather than in the individual bioreactors. A portion of the sulfate-rich and metal-poor effluent from the settling pond was recirculated to the head of the two bioreactors for generation of additional sulfide. The new configuration places less stress on the sulfate-reducing bacteria through reduced metals toxicity, higher influent pH, a more stable flow, and greatly reduces the need to flush solids from the bioreactors.
- Operation of the treatment system in the recirculation configuration eliminated the need for the pretreatment pond for initial pH adjustment and the

long term requirement to periodically flush solids from the pond.

- Sodium hydroxide was demonstrated during operation of the pilot-scale treatment system as the preferred method of base addition. During the evaluation of the full-scale treatment system, alternative sources for addition of base were evaluated. Sodium carbonate, sodium acetate, potassium acetate, and syn-rock were evaluated and were found to provide inadequate base delivery due to large dose required, poor solubility, freezing, or sealing of the reagent surface.
- During the evaluation of the full-scale treatment system, alternative locations for addition of base were evaluated. Adjustment of influent pH to approximately 4.0 was found to be necessary prior to bioreactor treatment to reduce stress on the sulfate-reducing bacteria. Addition of base prior to the settling pond to a neutral pH showed an improvement in metals removal.
- In order to provide an opportunity for extended contact of sulfides and metals and extended settling of metal sulfides, the flushing pond was brought on line to receive effluent from the settling pond, effectively doubling settling time.
- Rather than setup and periodically pump settled solids through bag filters for dewatering, settled solids from the pretreatment pond and settling pond were discharged to the flushing pond. Settled solids were allowed to accumulate in the flushing pond prior to bag filtration in the fall.

2.4.4 Evaluation Monitoring Activities

This section discusses monitoring activities conducted during the evaluation of each mode of treatment technology operation. The discussion includes a summary of sampling dates and locations for system performance, unit operations, solids handling, and solids disposal samples outlined in the sampling program (see Section 2.3.2). Summary tables documenting the water, sludge, and solids samples collected and the analyses performed for each mode of treatment system operation are presented in Appendix A.

The bioreactor treatment system was operated in the gravity flow mode from November 2003 through mid-May 2004, and in recirculation mode from mid-May 2004 through July 2005. A description of evaluation monitoring activities for each mode of operation is presented below.

Gravity Flow Evaluation Monitoring Activities. Both system performance and unit operations sampling was performed in 2003 and 2004. System performance and unit operations samples were collected from the system influent

and effluent on November 14 and 25, 2003; and January 29, February 19, March 24, and April 29, 2004. No solids samples were collected during gravity flow monitoring activities as the settling ponds were just beginning to fill with metal sulfide precipitates.

Recirculation Evaluation Monitoring Activities. Both system performance and unit operations sampling was performed in 2004 and 2005. System performance and unit operations samples were collected from the system influent and effluent on June 16, August 19, and December 3, 2004; and February 3, March 17, April 27, and June 2, 2005.

A settling pond sample was collected on June 14, 2004. Pretreatment pond, settling pond, flushing pond, and aeration channel sludge samples were collected on July 13, 2005. A composite sample of dewatered bag filter solids was collected on September 29, 2005 for waste characterization.

2.4.5 Demobilization Activities

The bioreactor treatment system has been permanently constructed at Leviathan Mine and operates on a year round basis. Therefore, no demobilization activities were observed. However, activities associated with preparation for winter conditions were observed and documented.

Winterization activities observed for the bioreactor treatment system include:

- Filling reagent and fuel tanks prior to build up of snow pack
- Inspect and replace reagent delivery lines as necessary
- Perform solar cell and battery maintenance
- Perform generator maintenance (replacement or overhaul)
- Remove solids from settling ponds to provide sufficient pond capacity for the winter
- Ship accumulated bag filter solids to an off-site non-hazardous waste landfill or dispose of on-site.
- Lower level on pond decant structures to allow extra precipitation capacity in settling/flushing ponds
- Clear decant structures of debris
- Remove portable toilets

2.4.6 Lessons Learned

This section discusses the lessons learned during the technical evaluation of the bioreactor treatment system. The discussion includes observations, recommendations, and ideas to be

implemented during future operations and for similar treatment systems.

Lessons learned during the operation of bioreactor treatment system include:

- Gravity flow operation of the bioreactor treatment system allows precipitation and accumulation of metal sulfides within the bioreactor. The recirculation mode of operation evaluated at Leviathan Mine promoted the generation of sulfide in the bioreactors and the majority of metal sulfide precipitation in the settling pond rather than in the individual bioreactors. In addition, less stress was placed on the sulfate-reducing bacteria by reducing metals loading, operating at a higher influent pH, and reducing frequency of solids flushing from the bioreactors.
- Adjustment of influent pH to approximately 4.0 was found to be necessary prior to bioreactor treatment to reduce stress on the sulfate-reducing bacteria. Addition of base prior to the settling pond to a neutral pH showed an improvement in metals removal.
- Sodium hydroxide was demonstrated during operation of the pilot-scale and full-scale treatment system as the preferred method of base addition. Other source materials were found to be inadequate due to large dose required, poor solubility, freezing, or sealing of the reagent surface.
- Health and safety issues observed during the technology evaluation include skin and eye splash contact when working with sodium hydroxide; accumulation of hydrogen sulfide gas in depressions and valve vaults; and slip hazards around the perimeter of the settling and flushing ponds. Mitigation of hazards associated with sodium hydroxide includes arm length chemical gloves, chemical apron, eye protection, and a face shield. Mitigation of hazards associated with hydrogen sulfide gas includes the use of gas detection meters and blowers. Mitigation of slips hazards around the settling and flushing ponds should include perimeter fencing, barriers around open ponds, and a safety rope when working inside the fenced area.
- During periods of high flow, base delivery upsets, recirculation upsets, and extra pond capacity may be required to provide sufficient HRT for precipitate settling due to formation of smaller particles. At Leviathan Mine, the flushing pond was brought on line to receive effluent from the settling pond, effectively doubling settling time.
- Sludge should be periodically transferred to the flushing pond to provide adequate settling capacity in the pretreatment and settling ponds.

-
- Rather than setup and continuously pump settled solids through bag filters for dewatering, settled solids should be allowed to accumulate in the flushing pond prior to periodic bag filtration.
 - Bag filters may limit operations during freezing temperatures in due to icing of the filter fabric, which will create backpressure within the system. Therefore, bag filtration of sludge should occur from late spring through early fall.

2.5 Technology Evaluation Results

This section summarizes the evaluation of the metals data collected during the SITE demonstration with respect to meeting project objectives. Attainment of project primary objectives is described in Sections 2.5.1 and 2.5.2, while secondary objectives are provided in Section 2.5.3. Solids handling and disposal for is discussed in Section 2.5.4.

Preliminary evaluation of the influent, effluent, and 4-day average effluent metals data included an assessment of data characteristics through quantitative and graphical analysis. Influent, effluent, and 4-day average effluent concentrations for the 10 metals of interest for each mode of treatment system operation are presented in Tables B-1 through B-2 of Appendix B. Summary statistics calculated for these data sets include: mean, median, standard deviation, and coefficient of variation, which are presented in Tables B-3 through B-4 of Appendix B. Minimum and maximum concentrations are also presented.

Summary statistics for influent, effluent, and 4-day average effluent data were determined using Analyze-It Excel (Analyze-It 2004) and ProUCL (EPA 2004) statistical software. In addition, frequency, box-and-whisker, and probability plots were prepared to identify data characteristics and relationships, evaluate data fit to a distribution (for example, normal or lognormal), and to identify anomalous data points or outliers for the 10 target metals for each of treatment system operation. The results of statistical plotting showed only one significant outlier in the effluent dataset for iron. The iron effluent outlier was the result of inadequate sodium hydroxide addition prior to the settling pond. Summary statistics were prepared for the iron effluent data set both with and without the outlier for comparative purposes. No significant outliers were identified in the effluent data for the other target metals. No significant outliers were identified in the influent or 4-day average effluent datasets. No data were rejected from the data sets. The statistical plots also showed the metals influent and effluent concentrations to be normally distributed, with the exception of those samples at or near method detection limits. Statistical plots are documented in the Technology Evaluation Report Data Summary (Tetra Tech 2006).

2.5.1 Primary Objective No.1: Evaluation of Metals Removal Efficiencies

The evaluation of the bioreactor treatment system focused on two primary objectives. The first objective was to determine the removal efficiencies for the primary metals of concern and the secondary water quality indicator metals. To successfully calculate removal efficiencies for each metal, influent concentrations must be significantly different than effluent concentrations. Based on preliminary statistical plots described in Section 2.5, the influent and effluent metals data sets were found to be normally distributed; therefore a paired Student's-t test (as described in EPA guidance [EPA 2000]) was used to determine if the influent and effluent concentrations were statistically different. For this statistical evaluation, if the P-value (test statistic) was less than the 0.05 significance level (or 95 percent confidence level), then the two data sets were considered statistically different. Influent and effluent concentrations for up to 7 of the 10 metals from each bioreactor treatment system mode of operation were found to be statistically different (P-value was less than 0.05), and for these metals, removal efficiencies were calculated. Tables 2-2 through 2-3 present the average and range of removal efficiencies for filtered influent and effluent samples collected during each mode of treatment system operation during the SITE demonstration and also the P-value for the paired Student's-t test analysis. The average influent and effluent metals concentrations for each treatment system are also presented. Where influent and effluent concentrations for a particular metal were not statistically different (P-value was greater than 0.05), removal efficiencies were not calculated for that metal, as indicated in the summary tables. In addition, where one or both concentrations for a metal were not detected in an individual influent/effluent data pair, those data points were not included in the determination of removal efficiencies.

For the gravity flow mode of treatment system operation, the average removal efficiency for the primary target metals was 94 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 41 to 99 percent in both modes of operation; however, removal efficiencies were not calculated for chromium, lead, and selenium during gravity flow operations as the influent and effluent concentrations were not statistically different. Similarly, removal efficiencies were not calculated for cadmium and selenium during recirculation operations. In the case of arsenic, cadmium, chromium, and lead in the ARD, concentrations were near or below the EPA

Table 2-2. Removal Efficiencies for the Bioreactor Treatment System – Gravity Flow Operation

Target Metal	Number of Sampling Events	Average Filtered Influent Concentration (µg/L)	Average Filtered Effluent Concentration (µg/L)	Paired Student's-t test P-value ¹	Average Removal Efficiency ⁽²⁾ (%)	Range of Removal Efficiencies (%)
Primary Target Metals						
Aluminum	6	37,467	103	<0.05	99.7	99.5 to 99.9
Arsenic	6	2.1	4.7	0.192	NC	NC
Copper	6	691	4.8	<0.05	99.3	99.1 to 99.7
Iron	6	117,167	4,885	<0.05	95.8	65.6 to 99.9
Nickel	6	487	65.5	<0.05	86.6	72.1 to 92.6
Secondary Water Quality Indicator Metals						
Cadmium	6	0.61	<0.21	0.009	65.3	42.5 to 79
Chromium	6	12.2	7.8	0.126	NC	NC
Lead	6	3.6	4.7	0.386	NC	NC
Selenium	6	13.9	11.2	0.149	NC	NC
Zinc	6	715	15.8	<0.05	97.8	95.9 to 98.6
(1) A P-value less than 0.05 indicates that influent and effluent data are statistically different (2) Average removal efficiency calculated using the average influent and average effluent concentration data µg/L = Microgram per liter % = Percent NC = Not calculated as influent and effluent concentrations were not statistically different						

Table 2-3. Removal Efficiencies for the Bioreactor Treatment System – Recirculation Operation

Target Metal	Number of Sampling Events	Average Filtered Influent Concentration (µg/L)	Average Filtered Effluent Concentration (µg/L)	Paired Student's-t test P-value ¹	Average Removal Efficiency ⁽²⁾ (%)	Range of Removal Efficiencies (%)
Primary Target Metals						
Aluminum	7	40,029	52.7	<0.05	99.9	99.7 to 99.9
Arsenic	7	7.4	6.5	0.785	NC	NC
Copper	7	795	4.6	<0.05	99.4	98.8 to 99.8
Iron	7	115,785	2,704	<0.05	97.7	92.8 to 99.7
Nickel	7	529	69.7	<0.05	86.8	71.0 to 96.4
Secondary Water Quality Indicator Metals						
Cadmium	7	0.60	<0.20	0.083	NC	NC
Chromium	7	11.1	6.4	0.002	42.5	21.2 to 84.8
Lead	7	4.2	2.5	0.003	41.3	22.0 to 57.1
Selenium	7	11.5	8.5	0.057	NC	NC
Zinc	7	776	8.9	<0.05	98.9	97.7 to 99.8
(1) A P-value less than 0.05 indicates that influent and effluent data are statistically different (2) Average removal efficiency calculated using the average influent and average effluent concentration data µg/L = micrograms per liter % = Percent NC = Not calculated as influent and effluent concentrations were not statistically different						

interim discharge standards in the influent; therefore, the treatment system was not optimized for removal of these metals resulting in lower removal efficiencies. Removal efficiencies for sulfate ranged from 8 to 35 percent with an average reduction in sulfate of 17 percent. There was on average a 9 percent increase in sulfate removal during the recirculation mode of treatment system operation.

2.5.2 Primary Objective No.2: Comparison of Effluent Data to Discharge Standards

The second primary objective was to determine whether the concentrations of the primary metals of concern in the effluent from the two modes of bioreactor treatment system operation were below EPA interim (pre-risk assessment and record of decision) discharge standards, as presented in Table 2-4. The 4-day average discharge standard was originally intended for comparison to the average of four-consecutive-day sampling data. Instead, the average concentrations from four consecutive sampling events were compared against the four-day discharge standards. In addition, the attainment of discharge standards for the secondary water quality parameters was evaluated. Direct comparisons of the effluent data to the maximum and 4-day average discharge standards show that iron concentrations exceeded both sets of discharge standards, and that lead and selenium exceeded their respective 4-day average discharge standards. Additional statistical tests were used to evaluate whether any other metals concentrations in the effluent streams were statistically different from either set of discharge standards.

Based on statistical plots described in Section 2.5, the metals effluent and 4-day average effluent concentrations were shown to be normally distributed; therefore, the one-sample parametric Student's-t test (as described in EPA guidance [EPA 2000]) was used in the comparison of the metals concentrations to the discharge standards. The one-sample parametric Student's-t test was used to determine if metals effluent and 4-day average effluent concentrations were significantly greater than the discharge standards (alternative or H_a hypothesis). The maximum daily discharge standards, maximum detected effluent concentrations, and average effluent concentrations are summarized in Table 2-5 and the 4-day average discharge standards and 4-day average effluent concentrations are summarized in Table 2-6.

Based on preliminary statistical plots described in Section 2.5, the metals effluent and 4-day average effluent concentrations were shown to be normally distributed; therefore, the one-sample parametric Student's-t test (as described in EPA guidance [EPA 2000]) was used in the comparison of the metals concentrations to the discharge standards. The one-sample parametric Student's-t test was used to determine if metals effluent and 4-day average effluent concentrations were significantly greater than the discharge standards (alternative

or H_a hypothesis). The maximum daily discharge standards, maximum detected effluent concentrations, and average effluent concentrations are summarized in Table 2-5 and the 4-day average discharge standards and 4-day average effluent concentrations are summarized in Table 2-6.

Table 2-4. EPA Interim Discharge Standards

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 Water Quality Indicator Metals		
Cadmium	9.0	4.0
Chromium	970	310
Lead	136	5.0
Selenium	No Standard	5.0
Zinc	210	210
(a) Based on a daily composite of three grab samples		
(b) Based on the average of four consecutive daily composite samples		
µg/L = micrograms per liter		

For the metals data sets that could be analyzed, the 1-tailed P-values (test statistic) for all of the tests were above the 0.95 significance level (or 95 percent confidence level) required for acceptance of the alternative hypothesis with the exception of iron, lead, and selenium. Iron and selenium concentrations were consistently above discharge standards, while only one lead effluent sample was above discharge standards and contributed to an elevated 4-day average concentration. There is no maximum daily discharge standard for selenium; therefore, there are no statistical results for selenium in Table 2-5. In addition, cadmium was not detected in any of the effluent samples collected during either mode of treatment system operation; therefore, there are no statistical results for cadmium in either Table 2-5 or 2-6.

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. Internal trials run to refine base addition requirements and to evaluate various sources of base addition lead to significant excursions of effluent iron concentrations above the EPA interim discharge standards during a portion of the evaluation period. 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

Table 2-5. Results of the Student's-t Test Statistical Analysis for Maximum Daily Effluent Data

Analyte	Maximum Daily Discharge Limit (µg/L)	Maximum Detected Concentration in Effluent Stream (µg/L)	Average Concentration in Effluent Stream (µg/L)	1-Tailed P-value (Effluent Data > Maximum Daily Discharge Limit)	Effluent Concentration Significantly Greater than Maximum Daily Discharge Limit? (µg/L)
Bioreactor Treatment System- Gravity Flow Mode Student's-t test Comparisons					
Aluminum	4,000	160	103	1.0	No
Arsenic	340	12.5	4.7	1.0	No
Cadmium	9	<0.32	<0.21	NC	No
Chromium	970	16.3	7.8	1.0	No
Copper	26	6.5	4.8	1.0	No
Iron	2,000	39,200	4,597	0.107	Yes
Lead	136	9.8	4.7	1.0	No
Nickel	840	125	65.5	1.0	No
Selenium	No Standard	13.9	11.2	Not Tested	Not Tested
Zinc	210	29	15.8	1.0	No
Bioreactor Treatment System- Recirculation Mode Student's-t test Comparisons					
Aluminum	4,000	105	52.7	1.0	No
Arsenic	340	11.2	6.51	1.0	No
Cadmium	9	<0.3	<0.20	NC	No
Chromium	970	14.1	6.4	1.0	No
Copper	26	9.5	4.6	1.0	No
Iron	2,000	9,060	2,704	0.279	Yes
Lead	136	4.6	2.5	1.0	No
Nickel	840	154	69.7	1.0	No
Selenium	No Standard	12.3	8.5	Not Tested	Not Tested
Zinc	210	18.8	8.9	1.0	No
µg/L = micrograms per liter A P-value greater than 0.95 indicates that effluent data are not greater than the discharge standard NC = Not calculated as sample results indicate metal was not detected					

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. In addition, the concentrations of the secondary target metals, with the exception of selenium, were reduced to below the discharge standards.

2.5.3 Secondary Objectives for Evaluation of Bioreactor Treatment System Unit Operations

The evaluation of the bioreactor treatment system at Leviathan Mine also included evaluation of four secondary objectives. These secondary objectives included:

- Documentation of operating parameters and assessment of critical operating conditions necessary to optimize system performance.
- Monitoring the general chemical characteristics of the ARD water as it passes through the treatment system.

- Evaluating operational performance and efficiency of solids separation systems.
- Documenting solids transfer, dewatering, and disposal operations.
- Documentation of winter operating procedures and effectiveness
- Determining the volume and type of metal precipitate generated in the bioreactors and the optimal frequency and duration of bioreactor flushing

Documentation of year round operating conditions, discussion of reaction chemistry, evaluation of year round metals removal by unit operation, and evaluation of solids flushing and separation are presented in the following sections. The data presented were compiled from observations during the demonstration as well as data summarized in the Data Summary Report for Bioreactors at the Leviathan Mine Aspen Seep 2003 (Tsukamoto 2004), and the Data Summary Report for Bioreactors at the Leviathan Mine Aspen Seep 2004 (Tsukamoto 2005a). Solids characterization and handling is documented in Section 2.5.4.

Table 2-6. Results of the Student's-t Test Statistical Analysis for 4-Day Average Effluent Data

Analyte	4-Day Average Discharge Limit (µg/L)	Maximum 4-Day Average ⁽¹⁾ Concentration in Effluent Stream (µg/L)	Average 4-Day Average ⁽¹⁾ Concentration in Effluent Stream (µg/L)	1-Tailed P-value (Effluent Data > Maximum Daily Discharge Limit)	Effluent Concentration Significantly Greater than Maximum Daily Discharge Limit? (µg/L)
Bioreactor Treatment System- Gravity Flow Mode Student's-t test Comparisons					
Aluminum	2,000	128	108	1.0	No
Arsenic	150	5.2	3.6	1.0	No
Cadmium	4	<0.22	<0.21	NC	No
Chromium	310	6.8	5.8	1.0	No
Copper	16	5.6	4.8	1.0	No
Iron	1,000	15,783	14,118	0.005	Yes
Lead	5	5.8	5.5	0.096	Yes
Nickel	94	78.7	68.1	0.980	No
Selenium	5	11.2	10.7	0.002	Yes
Zinc	210	18.2	14.9	1.0	No
Bioreactor Treatment System- Recirculation Mode Student's-t test Comparisons					
Aluminum	2,000	58.3	52.1	1.0	No
Arsenic	150	7.6	5.3	1.0	No
Cadmium	4	<0.21	<0.18	NC	No
Chromium	310	7.4	5.0	1.0	No
Copper	16	5.1	3.9	1.0	No
Iron	1,000	3,760	2,951	0.012	Yes
Lead	5	2.4	2	1.0	No
Nickel	94	85.8	73	0.991	No
Selenium	5	9.8	8.4	0.004	Yes
Zinc	210	8.0	7.4	1.0	No
(1) The data from four consecutive sampling events were used in the calculation of the average instead of four consecutive days					
µg/L = micrograms per liter					
A P-value greater than 0.95 indicates that effluent data are not greater than the discharge standard					
NC = Not calculated as sample results indicate metal was not detected					

2.5.3.1 Operating Conditions

Operating conditions for the bioreactor treatment system in gravity flow and recirculation modes of operation are described below.

Gravity Flow Operations. Operation of the treatment system in gravity flow mode (Figure 1-2) involved the collection of ARD from Aspen Seep in a rock-filled basin that was covered with soil to limit entrainment of oxygen. Minimization of dissolved oxygen in the influent ARD maximizes the efficiency of sulfate-reducing bacteria within the bioreactors. ARD discharges from the collection basin through a flow measurement weir at an average flow rate of 31.8 L/min. After passing through the weir, influent ARD discharges into a flow distribution box where 25 percent sodium hydroxide is dripped into the flow at an average dosage rate of 8.3 ml/min (83 mg/L) to reduce acidity and raise the pH of the ARD to approximately 4.0 which reduces the stress on the sulfate-reducing bacteria in the downstream bioreactors. Ethanol is also dripped into the flow at an average dosage rate of 13.7 ml/min (340 mg/L) to provide a carbon source for the sulfate-

reducing bacteria in the downstream bioreactors. The sodium hydroxide and ethanol are mixed into the ARD by turbulent discharge from the distribution box to a pretreatment pond. A small quantity of iron is typically precipitated out of solution and is retained in the pretreatment pond. However, the primary purpose of the pretreatment pond is to provide a flow equalization buffer for influent to the bioreactors. The average HRT of the pretreatment pond is 14.7 hours. Solids are flushed from the pretreatment pond approximately once a month, transferring from 2,000 to 7,000L of solids slurry to the flushing pond during warm weather conditions. More frequent flushing in winter is necessary due to limited operational volume when the pond ices over. A summary of the system operational parameters is presented in Table 2-7.

The ARD then flows by gravity into the first bioreactor. Influent flow to both bioreactors is controlled through the use of standpipes, rather than valves. The standpipes control flow by manipulation of the energy grade line across each bioreactor. Influent flow can be added to either end of each bioreactor and can be targeted to the bottom, middle, or top of each bioreactor to minimize the development of preferential

Table 2-7. Gravity Flow Unit Operations Parameters

Parameter	Units	Range	Average
System Influent Flow Rate	(L/min)	25 to 47	31.8
Influent Ethanol Dosage Rate	(ml/min)	10.8 to 20.2	13.7
Influent NaOH Dosage Rate	(ml/min)	6.5 to 12.2	8.3
Pretreatment Pond Settling Time	(hr)	9.9 to 18.7	14.7
Bioreactor No.1 Reaction Time	(hr)	53.2 to 100	78.6
Bioreactor No.2 Reaction Time	(hr)	30.1 to 56.7	44.6
Pre-Settling Pond NaOH Dosage Rate	(ml/min)	21.3 to 40	27
Settling Pond Residence Time	(hr)	165 to 310	244
Flushing Pond Residence Time	(hr)	181 to 340	267
Aeration Channel Residence Time	(min)	29.8 to 56	44
System Effluent Flow Rate	(L/min)	25 to 47	31.8
System Hydraulic Residence Time	(hr)	440 to 826	650
hr = hour		min = Minute	
L/min = Liter per minute		ml/min = Milliliter per minute	

flow paths. After sulfate reduction and precipitation of a moderate quantity of metal sulfide solids in the first bioreactor and generation of alkalinity through biological processes, effluent discharges to the second bioreactor for reduction of residual sulfate to sulfide and generation of additional alkalinity. Similar to influent flow, effluent flow from each bioreactor can be drawn from either end of each bioreactor and can be removed from the bottom, middle, or top of each bioreactor to minimize the development of preferential flow paths. Buildup of excess metal sulfide solids within either bioreactor can be drawn downward into flushing loops at the bottom of each bioreactor. The flushing loops are controlled by valves on a large flushing line that passes under the entire length of the treatment system and discharges to a flushing pond downstream of the pretreatment pond, the bioreactors, and the settling pond. The bioreactors were flushed about every two months during gravity flow operations, transferring an estimated 15,000 L of solids slurry to the flushing pond. The HRT of Bioreactor No.1 averages 78.6 hours, while the HRT of Bioreactor No.2 averages 44.6 hours at an average influent flow rate of 31.8 L/min.

After passing through the two bioreactors, partially treated ARD is dosed with sodium hydroxide and discharges to a settling pond to allow extended time (244 hour average HRT) for metal precipitation and settling. Twenty-five percent sodium hydroxide solution is added to the settling pond influent line at an average dosage rate of 27 ml/min (270 mg/L) to neutralize remaining acidity and raise the pH from about pH 5 to a near neutral condition (pH 7) necessary for precipitation of iron sulfide. The long HRT also allows settling of metal precipitates and degassing of carbon dioxide and hydrogen sulfide from solution, which reduces acidity and raises solution pH. Effluent from the settling pond can be discharged to a rock-lined aeration channel or to the flushing pond for additional extended precipitate settling time. In practice, effluent from the settling pond was always discharged to the flushing pond for additional settling (267 hour average HRT) due to elevated particulate iron concentrations. Effluent from the flushing pond discharges to

the rock-lined aeration channel to promote gas exchange and raise the ORP of the effluent. The aeration process promotes precipitation of additional metals that react with excess oxygen in solution. The average HRT for the system operated in gravity flow mode is 650 hours at an average flow rate of 31.8 L/min. System HRT is extended to 827 hours in winter when influent flows from Aspen Seep drop to 25 L/min. The extended HRT provides adequate treatment during periods of decreased biological activity, even at water temperatures of 1°C (degree Celsius). However, during the winter adequate base addition is necessary to convert all of the bisulfide generated in the bioreactors to sulfide necessary for iron sulfide precipitation. Lack of or inadequate base addition during the winter often leads to inability to meet iron discharge standards.

Approximately 32,000 L of solids slurry is transferred from the settling pond to the flushing pond prior to the onset of winter. Periodically, metal sulfide sludge is pumped out of the settling and flushing ponds and into bag filters for passive dewatering prior to disposal as a nonhazardous solid. The filtration process involves the filling of a bag filter with sludge and gravity drainage of water through the filter fabric. Free water is allowed to drain back into the flushing pond following filtration. The process is repeated using a new bag filter placed on top of an older bag. Additional solids dewatering occurs in the bags on the bottom of the stack due to compression. The process generated approximately 3,900 kilogram (kg) of dry solids over 100 days. The bag filtration process is limited to summer and early fall when temperatures are warm enough to prevent freezing of the filter membrane.

Recirculation Operations. The treatment system operated in recirculation mode (Figure 1-3) utilizes the same processes as the system operated in gravity flow mode; however, the metal-rich ARD influent bypasses the pretreatment pond and the two bioreactors and is combined with sulfide-rich bioreactor effluent and sodium hydroxide and introduced to the settling pond for metal sulfide precipitation. The key to recirculation is the precipitation of metal sulfides in the settling pond rather than in the two bioreactors, which reduces the need for and frequency of bioreactor flushing and provides a stable sulfate-reducing bacteria population within the bioreactors.

A portion of the sulfate-rich settling pond effluent containing residual concentrations of metals is recirculated at an average flow rate of 210 L/min to the head of Bioreactor No.1 and combined with ethanol to promote the generation of additional sulfide. Ethanol is dripped into recirculated flow at the head of Bioreactor No.1 at an average dosage rate of 105 ml/min (394 mg/L) to provide a carbon source for the sulfate-reducing bacteria in the downstream bioreactors. The recirculated settling pond effluent then flows by gravity through the two bioreactors. After sulfate reduction, precipitation of metal sulfides, and generation of alkalinity through biological processes in both bioreactors, effluent is combined with ARD influent at an average flow rate of 34.2 L/min and 25 percent

sodium hydroxide solution at an average dosage rate of 17.1 ml/min (159 mg/L) and discharges to the settling pond. The sodium hydroxide along with excess alkalinity in the bioreactor effluent neutralizes acidity and raises the ARD influent pH from about pH 3 to a near neutral condition (pH 7) necessary for precipitation of iron sulfide. The bioreactors were flushed every three to four months during recirculation operations, transferring an estimated 15,000 L of solids to the flushing pond. The HRT of Bioreactor No.1 averages 11.9 hours, while the HRT of Bioreactor No.2 averages 6.8 hours at an average recirculation flow rate of 210 L/min. A summary of the system operational parameters is presented in Table 2-8.

Table 2-8. Recirculation Unit Operations Parameters

Parameter	Units	Range	Average
System Influent Flow Rate	(L/min)	25 to 91	34.2
Bypass to Settling Pond	(L/min)	25 to 91	34.2
Recirculation from Settling Pond to Bioreactor No.1	(L/min)	189 to 227	210
Influent Ethanol Dosage Rate	(ml/min)	94.5 to 113.5	105
Bioreactor No.1 Reaction Time	(hr)	11 to 13.2	11.9
Bioreactor No.2 Reaction Time	(hr)	6.3 to 7.5	6.8
Pre-Settling Pond NaOH Dosage Rate	(ml/min)	12.5 to 45.5	17.1
Settling Pond Residence Time	(hr)	28.5 to 30.8	29.7
Settling Pond Discharge Rate	(L/min)	25 to 91	34.1
Flushing Pond Residence Time	(hr)	103 to 354	249
Aeration Channel Residence Time	(min)	17 to 56	41
System Effluent Flow Rate	(L/min)	25 to 91	34.1
System Hydraulic Residence Time	(hr)	149 to 407	298
hr = hour min = Minute L/min = Liter per minute ml/min = Milliliter per minute			

The settling pond allows extended time (29.7 hour average HRT empty) for metal sulfide precipitation and settling. The settling pond does not completely freeze over during winter due to the circulation of water within the pond. Effluent (34.2 L/min) from the settling pond was always discharged to the flushing pond for additional settling (249 hour average HRT) due to elevated residual iron concentrations. The long HRT also allows settling of metal precipitates and degassing of carbon dioxide and hydrogen sulfide from solution, which reduces acidity and raises solution pH. During recirculation upsets the ORP increases and metal hydroxides precipitate, which results in a pH decrease in the settling pond. Approximately 48,000 L of solids slurry is transferred from the settling pond to the flushing pond prior to the onset of winter. Periodically, metal sulfide sludge is pumped out of the settling and flushing ponds and into a bag filter for passive dewatering prior to disposal as a nonhazardous solid.

Effluent from the flushing pond is discharged to the rock-lined aeration channel to promote gas exchange, raise solution ORP, and precipitate residual metals from solution. The average HRT for the system operated in recirculation mode is 298 hours at an average flow rate of 34.2 L/min. System HRT is extended to 408 hours in winter when influent flows from Aspen Seep drop to 25 L/min. Adequate treatment is provided during winter, even at relatively short bioreactor HRT and

very low water temperatures, due to the limited stress (neutral pH and low metals concentrations) placed on the bioreactors. However, adequate base addition is necessary to convert all of the bisulfide generated in the bioreactors to sulfide for iron sulfide precipitation in the settling pond. Lack of or inadequate base addition during the winter can stress the bioreactors resulting in reduce sulfide generation and an overall inability to meet iron discharge standards.

2.5.3.2 Reaction Chemistry

The reaction chemistry for the bioreactor treatment system is described below for both the gravity flow and recirculation modes of operation. A warm weather date for the gravity flow mode of operation was not available as the system was converted to recirculation operations in May 2004. Instead, a cold weather date (March 24, 2004) was selected for gravity flow mode of operation and a warm weather date (August 19, 2004) was selected for recirculation mode to evaluate potential impact of cold weather on system effectiveness.

Gravity Flow Reaction Chemistry. Changes in ARD chemistry within the pretreatment pond are driven by the addition of sodium hydroxide to the influent ARD at the influent weir box. Sodium hydroxide addition consumes mineral acidity, raises solution pH, increases the kinetics of iron oxidation, and provides a source of hydroxide ion for ferric hydroxide formation. A small quantity of iron precipitate formed, a portion of which is deposited in the pond.

During the pretreatment process, solution pH increased from 3.1 to 3.6 after sodium hydroxide addition and target metals decreased 28 percent (primarily aluminum at 7 percent, iron at 35 percent) in response to excess hydroxide ion. The data also indicate that mineral acidity was reduced as evidenced by an increase in pH and a decrease in solution ORP. Field and analytical laboratory chemical parameters documenting reaction chemistry on March 24, 2004 are provided in Table 2-9.

Supernatant from the pretreatment pond discharges to the head of Bioreactor No.1, where it is combined with ethanol to provide a carbon substrate for the sulfate-reducing bacteria. Observed changes in ARD chemistry in the effluent from the two bioreactors were primarily due to the reduction of sulfate to sulfide by sulfate-reducing bacteria and the generation of acetate associated with incomplete oxidation of ethanol and alkalinity during the complete oxidation of ethanol to carbon dioxide. Sulfide combines with excess metals to form metal sulfide precipitates. Alkalinity raises the pH of ARD in the bioreactors and facilitates precipitation reactions. However, the pH is not high enough to convert bisulfide to sulfide and precipitate the majority of the iron as iron sulfide; therefore the majority of the iron and bisulfide pass out of the two bioreactors.

Table 2-9. Gravity Flow Unit Operation Reaction Chemistry

Parameter	Unit	Pretreatment Pond			Bioreactor No.1			Bioreactor No.2		
		Influent	Effluent	Change	Influent	Effluent	Change	Influent	Effluent	Change
pH	(SU)	3.1	3.6	0.5	3.6	4.7	1.1	4.7	4.8	0.1
Oxidation Reduction Potential	(mV)	425	324	-101	324	-117	-441	-117	-122	-5
Total Iron (dissolved)	(mg/L)	113	73.1	-39.9	73.1	71.7	-1.4	71.7	63.7	-8
Specific Conductance	(µmhos/cm)	2,368	2,335	-33	2,335	2,166	-169	2,166	1,989	-177
Dissolved Oxygen	(mg/L)	3.3	6.8	3.6	6.8	6.1	-0.7	6.1	6.4	0.3
Temperature	(°C)	12.4	12.4	0	12.4	11.5	-0.9	11.5	11.3	-0.2
Sulfate	(mg/L)	1,510	1,520	10	1,520	1,480	-40	1,480	1,310	-170
Sulfide	(mg/L)	0	0	0	0	37	37	37	38	1
Total Alkalinity	(mg/L)	<2	<2	0	<2	<2	0	<2	<2	0
Total Dissolved Solids	(mg/L)	2,200	2,240	40	2,240	2,380	140	2,380	2,090	-290

µmhos/cm = Micromhos per centimeter mV = Millivolt NC = Not calculated
°C = Degree Celsius mg/L = Milligram per liter SU = Standard unit

Data collected on March 24, 2004 at a system influent and effluent flow rate of 45 L/min

Parameter	Unit	Settling and Flushing Ponds			Aeration Channel		
		Influent	Effluent	Change	Influent	Effluent	Change
pH	(SU)	4.8	7.5	2.7	7.5	7.7	0.2
Oxidation Reduction Potential	(mV)	-122	91	213	91	40	-51
Total Iron (dissolved)	(mg/L)	63.7	0.19	-63.5	0.19	0.39	0.2
Specific Conductance	(µmhos/cm)	1,989	2,235	246	2,235	2,181	-54
Dissolved Oxygen	(mg/L)	6.4	8.6	2.2	8.6	8.8	0.2
Temperature	(°C)	11.3	12.6	1.3	12.6	12	-0.6
Sulfate	(mg/L)	1,310	1,170	-140	1,170	1,160	-10
Sulfide	(mg/L)	38	0	-38	0	0	0
Total Alkalinity	(mg/L)	<2	113	113	113	110	-20
Total Dissolved Solids	(mg/L)	2,090	1,900	-190	1,900	1,720	-180

µmhos/cm = Micromhos per centimeter mV = Millivolt SU = Standard unit
°C = Degree Celsius mg/L = Milligram per liter

Data collected on March 24, 2004 at a system influent and effluent flow rate of 45 L/min

Bioreactor No.1 effluent pH increased from 3.6 to 4.7, ORP shifted from highly oxidizing (+324 mV [millivolt]) to moderately reducing (-117 mV), sulfate decreased from 1,520 to 1,480 mg/L, and 37 mg/L of excess sulfide was generated. Target metals decreased 10 percent (primarily aluminum at 24 percent, copper at 99 percent, nickel at 22 percent, and zinc at 95 percent). Divalent metals were removed primarily by sulfide precipitation, while aluminum was removed by hydroxide precipitation. The data also indicate that mineral acidity was reduced as evidenced by an increase in pH and a decrease in solution ORP. Bicarbonate alkalinity was generated as solution pH increased by over one standard unit, though excess alkalinity was not observed in bioreactor effluent. Biological generation of bicarbonate alkalinity reduces the sodium hydroxide dosage required.

Bioreactor No.2 effluent pH increased from 4.7 to 4.8, ORP shifted to slightly more reducing (-117 to -122 mV), sulfate decreased from 1,480 to 1,310 mg/L, and excess sulfide generated increased slightly (37 to 38 mg/L). Target metals decreased 12 percent (primarily aluminum at 15 percent, iron at 11 percent, and nickel at 14 percent). Divalent metals were removed primarily by sulfide precipitation,

while aluminum was removed by hydroxide precipitation. The data indicate that mineral acidity continued to be reduced. Bicarbonate alkalinity was generated as solution pH continued to increase, though excess alkalinity was not observed in bioreactor effluent. Organic analysis for residual ethanol or metabolites was not conducted as a part of the demonstration. However, the technology developer has indicated that approximately one-third of the ethanol is incompletely oxidized to acetate within the bioreactors (Tsukamoto 2005b).

As a point of comparison, during cold weather conditions (water temperature 5°C) on February 19, 2004, sulfate decreased from 1,520 to 1,290 mg/L (15 percent) and total iron decreased from 70 to 67 mg/L (5 percent) across the bioreactors. A lack of adequate base addition was responsible for elevated iron concentrations, rather than insufficient sulfate reduction. Across the system as a whole, both low temperature and high flow suppresses sulfate reduction to sulfide and iron removal. The impact on temperature on sulfate reduction and iron removal is presented in Table 2-10.

Table 2-10. Impact of Temperature on Sulfate Reduction and Iron Removal During Gravity Flow Operations

Date	Temp (°C)	Sulfate Mass Removed (kg/day)	Sulfate Removal Efficiency (%)	Iron Mass Removed (kg/day)	Iron Removal Efficiency (%)	Flow (L/min)
11/14/03	4.8	10.5	17.5	4.4	95.8	26
11/25/03	4.5	11.2	18.1	4.3	89.6	26
1/29/04	3.8	5.8	9.9	2.9	63.1	29
2/19/04	5.2	11.3	17.4	4.2	93.7	29
3/24/04	10.9	22.7	23.2	7.2	98.5	45
4/29/04	10.1	11.2	13.4	6.6	99.7	39
% = Percent kg/day = Kilogram per day °C = Degree Celsius L/min = Liter per minute						

After partially-treated ARD passes out of Bioreactor No.2, the effluent is combined with sodium hydroxide and discharged to the settling pond. Sodium hydroxide addition consumes the remaining mineral acidity, and converts a portion of the bisulfide to sulfide, which is necessary to precipitate the remaining iron as iron sulfide in the settling pond. Sodium hydroxide also provides a source of hydroxide ion for metals that do not form precipitates with sulfide. Excess sulfide from bioreactor No.2 is generally completely consumed by metals or is oxidized to sulfate during the extended settling pond HRT.

The effluent pH from the flushing pond increased from 4.8 to 7.5, ORP shifted from moderately reducing (-122 mV) to moderately oxidizing (+91 mV), and sulfate decreased from 1,310 to 1,170 mg/L. No excess sulfide was observed in the flushing pond effluent, though sulfide may have been generated by sulfate-reducing bacteria in the settling pond and consumed in the flushing pond given the substantial decrease in sulfate concentrations across the two ponds. Target metals decreased 99.7 percent (primarily aluminum at 99.9 percent, iron at 99.7 percent, nickel at 84 percent, and zinc at 87 percent). Divalent metals were removed primarily by sulfide precipitation in the settling pond, while aluminum was removed by metal hydroxide and oxyhydroxide precipitation at a neutral pH condition. Additional metals removal in the flushing pond was likely related to agglomeration of colloidal metals and particle settling. The remaining mineral acidity was completely consumed by excess sodium hydroxide in solution, yielding a bicarbonate alkalinity of 113 mg/L.

After settling, treated ARD passes out of the flushing pond to an aeration channel to introduce oxygen, off-gas carbon dioxide, and precipitate residual metals from solution as metal hydroxides. Effluent dissolved oxygen was 8.8 mg/L. The effluent pH from the aeration channel increased from 7.5 to 7.7, ORP decreased from +91 to +40 mV, and sulfate decreased slightly from 1,170 to 1,160 mg/L. No excess sulfide was observed. All of the target metals except for soluble chromium increased slightly. Excess alkalinity decreased slightly, likely in response to residual metals precipitating as metal hydroxides.

Recirculation Reaction Chemistry. Influent ARD is combined with the effluent from Bioreactor No.2 and sodium hydroxide to form precipitates in the settling pond. Settling pond supernatant is at a near neutral pH and is slightly reducing, containing residual metals, excess sulfate, and excess bicarbonate alkalinity. A portion of the settling pond supernatant is recirculated to the head of Bioreactor No.1, where it is combined with ethanol to provide a carbon substrate for the sulfate-reducing bacteria.

Observed changes in ARD chemistry in the effluent from the two bioreactors were primarily due to the reduction of sulfate to sulfide by sulfate-reducing bacteria and the generation of acetate associated with incomplete oxidation of ethanol and alkalinity during the complete oxidation of ethanol to carbon dioxide. Sulfide combines with excess metals to form metal sulfide precipitates. Because the partially-treated ARD in the bioreactors is at a neutral pH condition, residual metals actively precipitate in the bioreactors, while excess sulfides pass out of the two bioreactors to the settling pond.

System influent ARD and the effluent from Bioreactor No.2 are combined at the head of the settling pond. On August 19, 2004, after combining the two ARD streams (8:1 dilution), pH increased from 3 to 6.8, ORP decreased from 510 to -114 mV, sulfate decreased from 1,630 to 1,156 mg/L, and sulfide increased from 0 to 44 mg/L, and target metals decreased from 142 mg/L to 18 mg/L. Field and analytical laboratory chemical parameters documenting reaction chemistry are provided in Table 2-11.

After the two ARD streams are combined, chemistry is driven by the addition of sodium hydroxide. Sodium hydroxide addition consumes mineral acidity, and converts bisulfide to sulfide, which is necessary to precipitate iron as iron sulfide. Sodium hydroxide also provides a source of hydroxide ion for ferric hydroxide precipitation, which occurs if the recirculation system is nonfunctional.

During the contact of metal-rich influent ARD and sulfide-rich Bioreactor No.2 effluent in the settling pond, combined solution pH increased from 6.8 to 7.2 in the pond supernatant, ORP shifted from moderately to slightly reducing (-117 to -27 mV), sulfate increased from 1,156 to 1,190 mg/L, and all of the excess sulfide (44 mg/L) from the bioreactors was oxidized or consumed. The data also indicate that mineral acidity was reduced as evidenced by an increase in pH and a decrease in solution ORP. Bicarbonate alkalinity decreased from 233 to 210 mg/L after addition of acidic influent ARD.

Target metals decreased 71 percent across the settling pond (primarily aluminum at 97 percent, copper at 92 percent, iron at 61 percent, and zinc at 83 percent). Divalent metals were removed primarily by sulfide precipitation, while aluminum was removed by metal hydroxide and oxyhydroxide precipitation at a neutral pH condition. Insufficient sulfide was present in the settling pond to precipitate all of the metals

Table 2-11. Recirculation Unit Operation Reaction Chemistry

Parameter	Unit	Bioreactor No.1			Bioreactor No.2			System Influent	Combined Influent
		Influent	Effluent	Change	Influent	Effluent	Change		
pH	(SU)	7.2	7.2	0	7.2	7.3	0.1	3	6.8
Oxidation Reduction Potential	(mV)	-27	-174	-147	-174	-202	-28	510	-114
Total Iron (dissolved)	(mg/L)	4.9	0.26	-4.6	0.26	0.25	-0.01	99.5	12.5
Specific Conductance	(µmhos/cm)	2,595	2,569	-26	2,569	2,555	-14	2,572	2,557
Dissolved Oxygen	(mg/L)	1.9	0.3	-1.6	0.3	1.4	1.1	1.6	1.4
Temperature	(°C)	19.4	20.1	0.7	20.1	20.1	0	16.7	19.7
Sulfate	(mg/L)	1,190	1,160	-30	1,160	1,090	-70	1,630	1,156
Sulfide	(mg/L)	0	27	27	27	50	23	0	43.8
Total Alkalinity	(mg/L)	210	209	-1	209	266	57	<2	233
Total Dissolved Solids	(mg/L)	2,090	2,060	-30	2,060	2,150	90	3,040	2,260

µmhos/cm = Micromhos per centimeter mV = Millivolt SU = Standard unit
 °C = Degree Celsius mg/L = Milligram per liter

Data collected on August 19, 2004 at a system influent flow rate of 32 L/min, a recirculation rate of 227 L/min, and a system effluent rate of 28 L/min

Parameter	Unit	Settling Pond			Flushing Pond			Aeration Channel		
		Combined Influent	Effluent	Change	Influent	Effluent	Change	Influent	Effluent	Change
pH	(SU)	6.8	7.2	0.4	7.2	7.6	0.4	7.6	7.6	0
Oxidation Reduction Potential	(mV)	-114	-27	87	-27	103	130	103	10	-93
Total Iron (dissolved)	(mg/L)	12.5	4.9	-7.6	4.9	0.1	-4.8	0.1	0.27	0.17
Specific Conductance	(µmhos/cm)	2,557	2,595	38	2,595	2,674	79	2,674	2,660	-14
Dissolved Oxygen	(mg/L)	1.4	1.9	0.48	1.9	4.1	2.2	4.1	2.1	-2
Temperature	(°C)	19.7	19.4	-0.3	19.4	21	1.6	21	21.3	0.3
Sulfate	(mg/L)	1,156	1,190	34	1,190	1,260	70	1,260	1,200	-60
Sulfide	(mg/L)	44	0	-44	0	0	0	0	0	0
Total Alkalinity	(mg/L)	233	210	-23	210	208	-2	208	202	-6
Total Dissolved Solids	(mg/L)	2,260	2,090	-170	2,090	2,160	70	2,160	2,140	-20

µmhos/cm = Micromhos per centimeter mV = Millivolt NC = Not calculated
 °C = Degree Celsius mg/L = Milligram per liter SU = Standard unit

Data collected on August 19, 2004 at a system influent flow rate of 32 L/min, a recirculation rate of 227 L/min, and a system effluent rate of 28 L/min

out of solution. Recirculation of a portion of the settling pond supernatant to the head of Bioreactor No.1 provides an opportunity to generate additional sulfide necessary to remove residual metals (primarily iron) from solution.

After recirculation of a portion of the settling pond supernatant to Bioreactor No.1, the bioreactor effluent pH remained at 7.2, ORP shifted from slightly to moderately reducing (-27 to -174 mV), sulfate decreased from 1,190 to 1,160 mg/L, and 27 mg/L of excess sulfide was generated. Target metals decreased 92 percent across bioreactor No.1 (primarily aluminum at 33, iron at 95 percent, and nickel at 84 percent). Divalent metals were removed primarily by sulfide precipitation. All soluble metals concentrations were below discharge standards. Bicarbonate alkalinity essentially remained unchanged.

Bioreactor No.2 effluent pH increased slightly from 7.2 to 7.3, ORP shifted to slightly more reducing (-174 to -202 mV),

sulfate decreased from 1,160 to 1,090 mg/L, and excess sulfide generated doubled (27 to 50 mg/L). Target metals concentrations remained essentially unchanged. Excess sulfide generated in the bioreactor is combined with system influent ARD as described above to precipitate metal sulfides in the settling pond. Bicarbonate alkalinity increased from 209 to 266 mg/L due to biological oxidation of ethanol. Organic analysis for residual ethanol or metabolites was not conducted as a part of the demonstration. However, the technology developer has indicated that approximately one-third of the ethanol is incompletely oxidized to acetate within the bioreactors (Tsukamoto 2005b).

As a point of comparison, during cold weather conditions (water temperature 3°C) on December 3, 2004, sulfate decreased from 1,310 to 1,300 mg/L (0.8 percent) and total iron decreased from 10.1 to 7.0 mg/L (30.7 percent) across the two bioreactors. Colder water temperature (3°C versus 20°C) appears to slow sulfate reduction (0.8 versus 8 percent) as well

as iron removal (30.7 versus 95 percent). A larger amount of residual iron was recirculated from the settling pond to the head of the bioreactors in response to less available sulfide necessary for iron sulfide precipitation. Across the system as a whole, both low temperature and high influent and recirculation flows suppress sulfate reduction to sulfide and iron removal. The impact on temperature on sulfate reduction and iron removal is presented in Table 2-12.

Table 2-12. Impact of Temperature on Sulfate Reduction and Iron Removal During Recirculation Operations

Date	Temp (°C)	Sulfate Mass Removed (kg/day)	Sulfate Removal Efficiency (%)	Iron Mass Removed (kg/day)	Iron Removal Efficiency (%)	Flow (L/min)
6/14/04	13.7	7.3	7.6	6	96.6	42
8/19/04	14.7	19.8	26.4	4.5	99.5	32
12/3/04	3.1	7.9	12.5	4.8	91.7	29
2/3/05	6.3	10.8	19.7	4.3	97.3	25
3/17/05	5.5	21.9	35.3	4.5	99.4	28
4/24/05	8.6	33.5	18.5	13.3	98.3	83
6/2/05	13.7	15.6	8	13.5	97.8	72
% = Percent kg/day = Kilogram per day °C = Degree Celsius L/min = Liter per minute						

A portion of the settling pond supernatant also discharges to the flushing pond for extended settling. The effluent pH from the flushing pond increased from 7.2 to 7.6, ORP shifted from slightly reducing (-27 mV) to moderately oxidizing (+103 mV), and sulfate increased from 1,190 to 1,260 mg/L. The increase in sulfate may be the result of the dissolution of suspended colloidal material and oxidation of sulfide. Soluble iron decreased by 98 percent from 4.9 to 0.1 mg/L likely in response to agglomeration of colloidal iron and particle settling. All other target metal concentrations, with the exception of aluminum, nickel, and zinc increased slightly. Bicarbonate alkalinity remained essentially unchanged at 208 mg/L.

After extended settling, treated ARD passes out of the flushing pond to an aeration channel off-gas carbon dioxide, introduce oxygen to the water, and precipitate residual metals from solution. Effluent dissolved oxygen was 2.1 mg/L, which is lower than observed during gravity flow operations. Low dissolved oxygen was observed for about 3 months following conversion to recirculation operations then increased to levels observed during gravity flow operations. The effluent pH from the aeration channel remained at about 7.6, ORP decreased from +103 to +10 mV, and sulfate decreased from 1,260 to 1,200 mg/L. No excess sulfide was observed. Soluble aluminum, iron, and arsenic increased slightly, while all other target metals decreased slightly in response to metal hydroxide precipitation at a neutral pH condition. Excess alkalinity decreased slightly, likely in response to residual metals precipitating as metal hydroxides.

2.5.3.3 Metals Removal by Unit Operation

Metals removal by each bioreactor unit operation is described below for both the gravity flow mode (March 24, 2004) and recirculation mode (August 19, 2004) of operation.

Gravity Flow Operations. Aluminum, copper, iron, lead, nickel, selenium, and zinc are the metals of concern in the ARD from Aspen Seep. All of the dissolved metals of concern exceeded their discharge standards after sodium hydroxide addition and initial settling in the pretreatment pond. Pretreatment pond dissolved metals removal efficiencies ranged from -48 to 35 percent, with the majority of the mass removal associated with aluminum and iron oxides and oxyhydroxides. No sulfate reduction occurred in the pretreatment pond. A summary of unit operations concentration and removal efficiency data for the dissolved metals of concern is presented in Table 2-13 for gravity flow unit operations on March 24, 2004.

Following about a 3 percent reduction in sulfate concentration (40 mg/L) within Bioreactor No.1, the majority of the dissolved metals of concern continued to exceed their discharge standards, with the exception of copper and zinc, which appear to have precipitated as metal sulfides from solution. The concentration of aluminum and iron also decreased substantially, but precipitation was limited by too low of a pH in the bioreactor. Bioreactor No.1 dissolved metals removal efficiencies ranged from 2 to 99.1 percent, with the majority of the mass removal associated with aluminum, copper, iron, and zinc. Following an 12 percent reduction in sulfate concentration (170 mg/L) within Bioreactor No.2, the majority of dissolved metals of concern continued to exceed their discharge standards, with the exception of copper, lead, and zinc, which appear to have continued to precipitate as metal sulfides from solution. The concentration of aluminum and iron also continued to decrease substantially. Bioreactor No.2 dissolved metals removal efficiencies ranged from 10 to 15 percent, with the majority of the mass removal associated with aluminum and iron.

Following sodium hydroxide addition to bioreactor effluent, which raised the pH to near neutral condition, and additional sulfide generation, metal sulfide precipitation, and solids settling in the settling and flushing ponds, only selenium exceeded its discharge standard, though not at a concentration that was statistically significant. Settling and flushing pond dissolved metals removal efficiencies ranged from 25 to 99.9 percent, with the majority of the mass removal associated with aluminum and iron. Precipitation of aluminum and iron required a near neutral pH condition.

All of the metals of concern, with the exception of selenium, met discharge standards at the toe of the rock lined aeration channel after hydrogen sulfide off-gassing and oxygen

Table 2-13. Gravity Flow Unit Operation Dissolved Metals Removal Efficiencies

Parameter	Pretreatment Pond			Bioreactor No.1		Bioreactor No.2		Settling and Flushing Ponds		Aeration Channel		System Removal Efficiency (%)
	Influent (µg/L)	Effluent (µg/L)	Removal Efficiency (%)	Effluent (µg/L)	Removal Efficiency (%)	Effluent (µg/L)	Removal Efficiency (%)	Effluent (µg/L)	Removal Efficiency (%)	Effluent (µg/L)	Removal Efficiency (%)	
Aluminum	36,900	34,200	7.3	26,100	23.7	22,200	14.9	31.7	99.9	144	-354	99.6
Arsenic	2.8	<2.3	NC	3	NC	<2.3	NC	<2.3	NC	2.4	NC	14.3
Cadmium	0.4	<0.23	NC	<0.23	NC	<0.23	NC	<0.23	NC	<0.23	NC	42.5
Chromium	17.2	13.9	19.2	13.3	4.3	14.3	NC	6.9	51.8	6.4	7.3	62.8
Copper	656	614	6.4	5.7	99.1	6.1	NC	4.3	29.5	5.6	NC	99.1
Iron	113,000	73,100	35.3	71,700	1.9	63,700	11.2	186	99.7	389	-109	99.7
Lead	5.3	5.8	NC	5.8	NC	5	NC	2.9	42.0	3.4	NC	35.8
Nickel	481	449	6.7	350	22.1	300	14.3	49.2	83.6	53.1	-7.9	89
Selenium	9.6	14.2	-47.9	10.8	23.9	10.6	NC	7.9	25.5	8.7	NC	9.4
Zinc	702	661	5.8	32	95.2	28.8	10.0	3.7	87.2	10.3	-178	98.5

% = Percent
µg/L = Microgram per liter
NC = Not calculated as influent and effluent concentrations were not statistically different
Data collected on March 24, 2004 at a flow rate of 45 L/min

Table 2-14. Gravity Flow Unit Operation Metals and Sulfate Load Reduction

Parameter	Pretreatment Pond			Bioreactor No.1		Bioreactor No.2		Settling and Flushing Ponds		Aeration Channel	
	Influent (g/day)	Effluent (g/day)	Mass Change (g/day)	Effluent (g/day)	Mass Change (g/day)	Effluent (g/day)	Mass Change (g/day)	Effluent (g/day)	Mass Change (g/day)	Effluent (g/day)	Mass Change (g/day)
Aluminum	2,391	2,341	-50	1,834	-508	1,471	-363	7.9	-1,463	30.3	22.4
Arsenic	0	0.23	0.23	0	-0.23	0.22	0.22	0	-0.22	0.29	0.29
Cadmium	0.027	0.027	0	0	-0.03	0	0	0	0	0	0
Chromium	1.06	0.95	-0.11	0.90	-0.05	0.83	-0.07	1.5	0.67	0.52	-0.98
Copper	41.9	42.1	0.2	4.4	-37.3	3.5	-0.90	0.28	-3.2	0.51	0.23
Iron	7,322	5,612	-1,710	5,035	-577	4,128	-907	103.7	-4,204	108	3.9
Lead	0.32	0.38	0.06	0.356	-0.02	0.29	-0.07	0.13	-0.16	0.19	0.06
Nickel	31.0	30.6	-0.34	24.0	-6.7	19.4	-4.5	4.0	-15.4	4.6	0.59
Selenium	0.79	0.90	0.11	0.804	-0.10	0.64	-0.16	0.58	-0.06	0.34	-0.24
Zinc	44.8	46.1	1.21	8.1	-37.9	6.0	-2.1	0.38	-5.6	0.95	0.57
Target Metals	9,801	8,074	-1,759	6,907	-1,166	5,630	-1,278	119	-5,511	145	26.8
Total Metals ⁽¹⁾	38,350	36,690	-1,660	36,290	-400	31,085	-5,205	24,200	-6,885	23,120	-1,080
Sulfate	97,850	98,500	650	95,900	-2,600	84,890	-11,010	75,820	-9,070	75,170	-650
Sulfide	0	0	0	870	870	3,670	2,800	0	-3,670	0	0

(1) Total metals excluding added sodium from sodium hydroxide addition
g/day = gram per day
Data collected on March 24, 2004 at a flow rate of 45 L/min

entrainment. Selenium exceeded its discharge standard, though not at a concentration that was statistically significant. Removal efficiencies for almost all of the dissolved metals were negative, indicating that either suspended solids discharged from the flushing pond were dissolving into solution or that solids were being flushed out of the aeration channel. Review of unfiltered channel influent and effluent data indicate that solids were being actively flushed from the channel during the sampling event. Treatment system removal efficiencies for the dissolved metals of concern ranged from 9 percent for selenium to 99.7 percent for iron at a concurrent sulfate removal efficiency of 23 percent.

An evaluation of target metals load reduction, sulfate load reduction, and sulfide generation was prepared for gravity flow operations based on unit operations data collected on

March 24, 2004 and is presented in Table 2-14. A total metals load of 38.3 kg and a sulfate load of 97.9 kg entered the bioreactor treatment system at 45 L/min. A total of 1.7 kg of metals was precipitated out of solution, following the addition of 4.1 kg of sodium hydroxide to the ARD in the pretreatment pond, leaving 36.7 kg of metals (excluding sodium addition) and 98.5 kg of sulfate in pretreatment pond effluent.

Sulfate-reducing bacteria in Bioreactor No.1 removed 2.6 kg of sulfate (generating 0.9 kg sulfide) and 0.4 kg of metals from solution as a metal sulfide precipitate, leaving 36.3 kg of metals (excluding sodium addition) and 95.9 kg of sulfate in Bioreactor No.1 effluent for further treatment in Bioreactor No.2. An additional 5.2 kg of metals and 11 kg of sulfate (generating 3.7 kg sulfide) were removed from solution as a metal sulfide precipitate in Bioreactor No.2.

A total of 31 kg of metals (excluding sodium addition) and 84.9 kg of sulfate were discharged from Bioreactor No.2 to the settling and flushing ponds in conjunction with 11.9 kg of sodium hydroxide for extended metal sulfide and metal oxide and oxyhydroxide contact, precipitation, and settling, removing 6.9 kg of metals and 9.1 kg of sulfate from solution. A total of 24.2 kg of metals (excluding sodium addition) and 75.8 kg of sulfate were discharged from the settling and flushing ponds to the rock lined aeration channel to entrain oxygen and remove additional metals from solution as metal hydroxides and oxyhydroxides. A total of 1.1 kg of metals and 0.7 kg of sulfate were removed from solution along the aeration channel. Overall, a total of 16 kg of sodium hydroxide and 4.5 kg of sulfide were required to neutralize acidity and precipitate 15.2 kg of total metals (9.7 kg of target metals) from ARD.

Recirculation Operations. Aluminum, copper, iron, lead, nickel, selenium, and zinc are the metals of concern in the ARD from Aspen Seep. Iron and selenium were the only dissolved metals of concern that exceeded their discharge standards in the settling pond effluent after combining the influent ARD, Bioreactor No.2 effluent, and sodium hydroxide in the settling pond. Settling pond metals removal efficiencies ranged from 3 to 97 percent, with the majority of the mass removal associated with aluminum, copper, iron, and zinc. No sulfate reduction occurred in the settling pond likely due to the short HRT and biologically stressful pond conditions. A summary of unit operations concentration and removal efficiency data for the metals of concern is presented in Table 2-15 for recirculation unit operations.

Following recirculation of a portion of the settling pond effluent to the head of Bioreactor No.1, the sulfate-reducing bacteria removed an additional 3 percent reduction of sulfate from solution (30 mg/L). All of the dissolved metals of concern were below their discharge standards, with the exception of selenium. Bioreactor No.1 metals removal efficiencies ranged from -52 to 95 percent, with the majority of the mass removal associated with aluminum, iron, and nickel as the pH within the bioreactor was near neutral condition. Following a 6 percent reduction in sulfate concentration (70 mg/L) within Bioreactor No.2, all of the dissolved metals of concern were below their discharge standards, with the exception of selenium. Bioreactor No.2 metals removal efficiencies ranged from -65 to 13 percent. There was no significant reduction in metals mass within Bioreactor No.2. Instead, biological activity generated excess sulfide in the bioreactor effluent for downstream blending with ARD influent in the settling pond. Comparison of the amount of sulfate reduced between the two modes of operation is difficult because the flow rate through the bioreactors is up to 8 times higher with recirculation. In fact, if the recirculation rate was decreased slightly sulfate reduction would exceed that of the gravity flow system due to the more favorable environmental conditions (neutral pH and low metals concentrations).

After initial precipitation in the settling pond, effluent was held in the flushing pond to allow extended time for metal sulfide precipitation and settling. Only selenium exceeded its discharge standard, though not at a concentration that was statistically significant. Sulfate-reducing bacteria did not appear to be active in the flushing pond. Flushing pond metals removal efficiencies ranged from -60 to 98 percent, with the majority of the mass removal associated with aluminum, iron, and nickel.

All of the metals of concern, with the exception of selenium, met discharge standards at the toe of the rock lined aeration channel following gas exchange. Selenium exceeded its discharge standard, though not at a concentration that was statistically significant. Removal efficiencies for aluminum, arsenic, and iron were negative, indicating that suspended solids or colloids discharged from the flushing pond were dissolving into solution. The system as a whole removed from 40 to 99.7 percent of the target metals from solution. Treatment system removal efficiencies for the metals of concern ranged from 41 percent for arsenic to 99.7 percent for iron at a concurrent sulfate removal efficiency of 26 percent.

An evaluation of target metals load reduction, sulfate load reduction, and sulfide generation was prepared for recirculation operations based on unit operations data collected on August 19, 2004 and is presented in Table 2-16. A total metals load of 28.2 kg and a sulfate load of 75.1 kg entered the bioreactor treatment system at 32 L/min. The influent ARD was blended with 152 kg of metals and 356 kg of sulfate discharging from Bioreactor No.2 at 227 L/min. The combined influent metals load of 180 kg and sulfate load of 431 kg was blended with 5.8 kg of sodium hydroxide and discharged to the settling pond at 259 L/min. A total of 4.1 kg of metals was removed from solution and 12.4 kg of sulfate entered solution (sulfide oxidation) in the settling pond, leaving 176 kg of metals (excluding sodium addition) and 443 kg of sulfate in settling pond supernatant, a portion of which was recirculated to the head of Bioreactor No.1 at 227 L/min.

Sulfate-reducing bacteria in Bioreactor No.1 removed 9.8 kg of sulfate (generating 3.3 kg sulfide), leaving 379 kg of sulfate in solution for further treatment in Bioreactor No.2. Approximately 1.2 kg of metals was deposited in Bioreactor No.1. An additional 1.2 kg of metals and 22.9 kg of sulfate (generating 4.4 kg sulfide) were removed from solution as a metal sulfide precipitate in Bioreactor No.2.

A portion of the settling pond supernatant containing 21.8 kg of metals and 54.8 kg of sulfate was also discharged (32 L/min) to the flushing pond for extended metal sulfide precipitation and settling, removing 2.3 kg of metals and 4 kg of sulfate from solution. A total of 19.5 kg of metals (excluding sodium addition) and 50.8 kg of sulfate were discharged from the flushing pond to the rock lined aeration channel to entrain oxygen and remove additional metals from

Table 2-15. Recirculation Unit Operation Dissolved Metals Removal Efficiencies

Parameter	Bioreactor No.1		Bioreactor No.2		Settling Pond				Flushing Pond		Aeration Channel		System
	Effluent (µg/L)	Removal Efficiency (%)	Effluent (µg/L)	Removal Efficiency (%)	System Influent (µg/L)	Combined Influent (µg/L)	Effluent (µg/L)	Removal Efficiency (%)	Effluent (µg/L)	Removal Efficiency (%)	Effluent (µg/L)	Removal Efficiency (%)	Removal Efficiency (%)
Aluminum	104	32.9	108	NC	40,400	5,086	155	97.0	94.7	57.4	105	-10.9	99.7
Arsenic	5.9	NC	5	NC	<2.1	4.64	4.4	NC	3.7	15.9	14.7	-297	-600
Cadmium	0.21	40.0	0.41	NC	0.94	0.48	0.35	26.4	0.39	NC	<0.16	59.0	83.0
Chromium	11.8	NC	12	NC	19.3	12.9	12.2	5.4	12.2	NC	11.6	4.9	39.9
Copper	7.1	14.5	7.6	NC	766	101.3	8.3	91.8	10	-20.5	9.5	NC	98.8
Iron	266	94.6	247	7.1	99,500	12,510	4,900	60.8	109	97.8	269	-147	99.7
Lead	4.2	NC	4	NC	5.9	4.23	4.2	NC	6.7	-59.5	3.1	53.7	47.5
Nickel	11.7	83.9	10.2	12.8	531	74.6	72.6	2.6	54.8	24.5	18.9	65.5	96.4
Selenium	11.4	-52.0	11.6	NC	14.4	11.95	7.5	37.2	11.1	-48.0	7.8	29.7	45.8
Zinc	6.3	63.4	10.4	-65.1	755	102.4	17.2	83.2	10.2	40.7	4.5	55.9	99.4

% = Percent
µg/L = Microgram per liter

NC = Not calculated as influent and effluent concentrations were not statistically different
Data collected on August 19, 2004 at a system influent flow rate of 32 L/min, a recirculation rate of 227 L/min, and a system effluent rate of 28 L/min

Table 2-16. Recirculation Unit Operation Metals and Sulfate Load Reduction

Parameter	Bioreactor No.1		Bioreactor No.2		Settling Pond				Flushing Pond			Aeration Channel	
	Effluent (g/day)	Mass Change (g/day)	Effluent (g/day)	Mass Change (g/day)	System Influent (g/day)	Combined Influent (g/day)	Pond ⁽²⁾ Effluent (g/day)	Mass Change (g/day)	Influent (g/day)	Effluent (g/day)	Mass Change (g/day)	Effluent (g/day)	Mass Change (g/day)
Aluminum	127	-255	109	-18	1,862	1,971	436	-1,535	53.9	6.9	-47	4.8	-2.1
Arsenic	0	0	0.85	0.85	0	0.85	0	-0.85	0	0	0	0.6	0.6
Cadmium	0	-0.08	0.08	0.08	0.05	0.14	0.09	-0.05	0.01	0	-0.01	0	0
Chromium	3.92	0	3.82	-0.10	0.91	4.74	4.47	-0.27	0.55	0.48	-0.07	0.53	0.05
Copper	3.5	-4.45	3.73	0.23	34.9	38.61	9.06	-29.6	1.12	0.47	-0.65	0.32	-0.15
Iron	1,026	-1,566	879	-147	4,567	5,446	2,958	-2,488	365	41.5	-324	21.5	-20.1
Lead	1.54	0.13	1.24	-0.29	0.33	1.57	1.6	0.03	0.2	0.16	-0.04	0.26	0.1
Nickel	10.9	-13.1	9.35	-1.57	24.4	33.7	27.4	-6.3	3.38	2.15	-1.23	0.9	-1.25
Selenium	3.37	-0.69	2.91	-0.46	0.92	3.83	4.62	0.79	0.57	0.38	-0.19	0.44	0.06
Zinc	4.48	-4.67	4.77	0.29	34.9	39.7	10.5	-29.2	1.29	1.25	-0.04	0.43	-0.82
Sum of Target Metals	1,181	-1,844	1,015	-166	6,525	7,540	3,452	-4,088	426.5	53.4	-373	29.8	-23.6
Total Metals ⁽¹⁾	153,350	1,160	152,140	-1,210	28,200	180,350	176,300	-4,050	21,780	19,450	-2,330	20,150	700
Sulfate	379,200	-9,800	356,300	-22,900	75,110	431,400	443,820	12,420	54,840	50,800	-4,040	48,380	-2,420
Sulfide	3,270	3,270	7,640	4,370	0	7,640	0	-7,640	0	0	0	0	0

(1) Total metals excluding added sodium from sodium hydroxide addition g/day = gram per day Recirc = Recirculation
(2) Settling pond effluent loads are split between recirculation and flushing pond influent
Data collected on August 19, 2004 at a system influent flow rate of 32 L/min, a recirculation rate of 227 L/min, and a system effluent rate of 28 L/min

solution as metal hydroxides and oxyhydroxides. A total of 2.4 kg of sulfate was removed from solution along the aeration channel, while total metals mass increased by 0.7 kg due to entrainment of metals along the aeration channel. Overall, a total of 5.8 kg of sodium hydroxide and 7.6 kg of sulfide were required to neutralize acidity and precipitate 8 kg of total metals (6.5 kg of target metals) from ARD.

Operation of the treatment system in recirculation mode required 49 percent less sodium hydroxide and reduced 41 percent more sulfate to sulfide than the treatment system operated in gravity flow mode. Metals removal in each mode of operation was similar.

2.5.3.4 Solids Separation

Solids separation techniques used during both the gravity flow mode (March 24, 2004) and recirculation mode (August 19, 2004) of operation are described below.

Gravity Flow Operations. Precipitate generated during operation of the bioreactor treatment system in gravity flow mode is separated from ARD using a pretreatment pond, bioreactor pore space, a settling pond, and a flushing pond. Sodium hydroxide is used during the pretreatment process to raise the influent pH to Bioreactor No.1 to approximately

Table 2-17. Gravity Flow Operation Solids Separation Efficiencies

Parameter	Pretreatment Pond			Bioreactor No.1			Bioreactor No.2		
	Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)	Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)	Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)
Aluminum	36,400	36,300	0.3	36,300	28,300	22	28,300	22,700	19.8
Arsenic	4.2	<2.2	47.6	<2.2	<2.3	-4.6	<2.3	3.4	-47.8
Cadmium	0.41	0.42	-2.4	0.42	<0.23	45.2	<0.23	<0.23	0
Chromium	16.4	14.7	10.4	14.7	13.9	5.4	13.9	12.8	7.9
Copper	647	653	-0.9	653	67.6	89.7	67.6	53.7	20.6
Iron	113,000	87,000	23	87,000	77,700	10.7	77,700	63,700	18
Lead	4.9	5.9	-20.4	5.9	5.5	6.8	5.5	4.4	20
Nickel	478	475	0.6	475	370	22.1	370	300	18.9
Selenium	12.2	14	-14.8	14	12.4	11.4	12.4	9.9	20.2
Zinc	692	714	-3.2	714	125	82.5	125	92.7	25.8
TSS	36,000	87,000	-142	87,000	9,000	89.7	9,000	16,000	-77.8

Data collected on March 24, 2004 at a flow rate of 45 L/min

% = Percent
µg/L = Microgram per liter

Parameter	Settling and Flushing Ponds			Aeration Channel			Cumulative Percent Removal (%)
	Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)	Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)	
Aluminum	22,700	122	99.5	122	468	-284	98.7
Arsenic	3.4	<2.3	32.4	<2.3	<2.2	4.4	47.6
Cadmium	<0.23	<0.23	0	<0.23	<0.23	0	43.9
Chromium	12.8	23.2	-81.3	23.2	8	65.5	51.2
Copper	53.7	4.3	92	4.3	7.8	-81.4	98.8
Iron	63,700	1,600	97.5	1,600	1,660	-3.8	98.5
Lead	4.4	2	54.6	2	2.9	-45	40.8
Nickel	300	62.4	79.2	62.4	71.5	-14.6	85
Selenium	9.9	8.9	10.1	8.9	5.2	41.6	57.4
Zinc	92.7	5.9	93.6	5.9	14.7	-149	97.9
TSS	16,000	6,000	62.5	6,000	6,000	0	83.3

Data collected on March 24, 2004 at a flow rate of 45 L/min

% = Percent
µg/L = Microgram per liter

pH 4. Metal hydroxide and oxyhydroxide precipitate is formed during the process, a portion of which settles within the 10.3 hour pond HRT at a flow rate of 45 L/min. Approximately 23 percent of the iron in the influent ARD precipitated and settled in the pretreatment pond during this process. An increase in TSS concentration in the pond effluent indicates that an additional 11 percent of the iron precipitate that was formed in the pretreatment pond was passed out of the pond and into bioreactor No.1. On average, approximately 3.9 kg of settled solids are generated in the pretreatment pond each day. From 2,000 to 7,000L of solids are flushed out of the pretreatment pond to the flushing pond approximately once a month. Settled solids are determined by calculating the differences between influent and effluent metals and anion concentrations for each unit operation, identifying likely metal-anion pairs, and summing the masses of metal-anion pairs that likely formed precipitates. Total metals removal efficiencies for each unit operation are provided in Table 2-17.

Metal sulfide precipitate is formed within the two bioreactors as sulfate is converted to sulfide by sulfate-reducing bacteria. Precipitate formation and settling within Bioreactor No.1 occurred over a 55.6 hour HRT. Metal sulfide precipitation and settling in Bioreactor No.1 provided an additional 5 to 90 percent removal of influent metals (primarily aluminum, copper, iron, nickel, and zinc) from solution. An additional 2 percent of the aluminum, 10 percent of the copper, and 13 percent of the zinc precipitates that were formed in bioreactor No.1 were passed out of the bioreactor to bioreactor No.2. However, the decrease in TSS concentration in the bioreactor effluent, primarily related to iron precipitate, confirmed that the majority of the solids were retained in the bioreactor.

Precipitate formation and settling within Bioreactor No.2 occurred over a 31.5 hour HRT. Metal sulfide precipitation and settling in Bioreactor No.2 provided an additional 8 to 26 percent removal of influent metals (primarily aluminum, copper, iron, nickel, and zinc) from solution. An additional 2 percent of the aluminum, 70 percent of the copper, and 66

percent of the zinc precipitates that were formed in bioreactor No.2 passed out of the bioreactor to the settling pond. The slight increase in TSS concentration in the bioreactor effluent confirmed that the majority of the solids were passed out of the bioreactor. On average, approximately 1 kg of settled solids are generated in Bioreactor No.1 and 12 kg of settled solids in Bioreactor No.2 each day. Every 2 months approximately 15,000 L of solids are flushed out of the two bioreactors to the flushing pond. Formation of sulfide precipitates is limited by low solution pH (4 to 5.5); therefore, the bulk of metal sulfide precipitate formation and settling occurs downstream of the bioreactors in the settling pond, after adjustment of effluent pH to a near neutral condition. Maintaining a low pH in the bioreactors reduces the volume of settled solids and the need for bioreactor flushing, which places a stress on the sulfate-reducing bacteria.

Metals and sulfides in the Bioreactor No.2 effluent were combined with sodium hydroxide to raise the pH to a neutral condition, and discharged to the settling pond for the bulk of precipitate formation and solids settling. Effluent from the settling pond was discharged to the flushing pond for extended settling. Metal sulfide, metal hydroxide, and metal oxyhydroxide precipitate is formed during the process, which is allowed to settle within the 172 hour settling pond HRT and 188.9 hour flushing pond HRT. Precipitate formation and settling within the two ponds provided an additional 25.5 to 99.9 percent removal of influent metals (primarily aluminum, copper, iron, nickel, and zinc) from solution. An additional 0.4 percent of the aluminum, 2.2 percent of the iron, and 4.4 percent of the nickel precipitates that were formed in the flushing pond were passed out of the pond to the aeration channel. The decrease in TSS concentration in the effluent confirmed that solids were retained in the settling and flushing ponds. Depth of accumulated solids within the two ponds suggests that approximately 95 percent of the solids are retained in the settling pond, with the other 5 percent of solids retained in the flushing pond. On average, approximately 15.5 kg of settled solids are generated each day in the settling pond and 0.8 kg of settled solids in the flushing pond. Prior to the onset of winter, approximately 32,000 L of solids are transferred out of the settling pond to the flushing pond to maintain an adequate HRT necessary for solids settling.

The concentration of aluminum, copper, iron, lead, nickel, and zinc increased slightly in aeration channel effluent. However, TSS concentrations did not increase and effluent from the aeration channel met EPA discharge criteria. On average, approximately 2.5 kg of solids settle in the aeration channel each day. Collectively, the treatment system generated 33.2 kg of solids each day. Settled solids are pumped out of the flushing pond and settling pond and passed through bag filters for dewatering each fall to provide adequate solids storage capacity over the following winter. During the fall of 2005, a bag filtration process was used to dewater settled solids pumped out of the settling and flushing ponds prior to disposal

as a nonhazardous solid. The settled solids were generated by both gravity flow and recirculation modes of operation. The bag filtration process involved the filling of a bag filter with settled solids, followed by gravity drainage of water through the filter fabric for up to two weeks. Free water was allowed to drain back into the flushing pond following filtration. The process was repeated using a new bag filter placed on top of an older bag. Additional solids dewatering occurred in the bags on the bottom of the stack due to compression.

Approximately 200,000 L of settled solids from both modes of operation were discharged to seven bag filters over 100 days of solids dewatering, generating approximately 3,900 kg (4.3 dry tons) of solids in the fall of 2005. The bag filters removed 10 percent of the water from the settled solids and concentrated metals by 120 percent. The bag filters remain on site and are being allowed to air dry to further reduce moisture content prior to disposal. The bag filtration process is limited to summer and early fall when temperatures are warm enough to prevent freezing of the filter membrane.

Recirculation Operations. Precipitate generated during operation of the bioreactor treatment system in recirculation mode is separated from ARD using a settling pond, bioreactor pore space, and a flushing pond. Residual metals and excess sulfide in Bioreactor No.2 effluent were combined with influent ARD and sodium hydroxide to raise the pH to a neutral condition, and discharged to the settling pond for the bulk of precipitate formation and solids settling. A small portion of the settling pond effluent was discharged to the flushing pond, while the majority was recirculated to the head of Bioreactor No.1 for additional sulfide generation. Metal sulfide, metal hydroxide, and metal oxyhydroxide precipitate is formed in the pond, which is allowed to settle within the 29.9 hour settling pond HRT at a combined flow rate of 259 L/min. Precipitate formation and settling provided 6 to 78 percent removal of combined influent metals and 38 to 97 percent removal of system influent metals (primarily aluminum, copper, iron, nickel, and zinc) from solution. An additional 19.1 percent of the aluminum, 15.2 percent of the copper, 15.1 percent of the iron, and 9.6 percent of the zinc precipitates that were formed in the settling pond were passed out of the pond to both the head of Bioreactor No.1 and the flushing pond for extended settling. The TSS concentration increased in settling pond effluent, indicating that the HRT of the pond was too short to allow adequate solids settling. On average, approximately 9.9 kg of settled solids are generated each day in the settling pond. Prior to the onset of winter, approximately 48,000 L of solids are transferred out of the settling pond to the flushing pond to maintain an adequate HRT necessary for solids settling. Settled solids are determined by calculating the differences between influent and effluent metals and anion concentrations for each unit operation, identifying likely metal-anion pairs, and summing the masses of metal-anion pairs that likely formed precipitates. Total metals removal efficiencies for each unit operation are provided in Table 2-18.

Table 2-18. Recirculation Operation Solids Separation Efficiencies

Parameter	Bioreactor No.1			Bioreactor No.2			Settling Pond			
	Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)	Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)	System Unfiltered Influent (µg/L)	Combined Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)
Aluminum	1,170	389	66.8	389	334	14.1	40,400	5,284	1,170	77.9
Arsenic	<2.1	<2.1	0	<2.1	2.6	-23.8	<2.1	2.3	<2.1	8.7
Cadmium	0.23	<0.16	30.4	<0.16	0.26	-62.5	1.1	0.36	0.23	36.1
Chromium	12	12	0	12	11.7	2.5	19.8	12.7	12	5.8
Copper	24.3	10.7	56	10.7	11.4	-6.5	757	104	24.3	76.6
Iron	7,930	3,140	60.4	3,140	2,690	14.3	99,100	14,602	7,930	45.7
Lead	4.3	4.7	-9.3	4.7	3.8	19.2	7.2	4.2	4.3	-2.4
Nickel	73.4	33.4	54.5	33.4	28.6	14.4	529	90.4	73.4	18.8
Selenium	12.4	10.3	16.9	10.3	8.9	13.6	19.9	10.3	12.4	-20.4
Zinc	28	13.7	51.1	13.7	14.6	-6.6	757	106	28	73.6
TSS	27,000	42,000	-55.6	42,000	7,000	83.3	<10,000	7,000	27,000	-286

% = Percent
µg/L = Microgram per liter

Data collected on August 19, 2004 at a system influent flow rate of 32 L/min, a recirculation rate of 227 L/min, and a system effluent rate of 28 L/min. Combined influent to the settling pond takes into account the mass of metals in the influent ARD as well as the mass of metals in the effluent from bioreactor No.2.

Parameter	Flushing Pond			Aeration Channel			Cumulative System Percent Removal (%)
	Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)	Unfiltered Influent (µg/L)	Unfiltered Effluent (µg/L)	Percent Removal (%)	
Aluminum	1,170	172	85.3	172	120	30.2	99.7
Arsenic	<2.1	<2.1	0	<2.1	14.9	-609	-548
Cadmium	0.23	<0.16	30.4	<0.16	<0.16	0	85.5
Chromium	12	11.9	0.8	11.9	13.2	-10.9	33.3
Copper	24.3	11.7	51.9	11.7	7.9	32.5	99
Iron	7,930	1,030	87	1,030	532	48.4	99.5
Lead	4.3	4	7	4	6.5	-62.5	9.7
Nickel	73.4	53.3	27.4	53.3	22.4	58	95.8
Selenium	12.4	9.4	24.2	9.4	10.8	-14.9	45.7
Zinc	28	31	-10.7	31	10.6	65.8	98.6
TSS	27,000	<10,000	63	<10,000	<10,000	0	0

% = Percent
µg/L = Microgram per liter

Data collected on August 19, 2004 at a system influent flow rate of 32 L/min, a recirculation rate of 227 L/min, and a system effluent rate of 28 L/min

A moderate quantity of metal sulfide precipitate is formed within the two bioreactors as sulfate is converted to sulfide by sulfate-reducing bacteria. Precipitate formation and settling within Bioreactor No.1 occurs over an 11.0 hour HRT at a recirculation rate of 227 L/min. Metal sulfide precipitation and settling in Bioreactor No.1 provided an additional 17 to 67 percent removal of influent metals (primarily aluminum, copper, iron, nickel, and zinc) from recirculated solution. An additional 34.2 percent of the iron, 29.4 percent of the nickel, and 12.3 percent of the zinc precipitates that were formed in bioreactor No.1 were passed out of the bioreactor No.1 to bioreactor No.2. The increase in TSS concentration in the bioreactor effluent confirmed that solids were being passed out of the bioreactor. On average, approximately 2.7 kg of solids settled in Bioreactor No.1 each day.

Precipitate formation and settling within Bioreactor No.2 occurs over a 6.2 hour HRT. Metal sulfide precipitation and settling in Bioreactor No.2 provided an additional 3 to 19 percent removal of influent metals (primarily aluminum, iron, and nickel) from recirculated solution. None of the aluminum, iron, or nickel precipitates were passed out of the bioreactor. The decrease in TSS concentration in the bioreactor effluent confirmed that solids were retained in the bioreactor. On average, approximately 2.7 kg of solids settled in Bioreactor No.2 each day. Every 3 to 4 months approximately 15,000 L of solids are flushed out of the two bioreactors to the flushing pond. Because recirculated ARD within the two bioreactors is near a neutral pH condition, formation and settling of precipitate can readily occur within the bioreactors. However, the majority of precipitate formation and settling occurs in the settling pond and only residual concentrations of metals enter

the bioreactors. Careful control of solids settling and depth of accumulation within the settling pond is required to prevent entrainment of settled solids during recirculation and deposition of solids in the two bioreactors.

Residual metals and sulfide in settling pond effluent are discharged to the flushing pond for extended metals and sulfide contact, precipitate formation, and settling. Metal sulfide, metal hydroxide, and metal oxyhydroxide precipitate is formed and allowed to settle within the 304 hour flushing pond HRT at 28 L/min. Extended settling provided an additional 0.8 to 85 percent removal of influent metals (primarily aluminum, copper, iron, and nickel) from solution. An additional 10.8 percent of the iron precipitate that was formed in the flushing pond was passed out of the pond to the aeration channel. The decrease in TSS concentration in the effluent confirmed that solids were retained in the flushing pond. On average, approximately 5.3 kg of settled solids are generated each day in the in the flushing pond.

Aeration promoted removal of 30 to 66 percent removal of the remaining aluminum, copper, iron, nickel, and zinc from solution. On average, approximately 0.1 kg of solids settled in the aeration channel each day when considering only target metals. However, calcium and magnesium concentrations also increased in system effluent, resulting in a net loss of approximately 1.6 kg of precipitate from the aeration channel each day. TSS concentrations did not increase and the system effluent from the aeration channel met EPA discharge criteria. Metals dissolution and suspended solids carryover to the aeration channel could be minimized by more frequent removal and dewatering of settled solids from the flushing pond. As a whole, the treatment system reduced metals concentrations from 9.7 to 99.7 percent, with many of the target metals exceeding 85 percent removal efficiency. Collectively, the treatment system generated a net mass of 19 kg of solids each day. Settled solids are pumped out of the flushing pond and settling pond and passed through bag filters for dewatering each fall to provide adequate solids storage capacity over the following winter. Bag filtration is discussed under gravity flow operations above.

2.5.4 Evaluation of Solids Handling and Disposal

This section describes solids handling activities conducted during the operation of the bioreactor treatment system. The discussion includes a summary of waste characterization and handling requirements, identifies the sources and quantity of solids from the treatment system, identifies the characteristics of each solid waste stream, and identifies the method of disposal for each solids waste stream.

2.5.4.1 Waste Characterization and Handling Requirements

Bioreactor treatment of ARD generates a metal sulfide, metal hydroxide, metal oxyhydroxide, and calcium carbonate solid waste stream. The solid waste residuals produced by the treatment system were analyzed for hazardous waste characteristics. Determination of waste characteristics is necessary to determine appropriate handling and disposal requirements. Therefore, total and leachable metals analyses were performed on the solid waste streams for comparison to state of California and Federal hazardous waste classification criteria. To determine if the solid waste streams are a Federal Resource Conservation and Recovery Act (RCRA) waste, TCLP results were compared to TCLP limits. To determine whether the solid waste streams are a California hazardous waste, total metals results (wet weight) were compared to California total threshold limit concentration (TTLC) criteria. If a solid waste stream exceeds either Federal TCLP criteria or California TTLC criteria, then the waste is considered to be hazardous and must be disposed of in a permitted treatment, storage, and disposal (TSD) facility.

If a solid waste stream is found to be non-hazardous, then the potential to impact water quality must be evaluated. The leachability of metals from a solid waste stream must be determined using the California WET procedure if disposed of in California or another accepted leaching procedure if disposed of in other states. Deionized water (DI) was used as the WET leaching solution. To determine whether a non-hazardous solid waste stream poses a threat to water quality in California, metals concentrations in WET leachate samples were compared to California soluble threshold limit concentration (STLC) criteria. Solid waste stream samples were also subject to the SPLP, a commonly accepted leaching procedure in other states. If a solid waste stream exceeds the California STLC criteria, then the waste is considered to be a threat to water quality and the waste must be disposed of in a permitted TSD facility or engineering controls implemented to protect water quality. Interpretation of SPLP data are state-specific and are beyond the scope of this discussion. Evaluation of the quantity, characteristics, and disposal of solid waste streams generated by the bioreactor treatment system is presented in Section 2.5.4.2.

2.5.4.2 Bioreactor Treatment System Solids

Operation of the bioreactor treatment system between November 2003 and July 2005 produced about 14.2 dry tons (12,900 kg) of sludge (86 to 99.6 percent moisture), which equals about 0.45 dry ton (410 kg) of sludge per million liters of ARD treated. The estimate of solids generated includes approximately 4.3 dry tons (3,900 kg) of bag filter solids,

10 dry tons (9,100 kg) of settling pond sludge, and 4.3 dry tons (3,900 kg) of flushing pond sludge. The sludge consists mainly of metal sulfides and hydroxides that are high in aluminum, copper, iron, nickel, and zinc. No other waste streams were generated the treatment system. The characteristics of the solid waste streams generated during

treatment system operation are presented in Table 2-19. None of the various sources of sludge were determined to be a RCRA or California hazardous waste and did not pose a threat to water quality. Bag filter solids were shipped off-site to a municipal landfill for disposal pending designation of an on-site disposal area.

Table 2-19. Bioreactor Treatment System Waste Characterization

Parameter	Total Metals ¹ (mg/kg)	Total Metals ² (mg/kg)	Exceed TTLC?	DI WET Metals (mg/L)	Exceed STLC?	TCLP (mg/L)	Exceed TCLP?	SPLP Metals (mg/L)
Pretreatment Pond Sludge								
Antimony	<4.7	<0.21	No	<0.015	No	<0.0058	NA	0.0082
Arsenic	15.1	0.664	No	0.321	No	<0.0052	No	0.0903
Barium	13.5	0.059	No	0.19	No	0.0677	No	0.105
Beryllium	5.2	0.229	No	0.0995	No	0.003	NA	0.0462
Cadmium	<0.31	<0.014	No	<0.0014	No	<0.00054	No	<0.00027
Chromium	11.1	0.488	No	0.13	No	<0.00084	No	0.0725
Cobalt	97.9	4.31	No	1.11	No	0.166	NA	0.174
Copper	487	21.4	No	4.61	No	0.0258	NA	0.614
Lead	<2.5	<0.11	No	0.0493	No	0.0107	No	0.0046
Mercury	1.3	0.057	No	0.00087	No	0.00037	No	0.00031
Molybdenum	<0.99	<0.044	No	<0.0034	No	<0.0013	NA	<0.00067
Nickel	111	4.88	No	1.54	No	0.312	NA	0.373
Selenium	<6.1	<0.268	No	0.293	No	0.0247	No	0.0875
Silver	<0.7	<0.031	No	<0.0023	No	<0.00092	No	<0.00046
Thallium	12.9	0.568	No	0.0398	No	0.0036	NA	0.0194
Vanadium	7	0.308	No	0.165	No	<0.00088	NA	0.0712
Zinc	320	14.1	No	4.6	No	0.795	NA	1.2
Settling Pond Sludge								
Antimony	<4.9	<0.211	No	<0.015	No	<0.0058	NA	<0.0029
Arsenic	98.4	4.23	No	0.45	No	<0.0052	No	<0.0026
Barium	83	3.569	No	0.323	No	0.0949	No	0.016
Beryllium	18.3	0.7869	No	0.105	No	0.003	NA	0.0002
Cadmium	1.5	0.0645	No	0.004	No	0.00076	No	<0.00027
Chromium	17.6	0.7568	No	0.0281	No	0.0035	No	0.0017
Cobalt	378	16.254	No	1.65	No	0.208	NA	0.0045
Copper	757	32.551	No	2.42	No	0.0165	NA	0.0078
Lead	6	0.258	No	0.0307	No	0.0062	No	<0.0013
Mercury	7.9	0.3397	No	0.0012	No	0.00049	No	0.00034
Molybdenum	<1	<0.043	No	<0.0034	No	<0.0013	NA	0.0012
Nickel	484	20.812	No	2.4	No	0.407	NA	0.01
Selenium	<6.3	<2.71	No	0.138	No	0.015	No	<0.0042
Silver	0.82	0.03526	No	<0.0023	No	0.0025	No	0.00099
Thallium	18	0.774	No	0.0737	No	0.0191	NA	0.0074
Vanadium	25.8	1.1094	No	0.122	No	<0.00088	NA	<0.00044
Zinc	728	31.304	No	3.57	No	0.586	NA	0.0135
Flushing Pond Sludge								
Antimony	<49	<0.196	No	<0.015	No	<0.0058	NA	<0.0029
Arsenic	172	0.688	No	0.016	No	<0.0052	No	<0.0026
Barium	135	0.54	No	0.076	No	0.0366	No	0.0401
Beryllium	11.6	0.0464	No	0.0041	No	<0.00022	NA	<0.00011
Cadmium	4.5	0.018	No	<0.0014	No	<0.00054	No	<0.00027
Chromium	27.7	0.1108	No	0.0022	No	<0.00084	No	<0.00042
Cobalt	409	1.636	No	0.0224	No	0.0031	NA	0.0035
Copper	707	2.828	No	0.0346	No	0.0085	NA	0.0063
Lead	<26	<0.104	No	<0.0065	No	<0.0026	No	0.0018
Mercury	47	0.188	No	0.00098	No	0.00027	No	0.00067
Molybdenum	<10	<0.04	No	0.0059	No	0.0045	NA	0.002
Nickel	627	2.508	No	0.104	No	0.027	NA	0.0384
Selenium	<63	<0.252	No	<0.021	No	0.0189	No	0.0045
Silver	<7.2	<0.288	No	0.0032	No	<0.00092	No	0.00092
Thallium	<35	<0.14	No	<0.0085	No	<0.0034	NA	<0.0017
Vanadium	13.5	0.054	No	0.0046	No	<0.00088	NA	0.0012
Zinc	850	3.4	No	0.0546	No	0.0163	NA	0.0086
¹ Metals data reported as dry weight ² Metals data reported as wet weight for comparison to TTLC								
DI WET = Waste extraction test using deionized water SPLP = Synthetic precipitation leaching procedure mg/kg = Milligram per kilogram STLC = Soluble threshold limit concentration mg/L = Milligram per liter TCLP = Toxicity characteristic leaching procedure NA = Not applicable TTLC = Total threshold limit concentration								

SECTION 3

TECHNOLOGY APPLICATIONS ANALYSIS

This section of the ITER describes the general applicability of the compost-free bioreactor treatment technology to reduce acidity and toxic levels of metals in water at ARD-contaminated mine sites. The analysis is based on the results from and observations made during the SITE demonstration.

3.1 Key Features

Oxidation of sulfur and sulfide minerals within the mine workings and waste rock forms sulfuric acid (H_2SO_4), which liberates toxic metals from the mine wastes creating ARD. Biological treatment of ARD reverses this process and relies on the biologically mediated reduction of sulfate to sulfide followed by metal sulfide precipitation. Biologically promoted sulfate-reduction has been attributed primarily to a consortium of sulfate-reducing bacteria, which utilize a variety of carbon substrates 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.



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.

At Leviathan Mine, biological treatment is conducted in two compost-free gravity-flow bioreactors, two settling ponds, and an aeration channel. The bioreactors are filled with river rock

because of the ease at which precipitates can be flushed through the matrix and the stability (little compaction) of the matrix. Operated in gravity flow mode, ARD is introduced to the pretreatment pond, where sodium hydroxide is added to adjust the influent pH of 3.1 up to 4 to maintain a favorable environment for sulfate-reducing bacteria and ethanol is added as a carbon source. Minimal chemically-mediated metals precipitation occurs in the pretreatment pond. ARD from the pre-treatment pond then flows through the first bioreactor to biologically 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. Precipitates in effluent from the second bioreactor are settled in a continuous flow settling pond.

Operated in recirculation mode, metal-rich influent ARD is combined with sodium hydroxide and sulfide-rich water discharged from the second bioreactor to precipitate metals in the settling pond rather than in the bioreactors. Precipitation of metal sulfides downstream of the two bioreactors greatly reduces the need for flushing and the associated stress on bacteria in the two bioreactors. A portion of the pond supernatant containing minimal residual metals and excess sulfate is pumped to the first bioreactor and combined with alcohol feed stock to promote additional sulfate reduction to sulfide in the two bioreactors. The pH of the supernatant recirculated through the bioreactors is near neutral, providing optimal conditions for sulfate-reducing bacteria growth.

During both modes of operation, the effluent from the continuous flow settling pond flows through a rock lined aeration channel to promote gas exchange prior to effluent discharge. Precipitate slurry is periodically flushed from the bioreactors to prevent plugging of the river rock matrix and provide adequate volume in the settling pond, and settled in a flushing pond. Settled solids from the flushing pond are periodically dewatered using bag filters.

3.2 Applicable Wastes

Conventional methods of treating ARD involve the capture, storage, and batch or continuous treatment of water using a large quantity of added lime, which neutralizes acidity and precipitates a large volume of metal hydroxide sludge. Biological treatment using sulfate-reducing bacteria is applicable to any waste stream containing metals and sulfate ion, requires a small quantity of base addition and a liquid carbon source, and generates a relatively small volume of metal sulfide sludge. Metals typically treated include aluminum, arsenic, cadmium, chromium, copper, iron, lead, nickel, and zinc. Biological treatment is also passive, requiring less labor for system O&M.

The compost-free bioreactor treatment system in operation at the Leviathan Mine site is an improvement to the current wood chip, compost, and manure biological treatment systems in place or being evaluated at many facilities today. The compost-free bioreactor technology removes the uncertainties related to carbon availability and sulfate reduction efficiency through the use of a liquid carbon substrate (ethanol). The compost-free bioreactor technology also eliminates the problems associated with matrix compaction and short circuiting through the use of river rock, which allows rapid flushing of solids in comparison to compost and wood chip matrices.

3.3 Factors Affecting Performance

Several factors can influence the performance of the bioreactor treatment system demonstrated at Leviathan Mine. These factors can be grouped into three categories: (1) mine drainage characteristics, (2) operating parameters, and (3) system design. The bioreactor treatment system is capable of treating a broad range of metals in ARD. The level of acidity, metals concentration, and metals composition directly impact the quantity of sulfide ion that must be generated, and the subsequent sodium hydroxide and ethanol dosages required to neutralize acidity and in conjunction with sulfate-reducing bacteria, generate the sulfide necessary to precipitate target metals.

Operating parameters for the bioreactors also directly impact system performance. Optimizing and limiting fluctuations in reagent dosages, bioreactor HRT, bioreactor temperature, gravity and recirculation flow rates, and settling pond HRT all impact the activity of sulfate-reducing bacteria, generation of sulfides, and removal of target metals. The system should be designed and operated to limit stress placed on the sulfate-reducing bacteria in the bioreactors. The system should be operated to allow as near neutral a pH in the bioreactors as possible and maintain a consistent ethanol dosage rate.

In order to minimize fluctuations in pH and maintain a near neutral pH, operation of the system in recirculation mode was

found to be optimal. Sodium hydroxide is added to the settling pond along with sulfide rich water to precipitate metal sulfides from solution. The pond supernatant, at a near neutral pH and with low metals concentrations, is recirculated through the bioreactors, which favors sulfate-reducing bacteria and minimizes metal toxicity. Settling of metal sulfides in the pond rather than the bioreactors also minimizes the need for bioreactor flushing and associated biological stress. In the absence of a recirculation pump, the system design should include a pretreatment pond upstream of the treatment system to reduce fluctuations in acidity and metals concentration in influent ARD and allow extended mixing time for sodium hydroxide and ethanol reagents added to solution, all of which will promote a tighter control of reaction chemistry enter the bioreactors.

In locations where extremely cold winter conditions persist over several months, consideration should be given to ensuring that the bioreactor and settling ponds are of sufficient depth to prevent deep freezing and insulate the active portion of the bioreactor from extreme cold. The bioreactors at Leviathan Mine are 3 meters deep and were not impact by extreme cold below a depth of approximately 0.6 meter. In addition, the settling ponds did not freeze below about 0.6 meter.

The rock substrate within the bioreactors is essentially non-compactable over time in comparison to traditional wood chip, compost, and manure substrate-based bioreactors. A stable substrate minimizes dead zones and preferential pathways within a bioreactor over time. The use of ethanol as a carbon substrate rather than traditional wood- or manure-based carbon sources provides a stable carbon supply and is a more efficient source of reducing equivalents for sulfate-reducing bacteria. Together, a rock matrix and a liquid carbon substrate allow long-term operation of a treatment system that traditionally requires excavation and replace of the wood or manure substrate every five years, depending on the initial quantity of wood or manure used.

Finally, the method and duration of precipitate settling and separation also impacts system performance. The treatment system relies on sodium hydroxide addition to generate settleable solids, a large settling pond to allow extended settling of pin floc, and bag filters to dewater sludge pumped out of the settling pond. A second settling pond should also be considered during system design to provide the system operator some room for error during system upsets. If sodium hydroxide addition to the settling pond is not controlled above a pH of 8, target metals may dissolve back into solution.

3.4 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 were met 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 to 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 partially treated 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 (1 to 2 days a week).

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.

3.5 Range of Suitable Site Characteristics

This section describes the site characteristics necessary for successful application of the bioreactor treatment technology.

Staging Area and Support Facilities: For full-scale bioreactor treatment systems such as those in operation at Leviathan Mine, minimal staging areas and support facilities are necessary for continuous operation of the treatment system. A small staging area is needed for storage of consumable materials, and supplies; loading and unloading equipment; and for placement of a Connex, which is used for storage of spare parts and equipment that are not weather resistant. Additional space is necessary for placement of a health and safety eyewash and shower; a portable toilet; and

power generating equipment. The staging and storage areas required for a treatment system should range from 300 and 500 square meters and are usually located adjacent to the treatment system. A reagent storage area of about 50 square meters for bulk quantities of ethanol and sodium hydroxide is also required up gradient of or at the head of the treatment system.

Treatment System Space 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 114 L/min at Leviathan Mine is about 3,000 square meters.

Climate: Operation of the bioreactor treatment system is slightly affected by freezing temperatures. In areas where freezing temperatures are normal throughout the winter months, such as at the Leviathan Mine site, biological activity does slow resulting in decreased sulfate reduction to sulfide. At Leviathan Mine, effluent discharge standards were generally met 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 to freezing during the winter.

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Utilities: The main utility requirement for the bioreactor treatment system is electricity, which is used to operate reagent delivery pumps, water recirculation pump, 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 is provided by a 6 KW-hour diesel generator. Diesel fuel for the generator is stored in a 3,785 L 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. A wind or water turbine and storage battery may also be used to provide power. Satellite phone service is also required due to the remoteness of the site.

Supervisory Control and Data Acquisition (SCADA) service through a satellite uplink may also be used to monitor water chemistry and control dosing of ethanol and sodium hydroxide to the bioreactor treatment system.

3.6 Personnel Requirements

Personnel requirements for operation of the treatment system following initial design and construction can be broken down into the following activities: startup and acclimation, and O&M. System start-up and acclimation includes the labor to setup pumps and pipes, fill and recirculate ARD within the system, adjust system hydraulics and reagent dosages, and optimize the operational HRT to meet discharge standards. System startup and acclimation occurs once after initial system construction as the system is design to operate year round, even in extremely cold weather. System start up of the treatment system will take a two-person crew two weeks to complete. After system construction and start up, an acclimation period is necessary to allow for the acclimation of sulfate-reducing bacteria to the source water, optimization of carbon substrate dosage and pH within the bioreactors, and the slow ramp up of ARD flow to attain discharge standards. System acclimation will require only one person visiting the system 3 days a week over a 10 week period.

Field personnel are necessary to operate the treatment system, perform weekly maintenance, collect weekly discharge monitoring samples, monitor unit operation chemistry and flow rates, and to adjust ethanol and sodium hydroxide dosages, adjust unit operation HRT, and adjust recirculation rates. Due to the passive nature of the treatment system, minimal O&M labor is necessary in comparison to an active treatment system. Long-term O&M of the treatment system will require only one person visiting the system 1 day a week over the course of a year.

In addition to field personnel, support staff is required for project management and administrative support functions. The level of effort required for support staff is approximately 15 percent of the total project level of effort.

3.7 Materials Handling Requirements

There is one process residual associated with bioreactor treatment of ARD. The process produces a relatively small quantity of sludge containing metal sulfides, oxides, and oxyhydroxides. During operation from November 2003 through July 2005, the bioreactor generated about 14.2 dry tons (12,900 kg) of sludge consisting mainly of iron sulfide. This equals 1.7 dry tons (1,550 kg) of sludge per million gallons (0.45 dry ton [410 kg] per million liters) of ARD treated.

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 TTLC criteria. To determine whether metals concentrations in the solid waste residuals pose a threat to water quality, DI WET leachate results were compared to STLC criteria. To determine if the residuals are a RCRA waste, TCLP leachate results were compared to TCLP limits. The hazardous waste characteristics determined for the solid waste stream are presented in Table 3-1. None of the solid wastes were found to be hazardous or a threat to water quality; however, the solids were disposed of off site pending designation of an on-site disposal area.

3.8 Permit Requirements

Actions taken on-site during a CERCLA cleanup action must comply only with the substantive portion of a given regulation. On-site activities need not comply with administrative requirements such as obtaining a permit, record keeping, or reporting. Actions taken off-site must comply with both the substantive and administrative requirements of applicable laws and regulations. All actions taken at the Leviathan Mine Superfund site were on-site; therefore permits were not obtained.

Permits that may be required for off-site actions or actions at non-CERCLA sites include: a permit to operate a hazardous waste treatment system, an National Pollutant Discharge and Elimination System (NPDES) permit for effluent discharge, an NPDES permit for discharge of storm water during construction activities, and an operations permit from a local air quality management district (AQMD) for activities generating particulate emissions. Permits from local agencies may also be required for grading, construction, and operational activities; transport of oversized equipment on local roads; and transport of hazardous materials on local roads.

Table 3-1. Determination of Hazardous Waste Characteristics for Bioreactor Solid Waste Streams

Treatment System	Solid Waste Stream	Total Solid Waste Generated	TTL	STL	TCL	Waste Handling Status
			Pass or Fail	Pass or Fail	Pass or Fail	
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			TTL = Total threshold limit concentration			
TCLP = Toxicity characteristic leaching procedure			1 dry ton = 907 kilogram			

3.9 Community Acceptance

Community acceptance for the compost-free bioreactor treatment system operated at Leviathan Mine is positive. The diversion and treatment of ARD at the mine site is seen as a necessary and positive step towards reestablishing a quality watershed within the Sierra Nevada mountain range. The treatment system is able to meet discharge standards and operates on a year round basis, promoting improved watershed and fishery health. Continued community involvement and regulatory agency support will be necessary for long term treatment and monitoring at a mine site such as Leviathan Mine.

Operation of the bioreactor treatment system presents minimal to no risk to the public since all system components and treatment operations occur within a contained site. Solids generated during the treatment process are nonhazardous. Hazardous chemicals used in the treatment system include ethanol, sodium hydroxide, and diesel fuel for generator power. These chemicals pose the highest risk to the public during transportation to the site by truck and trailer. Appropriate Department of Transportation (DOT) regulations are followed during shipment of these chemicals to minimize potential impacts to the public. During operation, the diesel generator used to power the treatment system creates the most noise and air emissions at the site. Hydrogen sulfide gas is also generated by the treatment process, but is only of concern within the treatment system valve vaults. Because of the remoteness of the Leviathan Mine site, the public is not impacted by these issues. Alternative power sources are currently being evaluated, including wind and water turbines, which will replace or augment the diesel-powered generator.

3.10 Availability, Adaptability, and Transportability of Equipment

The components of the compost-free bioreactor treatment system are generally available and not proprietary. System process components include (1) distribution piping and valving, pond liners, rock substrate, recirculation pumps, and reagent storage tanks; (2) control equipment such as a SCADA system, a pH monitoring system, a recirculation

pump controller, and ethanol and sodium hydroxide dosage and feed systems; and (3) solids handling equipment such as sludge pumps, bag filters, and roll-off bins. This equipment is available from numerous suppliers throughout the country and may be ordered in multiple sizes to meet flow requirements and treatment area accessibility. An integrated design is recommended to properly size and assemble individual components for proper system operation.

Transport of earth moving equipment, piping, stairs, bioreactor rock substrate, and reagent storage tanks to a site may require handling as oversize or wide loads. Additional consideration should be given to the stability of mine access roads, bridge clearances, and load limits for large shipments. Process reagents and consumables, such as ethanol, sodium hydroxide, and generator fuel, are considered hazardous materials and will require stable site access roads for delivery.

3.11 Ability to Attain ARARs

Under CERCLA, remedial actions conducted at Superfund sites must comply with Federal and state (if more stringent) environmental laws that are determined to be applicable or relevant and appropriate. Applicable or relevant and appropriate requirements (ARAR) are determined on a site-specific basis by the EPA remedial project manager. They are used as a tool to guide the remedial project manager toward the most environmentally safe way to manage remediation activities. The remedial project manager reviews each Federal environmental law and determines if it is applicable. If the law is not applicable, then the determination must be made whether the law is relevant and appropriate. Actions taken on-site during a CERCLA cleanup action must comply only with the substantive portion of a given ARAR. On-site activities need not comply with administrative requirements such as obtaining a permit, record keeping, or reporting. Actions conducted off-site must comply with both the substantive and administrative requirements of applicable laws and regulations.

On-site remedial actions, such as the compost-free bioreactor treatment system in operation at the Leviathan Mine site, must comply with Federal and more stringent state ARARs, however, ARARs may be waived under six conditions: (1) the

action is an interim measure, and the ARAR will be met at completion; (2) compliance with the ARAR would pose a greater risk to human health and the environment than noncompliance; (3) it is technically impracticable to meet the ARAR; (4) the standard of performance of an ARAR can be met by an equivalent method; (5) a state ARAR has not been consistently applied elsewhere; and (6) ARAR compliance would not provide a balance between the protection achieved at a particular site and demands on the Superfund for other sites. These waiver options apply only to Superfund actions taken on-site, and justification for the waiver must be clearly demonstrated.

The following sections discuss and analyze specific environmental regulations pertinent to operation of the bioreactor treatment system, including handling, transport, and disposal of both hazardous and non-hazardous treatment residuals. ARARs identified include: (1) CERCLA; (2) RCRA; (3) the Clean Air Act (CAA); (4) the Clean Water Act (CWA); (5) Safe Drinking Water Act (SDWA); and (6) Occupational Safety and Health Administration (OSHA) regulations. These six general ARARs, along with additional state and local regulatory requirements (which may be more stringent than Federal requirements) are discussed below. Specific ARARs that may be applicable to the bioreactor treatment system are identified in Table 3-2.

3.11.1 Comprehensive Environmental Response, Compensation, and Liability Act

CERCLA of 1980 authorizes the Federal government to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or to the environment. As part of the requirements of CERCLA, EPA has prepared the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) for hazardous substance response. The NCP, codified in Title 40 Code of Federal Regulations (CFR) Part 300, delineates methods and criteria used to determine the appropriate extent of removal and cleanup for hazardous waste contamination.

The 1986 SARA amendment to CERCLA directed EPA to:

- Use remedial alternatives that permanently and significantly reduce the volume, toxicity, or mobility of hazardous substances, pollutants, or contaminants.
- Select remedial actions that protect human health and the environment, are cost-effective, and involve permanent solutions and alternative treatment or resource recovery technologies to the maximum extent possible.

- Avoid off-site transport and disposal of untreated hazardous substances or contaminated materials when practicable treatment technologies exist (Section 121[b]).

In general, two types of responses are possible under CERCLA: removal and remedial actions. Removal actions are quick actions conducted in response to an immediate threat caused by release of a hazardous substance. Remedial actions involve the permanent reduction of toxicity, mobility, and volume of hazardous substances or pollutants. The bioreactor treatment technology implemented at the Leviathan Mine Superfund site fall under the purview of CERCLA and SARA; the treatment system is operated on site and reduces the mobility of toxic metals through metal sulfide precipitation and volume through metal concentration in sludge and bag filter solids. The technologies are protective of human health and the environment, cost effective, and permanent.

The bioreactor treatment technology can be applied at sites such as Leviathan Mine and operated as long-term CERCLA remedial actions; however, it may also be designed and operated for short term operation at a site in support of a CERCLA removal action, where immediate removal of toxic metals from a waste stream is necessary.

3.11.2 Resource Conservation and Recovery Act

RCRA, an amendment to the Solid Waste Disposal Act, was enacted in 1976 to address the problem of safe disposal of the enormous volume of municipal and industrial solid waste generated annually. The Hazardous and Solid Waste Amendments of 1984 greatly expanded the scope and requirements of RCRA. Regulations in RCRA specifically address the identification and management of hazardous wastes. Subtitle C of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste, most of which are applicable to CERCLA actions. In order to generate and dispose of a hazardous waste, the site responsible party must obtain an EPA identification number. However, mining wastes are generally not subject to regulation under RCRA (see the Bevill Amendment at Section 3001(a)(3)(A)(ii)), unless the waste is disposed of off-site. For treatment residuals determined to be RCRA hazardous, substantive and administrative RCRA requirements must be addressed if the wastes are shipped off site for disposal. If treatment residuals remain on-site, the substantive requirements of state disposal and siting laws and the Toxic Pits Control Act may be relevant and appropriate. Criteria for identifying RCRA characteristic and listed hazardous wastes are included in 40 CFR Part 261 Subparts C and D. Other applicable RCRA requirements include hazardous waste manifesting for off-site disposal and time limits on accumulating wastes.

Table 3-2. Federal Applicable or Relevant and Appropriate Requirements for the Bioreactor Treatment System

Regulated Activity	ARAR	Description	Applicability
Characterization of untreated AMD and ARD	RCRA: 40 CFR Part 261 or state equivalent	Standards that apply to identification and characterization of wastes.	Not applicable as mine wastes are not subject to RCRA under the Bevill Amendment.
Construction of Treatment System	OSHA: 29 CFR 1910.120	Protection of workers from toxic metals during earth moving activities and system construction.	Applicable. Provide air monitoring and appropriate personnel protective equipment.
	CAA: 40 CFR Part 50 or state equivalent	Standards that apply to the emission of particulates and toxic pollutants.	Relevant and appropriate. Control emissions during earthwork using engineering controls. May require air monitoring and record keeping.
	CWA: 40 CFR Part 122	Standards for discharge of storm water generated during construction activities. Requires compliance with best management practices and discharge standards in nationwide storm water discharge permit for construction activities.	Not applicable to a CERCLA action; however, the substantive requirements are relevant and appropriate. Best management practices should be implemented to meet discharge standards.
Treatment System Operation	OSHA: 29 CFR 1910.120	Protection of workers from toxic metals and hydrogen sulfide gas during system operation, splashes during sodium hydroxide handling, and dust emissions during treatment residual handling.	Applicable. Provide appropriate personnel protective equipment, air monitoring, and if necessary supplied air or blowers.
	RCRA: 40 CFR Part 264 or state equivalent	Standards apply to treatment of wastes in a treatment facility.	Not applicable as mine wastes are not subject to RCRA under the Bevill Amendment. However, may be relevant and appropriate. Requires operational and contingency planning as well as record keeping.
	CAA: 40 CFR Part 50 or state equivalent	Standards that apply to the emission of particulates and toxic pollutants.	Relevant and appropriate. Control emissions during treatment residual handling using engineering controls. May require air monitoring and record keeping.
Determination of Cleanup Standards	SARA: Section 121(d)(2)(A)(ii) SDWA: 40 CFR Part 141	Standards that apply to pollutants in waters that may be used as a source of drinking water.	Not applicable for removal actions. Effluent must meet interim discharge standards specified in the action memorandum. Applicable for remedial actions. Effluent must obtain MCL and to the extent possible MCLGs.
Waste Disposal	RCRA: 40 CFR Part 261 or state equivalent	Standards that apply to identification and characterization of wastes.	Applicable only when treatment residuals are disposed of off-site. May be relevant and appropriate for determination of waste type to guide selection of appropriate on-site disposal requirements.
	RCRA: 40 CFR Part 262 and 263	Standards that apply to generators of hazardous waste.	Applicable for off-site disposal of hazardous treatment residuals. Requires identification of the generator and disposal at a RCRA-permitted facility.
	CWA: 40 CFR Part 125	Standards for discharge of effluent to a navigable waterway. Requires a NPDES permit for discharge to a navigable waterway.	Not applicable to a CERCLA action; however, the substantive requirements are relevant and appropriate. Discharge standards may be more stringent than MCLs or MCLGs due to potential environmental impacts.
AMD = Acid mine drainage ARAR = Applicable or relevant and appropriate requirement ARD = Acid rock drainage CAA = Clean Air Act CERCLA = Comprehensive Environmental Response, Compensation, and Liability Act CFR = Code of Federal Regulation CWA = Clean Water Act		MCL = Maximum contaminant level MCLG = Maximum contaminant level goal NPDES = National Pollutant Discharge Elimination System OSHA = Occupational Safety and Health Administration RCRA = Resource Conservation and Recovery Act SARA = Superfund Amendments and Reauthorization Act SDWA = Safe Drinking Water Act	

At Leviathan Mine, treatment residuals generated from the bioreactor treatment system have been determined to be non-hazardous wastes. Non-hazardous waste residuals are either stored or disposed of on site.

3.11.3 Clean Air Act

The CAA establishes national primary and secondary ambient air quality standards for sulfur oxides, particulate matter, carbon monoxide, ozone, nitrogen dioxide, and lead. It also limits the emission of 189 listed hazardous pollutants. States are responsible for enforcing the CAA. To assist in this, air quality control regions (AQCR) were established. Allowable emission limits are determined by the AQCR and AQMD subunits. The emission limits are established based on attainment of national ambient air quality standards.

The CAA requires that TSD facilities comply with primary and secondary ambient air quality standards. Emissions resulting from solids handling during the construction and operation of the bioreactor treatment system may need to meet air quality standards. For example, dust generated during earthwork and residual solids handling may be regulated by a local AQMD. No air permits are required for the bioreactor treatment system operated at the Leviathan Mine Superfund site; however, dust emissions are limited through careful handling and maintaining soil moisture during construction and system operation.

3.11.4 Clean Water Act

The objective of the CWA is to restore and maintain the chemical, physical, and biological integrity of the nation's waters by establishing Federal, State, and local discharge standards. If treated water is discharged to surface water bodies or publicly-owned treatment works (POTW), CWA regulations will apply. A facility discharging water to a navigable waterway must apply for a permit under the NPDES. NPDES discharge permits are designed as enforcement tools with the ultimate goal of achieving ambient water quality standards. Discharges to POTWs also must comply with general pretreatment regulations outlined in 40 CFR Part 403, as well as other applicable state and local administrative and substantive requirements.

Treated effluent from the bioreactor treatment system is discharged to Aspen Creek, if EPA interim discharge standards (pre-risk assessment and record of decision) are met. An NPDES permit is not required under CERCLA, although the substantive requirements of the CWA are met.

3.11.5 Safe Drinking Water Act

The SDWA of 1974 and the Safe Drinking Water Amendments of 1986 require EPA to establish regulations to protect human health from contaminants in drinking water.

The law authorizes national drinking water standards and a joint Federal-State system for ensuring compliance with these standards. The National Primary Drinking Water Standards are found at 40 CFR Parts 141 through 149. These standards are expressed as maximum contaminant levels (MCL) and maximum contaminant level goals (MCLG). Under CERCLA (Section 121(d)(2)(A)(ii)), remedial actions are required to meet MCLs and MCLGs when relevant and appropriate. State drinking water requirements may also be more stringent than Federal standards.

Effluent from the bioreactor treatment system discharges to Aspen Creek, a tributary to Leviathan Creek which is a potential source of drinking water. Effluent from the treatment system generally met the EPA interim (pre-risk assessment and record of decision) discharge standards; however, iron concentrations do not meet the Federal secondary MCL. Attainment of the secondary MCL for iron is fully achievable through addition of more sodium hydroxide or increased HRT; however, under the current EPA action memorandum, operation of the Leviathan Mine bioreactor treatment system to meet MCLs is not required.

3.11.6 Occupational Safety and Health Act

CERCLA remedial actions and RCRA corrective actions must be conducted in accordance with OSHA requirements detailed in 29 CFR Parts 1900 through 1926, in particular Part 1910.120, which provides for health and safety of workers at hazardous waste sites. On-site construction at Superfund or RCRA corrective action sites must be conducted in accordance with 29 CFR Part 1926, which describes safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than Federal standards, also must be met. Workers involved with the construction and operation of the bioreactor treatment system are required to have completed an OSHA training course and be familiar with OSHA requirements relevant to hazardous waste sites. Workers on hazardous waste sites must also be enrolled in a medical monitoring program.

Minimum personal protective equipment (PPE) for workers at the Leviathan Mine site includes gloves, hard hat, steel-toe boots, and Tyvek® coveralls PPE, including respirators, eye protection, and skin protection is required when handling ARD and sodium hydroxide. Based on contaminants and chemicals used at the site, the use of air purifying respirators is not required. However, hydrogen sulfide gas generated by the bioreactors may accumulate in valve vaults. Therefore, the work area should be monitored for hydrogen sulfide gas and a blower or supplied air should be available to mitigate any hazards. Noise levels are generally not high, except during earthwork activities, which involve the operation of heavy equipment. During these activities, noise levels must be monitored to ensure that workers are not exposed to noise levels above a time-weighted average of 85 decibels over an

eight-hour day. If noise levels exceed this limit, workers are required to wear hearing protection.

3.11.7 State Requirements

State and local regulatory agencies may require permits prior to operation of a bioreactor treatment system. Most Federal permits will be issued by an authorized state agency. An air permit from the local AQMD may be required if air emissions in excess of regulatory standards are anticipated. State and local agencies will have direct regulatory responsibility for all environmental concerns. If a removal or remedial action occurs at a Superfund site, Federal agencies, primarily EPA, will provide regulatory oversight. If off-site disposal of contaminated waste is required, the waste must be taken to the disposal facility by a licensed transporter.

3.12 Technology Applicability to Other Sites

Bioreactor treatment of ARD at Leviathan Mine was evaluated for applicability to other mine sites based on the nine criteria used for decision making in the Superfund feasibility study process. The nine criteria and the results of the evaluation are summarized in Table 3-3. The bioreactor treatment system evaluated was specifically designed to treat ARD at the mine site to EPA interim discharge standards for aluminum, arsenic, copper, iron, and nickel. In addition to the five primary target metals of concern, EPA identified cadmium, chromium, lead, selenium, and zinc as secondary water quality indicator metals. The treatment system implemented at Leviathan Mine was also successful at reducing concentrations of these secondary metals in the ARD to below EPA interim discharge standards. The treatment system can be modified to treat wastes with varying metals concentrations and acidity.

Table 3-3. Feasibility Study Criteria Evaluation for the 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 in ARD. The bioreactor treatment system evaluated at Leviathan Mine reduced the concentrations of toxic metals in ARD, which was historically released to Aspen and Leviathan Creeks, to below EPA interim discharge standards, which were established to protect water quality and the ecosystem in Aspen and Leviathan Creeks and down-stream receiving waters. Resulting metals-enriched solid wastes were determined to be non-hazardous based on State and Federal criteria and do not pose a threat to water quality. The solid waste can be used disposed of at an off-site non-hazardous waste repository or on-site as a soil amendment depending regulatory approval.
Compliance with Applicable or Relevant and Appropriate Requirements (ARAR)	The bioreactor treatment system is generally compliant with EPA interim (pre-risk assessment and record of decision) discharge standards for the Leviathan Mine site. However, the effluent from the treatment system did not always meet the EPA interim discharge standards for the site or the secondary maximum contaminant limit (MCL) 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, evaluate alternate sources of base addition, optimize recirculation rates for sulfide generation, improve solids handling and dewatering processes, 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 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 35.75 liters 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 of California, 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.
<p>AMD = Acid mine drainage ARD = Acid rock drainage ARCO = Atlantic Richfield Company</p> <p>EPA = U.S. Environmental Protection Agency TSD = Treatment, storage, and disposal</p>	

SECTION 4 ECONOMIC ANALYSIS

This section presents an economic analysis of the compost-free bioreactor treatment system used to treat ARD with chemistry, flow rates, and site logistical issues similar to those at the Leviathan Mine.

4.1 Introduction

The information presented in this section has been derived from (1) observations made and experiences gained during the technology evaluation, (2) data compiled from the Leviathan Mine Site Engineering Evaluation/Cost Analysis (EE/CA) (EMC² 2004a), and (3) personal communications with Dr. Tim Tsukamoto (Tsukamoto 2005b). The costs associated with designing, constructing, and operating the bioreactor treatment system in a research mode have been broken down into the following 10 elements and are assumed to be appropriate for extrapolation to other mine sites with similar conditions. Because of the robust system design and a research mode of operation, a less robust system and reduced operational labor may be sufficient for long term operation.

Each cost element is further broken down to document specific costs associated with each treatment system. Demobilization is not addressed as the system operates on a year round basis.

- 1) Site Preparation
- 2) Permitting and Regulatory Requirements
- 3) Capital and Equipment
- 4) System Startup and Acclimation
- 5) Consumables and Rentals
- 6) Labor
- 7) Utilities
- 8) Residual Waste Handling and Disposal
- 9) Analytical Services
- 10) Maintenance and Modifications

This economic analysis is based primarily on data collected during the mid-November 2003 through mid-May 2004 evaluation period for the bioreactor treatment system

operated in gravity flow mode and the mid-May 2004 through July 2005 evaluation period for the Bioreactor treatment system operated in recirculation mode. During the 2003-2004 evaluation period the bioreactor treatment system operated in gravity flow mode for twenty-six weeks (November 14, 2003 to May 11, 2004) and treated 9.24 million liters of ARD from Aspen Seep at an average rate of 31.8 L/min. The bioreactor treatment system also operated in recirculation mode for sixty-four weeks (May 12, 2004 to July 31, 2005), treating 22.1 million liters of ARD from Aspen Seep at an average rate of 34.2 L/min. Costs are presented for each mode of system operation over their respective periods of operation. The cost per 1,000 L of water treated is presented as well as the present worth of the cumulative variable costs over 5, 15, and 30 years of treatment. A comparison of treatment costs between the two modes of system operation will also be discussed.

Section 4.2 presents a cost summary and identifies the major expenditures for each mode of treatment system operation (costs are presented in 2005 dollars). As with any cost analysis, caveats may be applied to specific cost values based on associated factors, issues and assumptions. The major factors that can affect estimated costs are discussed in Section 4.3. Assumptions used in the development of this economic analysis are identified in Section 4.4. Detailed analysis of each of the 10 individual cost elements for both modes of treatment system operation is presented in Section 4.5.

4.2 Cost Summary

The initial fixed costs to construct bioreactor treatment system are \$836,617 for the treatment system operated in gravity flow mode, and \$864,119 for the treatment system operated in recirculation mode. Fixed costs consist of site preparation, permitting, and capital and equipment costs. Site preparation includes system design, project and construction management, and preconstruction site work. Capital and equipment costs include all equipment, materials, delivery, earthwork, and initial system

construction. Equipment and materials include reagent storage tanks, pumps, piping, valves, pond liners, rock substrate, pH control equipment, automation equipment and satellite phone for reliable communication at a remote site. A breakdown of fixed costs for each system is presented in Section 4.5.

Variable costs to operate the bioreactor treatment system are \$82,155 in gravity flow mode and \$75,877 in recirculation mode. Variable costs consist of system startup and acclimation, consumable and rentals, labor, utilities, waste handling and disposal, analytical services, and maintenance and system modifications. A breakdown of variable costs for each system is presented in Section 4.5.

The total first year cost to design, construct, and operate the treatment system; yearly operational costs for each mode of treatment system operation; and the cumulative 5-year, 15-year, and 30-year treatment costs for each mode of treatment system operation are summarized in Table 4-1.

Table 4-1. Cost Summary for Each Mode of Operation

Description	Gravity Flow	Recirculation
Total First Year Cost	\$941,248	\$962,472
First Year Cost per 1,000 Gallons Treated	\$189.54	\$193.81
Total Variable Costs	\$82,155	\$75,877
Variable Costs per 1,000 Gallons Treated	\$16.54	\$15.28
Cumulative 5-Year Total Variable Cost (Present Worth at 7% Rate of Return)	\$343,834	\$321,654
Cumulative 15-Year Total Variable Cost (Present Worth at 7% Rate of Return)	\$764,950	\$715,681
Cumulative 30-Year Total Variable Cost (Present Worth at 7% Rate of Return)	\$1,045,005	\$977,880

4.3 Factors Affecting Cost Elements

A number of factors can affect the cost of treating ARD with the bioreactor treatment system. These factors generally include flow rate, concentration of contaminants, discharge standards, physical site conditions, geographical site location, and type and quantity of residuals generated. Increases in flow rate due to spring melt will slightly raise operating costs of each system due to proportional increases in ethanol and sodium hydroxide consumption. Flow rate increases can also impact fixed costs (number and size of the bioreactors and settling ponds) when the minimum system or unit operation HRT is not sufficient to meet discharge standards.

Operating costs may be slightly impacted by seasonal increases in contaminant concentration. Increases in metals concentrations generally require additional HRT to attain discharge standards. Higher contaminant concentrations may also change the classification of a residual waste from a non-hazardous to a hazardous waste, requiring increased disposal costs. Restrictive discharge standards impact both fixed and variable costs. System designers and operators

may be forced to extend system and unit operation HRTs (number and size of bioreactors and settling ponds) and increase sodium hydroxide dosage to meet stricter discharge requirements.

Physical site conditions may impact site preparation and construction costs associated with excavation and construction of the bioreactors and settling ponds. Cold climates may limit site access and decrease the activity of sulfate-reducing bacteria, requiring bioreactors with extended HRT. The characteristics of the residual solids produced during treatment may greatly affect disposal costs, where production of hazardous solids will require off site disposal at a permitted TSD facility.

4.4 Issues and Assumptions

The following assumptions have been used in the development of this economic analysis:

- Standard sized tanks are used for ethanol and sodium hydroxide storage.
- An appropriate staging area is available for equipment staging, setup and delivery.
- Construction and maintenance of access roads is not required.
- The treatment system will be operated year round.
- The treatment system will be operated unmanned, with the exception of a weekly maintenance visit.
- All site power is obtained from a water turbine and battery system, with a diesel generator as backup.
- Utility water can be obtained on site.
- Non-hazardous sludge will be disposed of at an off-site landfill or at an existing on-site repository.
- The site is located within 400 kilometers of an off-site landfill.
- Permitting for the treatment system is not required because of CERCLA status.
- Treatment goals and discharge standards apply to those presented in Table 2-4.
- Samples are collected and analyzed weekly to verify attainment of discharge standards.

4.5 Cost Elements

Each of the 10 cost elements identified in Section 4.1 has been defined and the associated costs for each treatment system element presented below. The cost elements for the each mode of bioreactor treatment system operation, at an average flow rate of 35.75 L/min, are summarized in Table 4-2. Cost element details for each mode of treatment system operation are presented in Appendix C.

Table 4-2. Summary of Cost Elements

Description	Gravity Flow	Recirculation
Site Preparation	\$288,185.95	\$309,568.00
Permitting and Regulatory Requirements	\$0.00	\$0.00
Compost-Free Bioreactor Treatment System	\$495,791.00	\$501,911.00
Equipment Mobilization/Demobilization	\$73,550.00	\$73,550.00
Pond and Pipe Trench Earthwork	\$136,442.00	\$136,442.00
Installation of Pond Liners, Stairs, and Decant Structures	\$63,756.00	\$63,756.00
Installation of Distribution Piping and Valve Vaults	\$149,263.00	\$149,263.00
Placement of Bioreactor Substrate	\$47,173.00	\$47,173.00
Erosion Control and Revegetation/Reseeding	\$10,907.00	\$10,907.00
Recirculation Pump and Piping	\$0.00	\$6,120.00
Water Turbine and Storage Batteries	\$14,700.00	\$14,700.00
Reagent Storage and Distribution	\$35,200.00	\$35,200.00
Ethanol Storage Tank and Delivery System	\$13,400.00	\$13,400.00
Sodium Hydroxide Storage Tank and Delivery System	\$15,800.00	\$15,800.00
Make up Water Storage Tank and Delivery System	\$2,000.00	\$2,000.00
Reagent Storage Area Fencing	\$4,000.00	\$4,000.00
Automation	\$15,945.00	\$15,945.00
Remote Monitoring/Alarm System	\$9,742.50	\$9,742.50
pH Controller System	\$6,202.50	\$6,202.50
Communications	\$1,495.00	\$1,495.00
Total Capital and Equipment Cost	\$548,431.00	\$554,551.00
Total Fixed Cost	\$836,616.95	\$864,119.00
System Start-up and Acclimation	\$22,476.00	\$22,476.00
Consumables and Rentals	\$26,854.15	\$25,046.35
Labor	\$28,198.24	\$28,198.24
Utilities	\$8,348.00	\$8,348.00
Residual Waste Handling and Disposal	\$14,315.00	\$9,844.00
Analytical Services	\$4,440.00	\$4,440.00
Maintenance and Modifications	\$16,200.00	\$21,200.00
Total 1st Year Variable Costs	\$104,613.39	\$98,352.59
Recurring Variable Costs	\$82,155.39	\$75,876.59
Periodic Variable Costs	\$16,200.00	\$21,200.00
Total 1st Year Costs	\$941,248.34	\$962,471.59
Total 1st Year Costs/1,000-gallons	\$189.54	\$193.81
Total Variable Costs/1,000-gallons	\$16.54	\$15.28
Cumulative 5-Year Total Variable Costs (Present Worth at 7 Percent Rate of Return)	\$343,834.00	\$321,654.00
Cumulative 15-Year Total Variable Costs (Present Worth at 7 Percent Rate of Return)	\$764,950.00	\$715,681.00
Cumulative 30-Year Total Variable Costs (Present Worth at 7 Percent Rate of Return)	\$1,045,005.00	\$977,880.00

4.5.1 Site Preparation

Site preparation for the treatment system addresses system design, construction management, project management, and preconstruction site work. System design is estimated at 20 percent of the capital and equipment cost for a treatment system. Construction management is estimated at 15 percent and project management at 10 percent of the capital and equipment costs for a treatment system (US Army Corp of Engineers [USACE] 2000). Preconstruction site work includes clearing trees and vegetation, chipping cleared vegetation, debris removal, and topsoil removal and stockpiling for site restoration purposes. The total site preparation cost for the bioreactor treatment system operated in gravity flow mode is \$288,186; while the total site preparation cost for the treatment system operated in recirculation mode is \$309,568. The difference in the costs is attributed directly to the capital costs associated with the recirculation system as the majority of the site preparation costs are a percentage of the capital costs.

4.5.2 Permitting and Regulatory Requirements

Permitting and regulatory costs vary depending on whether treatment occurs at a CERCLA-lead or a state- or local authority-lead site. At CERCLA sites such as Leviathan Mine, removal and remedial actions must be consistent with environmental laws, ordinances, and regulations, including Federal, State, and local standards and criteria; however, permitting is not required.

At a state- or local authority-lead site, a NPDES permit, an air permit, and a storm water permit will likely be required as well as additional monitoring, which can increase permitting and regulatory costs. National Environmental Policy Act or state equivalent documentation may also be required for system construction. For a treatment system similar to those described here, constructed at a state- or local authority-lead site, permitting and regulatory costs are estimated to be \$50,000.

4.5.3 Capital and Equipment

Capital costs include earthwork and pond construction; delivery and installation of piping, pond liners, substrate; and delivery and installation of reagent storage tanks, pumps, and automation equipment. Equipment and materials include reagent storage tanks, pumps, piping, valves, pond liners, rock substrate, pH control equipment, automation equipment and satellite phone for reliable communication at a remote site. This analysis assumes that an area of at least 3,000 to 4,000 square meters is available for bioreactor and settling pond construction, reagent storage tanks, support equipment, and staging supplies.

Total capital expenditures for the bioreactor treatment system operated in gravity flow mode are \$548,431 and \$554,551 for the system operated in recirculation mode. System construction involves equipment mobilization/demobilization (\$73,550), pond and pipe trench excavation (\$136,442), installation of pond liners, stairs, and decant structures (\$63,756), installation of distribution piping and valve vaults (\$149,263), placement of bioreactor rock substrate (\$47,173), erosion control/reseeding (\$10,907), and installation of a water turbine and battery to supply power (\$14,700). Ethanol and sodium hydroxide storage tanks, delivery systems, and containment are also required at a cost of \$35,200. Automation components of the system include an automatic pH control system and a SCADA remote monitoring/alarm system at a cost of approximately \$15,945, including installation. A satellite phone to provide reliable communication at a remote location is estimated at \$1,495. The cost for construction of the treatment system operated in gravity flow mode is \$495,791. An additional \$6,120 is required for construction of the recirculation system and is associated with the installation of the recirculation pump and bypass and return pipelines.

4.5.4 System Startup and Acclimation Costs

System start-up and acclimation includes the labor to setup pumps and pipes, fill and recirculate ARD within the system, adjust system hydraulics and reagent dosages, and optimize the operational HRT to meet discharge standards. System startup and acclimation occurs once after initial system construction as the system is design to operate year round, even in extremely cold weather.

The estimated start up cost for the bioreactor treatment system is \$22,476. It is assumed that start up of the treatment system will take a two-person crew two weeks to complete; while acclimation will require only one person visiting the system 3 days a week over a 10 week period. Startup and acclimation costs for this system are less than the active treatment system due to the simplicity of system design. However, acclimation does require at least 2 months before the system is able to meet discharge standards.

4.5.5 Consumables and Supplies

Consumables and rentals for the bioreactor treatment system consist of chemicals and supplies required to treat ARD, including ethanol and sodium hydroxide, health and safety equipment, air and water chemistry monitoring equipment, and storage Connex rental. Total consumable and rental costs for the bioreactor treatment system are \$26,854 for gravity flow operations and \$25,046 for operation in recirculation mode.

The two largest consumable expenditures are ethanol and sodium hydroxide. During gravity flow operations, ethanol was consumed at a rate of approximately 0.43 ml/L of ARD treated at a cost of \$5,655; while sodium hydroxide was consumed at a rate of approximately 1.1 ml/L of ARD treated at a cost of \$4,963. During operation in recirculation mode, ethanol was consumed at a rate of approximately 0.5 ml/L of ARD treated at a cost of \$6,575; while sodium hydroxide was consumed at a rate of approximately 0.5 ml/L of ARD treated at a cost of \$2,235.

The largest rental cost throughout the year is for a hydrogen sulfide gas meter and a water quality meter. The meters are necessary to safely access sampling locations and conduct internal system monitoring of pH, dissolved oxygen, ORP, temperature, and the specific conductance of water within the bioreactors and settling ponds. The annual cost for the meters, based of four site visits per month is \$12,000. Equipment storage from year to year is also required at a cost of \$3,900. A mobilization and set-up fee is included in the Connex rental. Purchase of air and water quality meters as well as a storage Connex should also be considered at a substantial long term cost savings.

4.5.6 Labor

Labor costs for the long-term O&M of the bioreactor treatment system include the field personnel necessary to operate the system, address day-to-day maintenance issues, collect weekly discharge monitoring samples, monitor unit operation chemistry and flow rates, adjust reagent dosages, adjust unit operation HRT, and adjust recirculation rates. Labor associated with system startup and acclimation is included in Section 4.5.4.

Due to the passive nature of the treatment system, minimal O&M labor is necessary in comparison to an active treatment system. It is assumed that long-term O&M of the treatment system will require only one person visiting the system 1 day a week over the course of a year. The field technician labor cost for O&M of the bioreactor treatment system is \$23,375. An additional labor cost of \$4,823 is required for project management and administrative support.

4.5.7 Utilities

Due to the remote nature of the site, utilities are not available. A water turbine and storage battery may be used to provide power. Utility costs generally consist of the cost to lease a 3kW backup generator, generator fuel, seasonal portable toilet rental, and satellite phone service. Water is gravity fed to the treatment system from upper Aspen Creek via the water turbine outfall. SCADA service through a satellite uplink may also be used to monitor water chemistry and control dosing of ethanol and sodium hydroxide to the

bioreactor treatment system. Total utility costs to support operation of the treatment system in either mode are \$8,348.

4.5.8 Residual Waste Handling and Disposal

The bioreactor treatment system produces metal sulfide sludge. Solids accumulation in the settling ponds occur at a slow enough rate to require removal once every two to three years; however, it is removed annually to allow extended HRT. Removal of sludge from the settling ponds and bag filtration is performed in late summer to allow time for profiling and disposal. The cost to dewater the sludge from the settling ponds, using eight to ten bag filters, is approximately \$3,795. The bioreactor treatment system operated in gravity flow mode generates approximately 8 dry tons (40 wet tons at 80 percent moisture content) of bag filter solids over the course of a year, while recirculation mode generates only 4.6 dry tons (23 wet tons at 80 percent moisture content)

Bag filter solids were evaluated for hazardous waste characteristics. The bag filter solids were determined to be non-hazardous. The solids may be disposed of off-site in a non-hazardous waste repository at a total cost of \$10,520 for gravity flow operations and \$6,049 for recirculation operations. Non-hazardous solid waste may also be disposed of on site after a designated repository has been identified.

4.5.9 Analytical Services

Analytical services consist of weekly sampling of the bioreactor treatment system to verify compliance with discharge standards. One effluent grab sample is collected each week and analyzed for metals using EPA Methods 6010B and 7470 to demonstrate compliance with discharge

standards. The cost for weekly analytical services is \$4,160 for the bioreactor treatment system.

A grab sample of bag filter solids is also collected to support waste characterization, profiling, and disposal. Each grab solid sample is analyzed for metals using EPA Methods 6010B and 7471 and leachable metals using the EPA Methods 1311, 6010B, and 7470 for comparison to Federal RCRA and TCLP criteria and California DI WET/EPA Method 6010B for comparison to State TTLC and STLC criteria. Analysis of one composite bag filter solids sample generated during solids filtration is required at a cost of \$280.

4.5.10 Maintenance and Modifications

Maintenance and modifications costs include regular equipment replacement due to wear and tear. Equipment expected to require replacement includes reagent pumps and delivery lines, recirculation pump, water turbine, and storage batteries.

Reagent pumps and delivery lines (\$2,000) should be replaced every two years. The recirculation pump (\$5,000) and water turbine storage battery (\$5,200) may require replacement every five years. It is estimated that the water turbine (\$9,000) may require replacement on a 20 year schedule. The annualized equipment replacement cost for the bioreactor treatment system operated in gravity flow and recirculation modes is approximately \$2,490 and \$3,490, respectively.

SECTION 5

DATA QUALITY REVIEW

SITE demonstration samples were collected in accordance with the 2003 TEP/QAPP (Tetra Tech 2003). As part of the quality assurance/quality control (QA/QC) requirements specified in the TEP/QAPP, any deviations from the sampling plan, such as missed sampling events, changes in sampling locations, or changes in analytical methods, were documented throughout the duration of the demonstration and are presented in Section 5.1. Documentation of these deviations is important because of the potential effects they have on data quality and on the ability of the data to meet the project objectives.

As part of the QA/QC data review, sample delivery groups (SDG) received from the laboratory underwent data validation through a third-party validator to ensure that the data generated is of a quality sufficient to meet project objectives. As specified in the TEP/QAPP, data packages underwent 10 percent full validation in accordance with EPA validation guidance (EPA 1995). A summary of the data validation performed on the bioreactor treatment technology SITE demonstration data is presented in Section 5.2.

5.1 Deviations from TEP/QAPP

Due to various operating issues, several changes were required in the sampling of the bioreactor treatment system during the SITE demonstration. Deviations from the TEP/QAPP related to each mode of treatment system operation were documented throughout the duration of the SITE demonstration and are presented below.

- The sample frequency was reduced from every two weeks to once a month, at the direction of the EPA task order manager (TOM), to extend the demonstration period over two successive winters of system operation.
- Began analysis of samples collected from the influent (S3) and effluent (S4) of Bioreactor No.1 for sulfate, TSS, TDS, and alkalinity after system acclimation period. The data will be used to allow independent

evaluation of each bioreactor, rather than a combination of the two bioreactors.

- Began analysis of samples collected from the influent (S5) and effluent (S7) of the settling ponds for sulfate at the start of the demonstration to determine if additional sulfate reduction is occurring in the settling and flushing ponds.
- Began analysis of samples collected from the influent (S5) and effluent (S7) of the settling ponds for alkalinity after system acclimation to evaluate the source of alkalinity observed in system effluent.
- Collected an unsettled solids slurry sample from settling pond (S14) to evaluate changes in settling pond chemistry after reconfiguration of the system for recirculation operation.
- Collected a solids composite sample (S15) from one of the bag filters used to dewater sludge from the settling pond to assess the content and leachability of metals in dewatered treatment system sludge. The solids sample was analyzed for total metals and metals after TCLP extraction, SPLP extraction, and California DI WET extraction. The solids sample was also analyzed for total solids and percent moisture in order to estimate the likely increase in metals concentration after drying.
- Samples were not collected from the settling pond outfall (S6) due to lack of accessibility. The system operator discharged directly from the settling pond to the flushing pond to allow extended settling. Therefore, effluent from the flushing pond (S7) represents the treatment effectiveness of both ponds.
- Aqueous samples were not collected from the flushing pond (S11) because the extended HRT of the pond limited changes in pond chemistry. In addition, the pond surface was frozen over for at least a one-third of the demonstration period. Instead, the pond effluent (S7) was used to represent changes in pond chemistry.

- A sample was not collected at the system point of discharge on February 3, 2005 due to lack of accessibility (iced over), instead the effluent from the flushing pond (S7) was used to represent the system effluent for the day.
- Samples of flushed metal sulfide precipitate were not collected from the two bioreactors (S8 and S9) because not enough solids have built up in the bioreactors to require flushing.

5.2 Summary of Data Validation and PARCC Criteria Evaluation

The critical data quality parameters evaluated during data validation include precision, accuracy, representativeness, completeness, and comparability (PARCC). Evaluation of these critical parameters provides insight on the quality of the data and is essential in determining whether the data is of sufficient quality to meet project objectives. A summary of the data validation for the SITE demonstration data and an evaluation of the PARCC parameters for the primary target analytes are presented below.

Based on data validation, no metals results were rejected in the samples analyzed. However, some metals data were qualified as estimated based on other QC issues. QC issues resulting in qualified data typically consisted of problems with calibration and method blank contamination, inductively coupled plasma (ICP) interference check sample analysis, percent recovery and relative percent difference (RPD) values outside of acceptable values, and ICP serial dilution problems. An evaluation of the PARCC parameters follows.

Precision: Precision for the SITE demonstration data was evaluated through the analysis of matrix duplicates (MD) samples for metals. The precision goal for MD samples was established at less than or equal to 25 percent RPD. Over the duration of the SITE demonstration, a total of 13 aqueous samples and two sludge samples were collected from the treatment system and analyzed in duplicate. Where one or both metals results in a duplicate pair were below the practical quantitation limit (PQL) or not detected, the RPD was not calculated. Out of the five primary target metals and the five secondary water quality indicator metals, none of the metals exceeded the 25 percent RPD criteria. Corresponding metals data for associated samples within each SDG were qualified as estimated based on duplicate precision problems; however, no data was rejected.

Accuracy: Accuracy for the SITE demonstration data was evaluated through the analysis of matrix spike (MS) samples for the metals analyses. The accuracy goal for MS samples was established at 75 to 125 percent for percent recovery. Over the duration of the SITE demonstration, a total of 13 aqueous samples were collected from the treatment system

and analyzed as MS samples. In addition, two sludge samples and six metals leachate samples were analyzed as MS samples. Potassium in one water sample and in one leachate sample was qualified based on MS recovery problems.

Representativeness: Representativeness expresses the degree to which sample data accurately and precisely represent the characteristics of a population, parameter variations at a sampling point, or an environmental condition that they are intended to represent. Representativeness is a qualitative parameter; therefore, no specific criteria must be met. Representative data were obtained during the SITE demonstration through selection of proper sampling locations and analytical methods based on the project objectives and sampling program described in Section 2.3. As specified in the TEP/QAPP, proper collection and handling of samples avoided cross contamination and minimized analyte losses. The application of standardized laboratory procedures also facilitated generation of representative data.

To aid in the evaluation of sample representativeness, laboratory-required method blank samples were analyzed and evaluated for the presence of contaminants. Sample data determined to be non-representative by comparison with method blank data was qualified, as described earlier in this section. The data collected during the SITE demonstration are deemed representative of the chemical concentrations, physical properties, and other non-analytical parameters that were being sampled or documented. No metals data were rejected.

Completeness: Completeness is a measure of the percentage of project-specific data deemed valid. Valid data are obtained when samples are collected and analyzed in accordance with QC procedures outlined in the TEP/QAPP and when none of the QC criteria that affect data usability are significantly exceeded. Other factors not related to the validity of the data can also affect completeness, such as lost or broken samples, missed sampling events, or operational changes by the system operator.

Due to the time required to acclimate the bioreactor treatment system in cold weather conditions, the original sampling frequency of twice a month during the acclimation period was not followed. Instead, a monthly sampling frequency was followed toward the end of the acclimation period. A monthly sampling frequency was followed for the duration of the demonstration, unless the site was inaccessible due to winter storms. A monthly sampling frequency was selected to provide a long-term evaluation of the treatment system over two winters.

From November 2003 through mid-May 2004, the bioreactor treatment system was evaluated based on the original system configuration. In mid-May 2004, UNR and ARCO modified the operation of the system to include introduction of system influent to the settling pond, contact of ARD influent with

sulfide-rich bioreactor effluent in the settling pond, and recirculation of settling pond effluent to the head of Bioreactor No.1. The treatment system was operated in recirculation mode from mid-May 2004 through the end of the demonstration period in July 2005.

Evaluation of the system during recirculation operation represented a significant departure from the TEP/QAPP. The original sample design was reviewed and retained and only modified where a sampling location was no longer valid or duplicative. The monthly evaluation of the treatment system in both modes of operation (gravity-flow and recirculation), though a modification in scope and frequency, was also fully achieved.

As specified in the TEP/QAPP, the project completeness goal for the SITE demonstration was 90 percent. Based on an evaluation of the data that was collected and analyzed and other documentation, completeness for the project was greater

than 99 percent. Deviations from the TEP/QAPP due to unplanned changes in system operation by the system operator did not impact the validity of the data. Instead, the unplanned changes provided an opportunity to evaluate different modes of system operation and system response to changes in flow rate and HRT.

Comparability: The comparability objective determines whether analytical conditions are sufficiently uniform throughout the duration of the project to ensure that reported data are consistent. For the SITE demonstration, the generation of uniform data was ensured through adherence of the contracted laboratory to specified analytical methods, QC criteria, standardized units of measure, and standardized electronic deliverables in accordance with the TEP/QAPP. Comparability for the SITE demonstration data was also ensured through third party validation. As a result of these efforts, no data comparability issues were documented by the project team for this project.

SECTION 6 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 treatment system has been demonstrated at full-scale and is currently operational at Leviathan Mine. The treatment system is scalable, requiring an increase in the size or number of bioreactors and settling ponds to achieve the required unit operation and system HRT necessary for sulfide generation, metal-sulfide contact, and precipitate settling. The bioreactor treatment system at Leviathan Mine has been operated at flows ranging from 25 to 91 L/min.

The treatment system is undergoing continuous refinement and optimization to reduce the quantity of ethanol and base required, evaluate alternate sources of base addition, reduce recirculation rates, improve attainment of discharge standards for iron and selenium, and improve solids handling and dewatering processes. 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. Because of the success of compost-free bioreactor treatment system at Leviathan Mine, ARCO will continue to use this technology to treat ARD at the Aspen Seep and are also evaluating the potential effectiveness, implementability, and costs for treatment of other ARD sources at the mine site.

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 determine the volume of metal sulfide precipitate that will be generated.

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APPENDIX A
SAMPLE COLLECTION AND ANALYSIS TABLES

Table A-1. Sample Register for the Compost-Free Bioreactor Treatment System, Gravity Flow Operations

Sample ID	Date	Location	Filtered?	Project Objective	Total Metals	Sulfate	Alkalinity	TSS	TDS	Comments
3-AW-01-5-S01-W-C	11/14/2003	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	MS/MSD
3-AW-01-5-S01-W-C-F	11/14/2003	System Influent at Weir	Yes	P1, P2	X					
3-AW-01-5-S02-W-C	11/14/2003	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
3-AW-01-5-S02-W-C-F	11/14/2003	System Effluent	Yes	P1, P2	X					
3-AW-01-5-S03-W-C	11/14/2003	Bioreactor 1 Influent	No	SG1, SG6	X	X				
3-AW-01-5-S03-W-C-F	11/14/2003	Bioreactor 1 Influent	Yes	SG1, SG6	X					
3-AW-01-5-S04-W-C	11/14/2003	Bioreactor 1 Effluent	No	SG1, SG6	X	X				
3-AW-01-5-S04-W-C-F	11/14/2003	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
3-AW-01-5-S05-W-C	11/14/2003	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X		X	X	
3-AW-01-5-S05-W-C-F	11/14/2003	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
3-AW-01-5-S07-W-C	11/14/2003	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X		X	X	
3-AW-01-5-S07-W-C-F	11/14/2003	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
3-AW-03-2-S01-W-C	11/25/2003	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
3-AW-03-2-S01-W-C-F	11/25/2003	System Influent at Weir	Yes	P1, P2	X					
3-AW-03-2-S02-W-C	11/25/2003	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
3-AW-03-2-S02-W-C-F	11/25/2003	System Effluent	Yes	P1, P2	X					MS/MSD
3-AW-03-2-S03-W-C	11/25/2003	Bioreactor 1 Influent	No	SG1, SG6	X	X				
3-AW-03-2-S03-W-C-F	11/25/2003	Bioreactor 1 Influent	Yes	SG1, SG6	X					
3-AW-03-2-S04-W-C	11/25/2003	Bioreactor 1 Effluent	No	SG1, SG6	X	X				
3-AW-03-2-S04-W-C-F	11/25/2003	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
3-AW-03-2-S05-W-C	11/25/2003	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X		X	X	
3-AW-03-2-S05-W-C-F	11/25/2003	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
3-AW-03-2-S07-W-C	11/25/2003	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	
3-AW-03-2-S07-W-C-F	11/25/2003	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
AW-1/29/04-S1-W-C	1/29/2004	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
AW-1/29/04-S1-W-C-F	1/29/2004	System Influent at Weir	Yes	P1, P2	X					
AW-1/29/04-S2-W-C	1/29/2004	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
AW-1/29/04-S2-W-C-F	1/29/2004	System Effluent	Yes	P1, P2	X					MS/MSD
AW-1/29/04-S3-W-C	1/29/2004	Bioreactor 1 Influent	No	SG1, SG6	X					
AW-1/29/04-S3-W-C-F	1/29/2004	Bioreactor 1 Influent	Yes	SG1, SG6	X					
AW-1/29/04-S4-W-C	1/29/2004	Bioreactor 1 Effluent	No	SG1, SG6	X					

Table A-1. Sample Register for the Compost-Free Bioreactor Treatment System, Gravity Flow Operations (continued)

Sample ID	Date	Location	Filtered?	Project Objective	Total Metals	Sulfate	Alkalinity	TSS	TDS	Comments
AW-1/29/04-S4-W-C-F	1/29/2004	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
AW-1/29/04-S5-W-C	1/29/2004	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X		X	X	
AW-1/29/04-S5-W-C-F	1/29/2004	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
AW-1/29/04-S7-W-C	1/29/2004	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X		X	X	
AW-1/29/04-S7-W-C-F	1/29/2004	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
4-AW-2/19/04-S1-W-C	2/19/2004	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
4-AW-2/19/04-S1-W-C-F	2/19/2004	System Influent at Weir	Yes	P1, P2	X					
4-AW-2/19/04-S2-W-C	2/19/2004	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
4-AW-2/19/04-S2-W-C-F	2/19/2004	System Effluent	Yes	P1, P2	X					MS/MSD
4-AW-2/19/04-S3-W-C	2/19/2004	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	
4-AW-2/19/04-S3-W-C-F	2/19/2004	Bioreactor 1 Influent	Yes	SG1, SG6	X					
4-AW-2/19/04-S4-W-C	2/19/2004	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
4-AW-2/19/04-S4-W-C-F	2/19/2004	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
4-AW-2/19/04-S5-W-C	2/19/2004	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
4-AW-2/19/04-S5-W-C-F	2/19/2004	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
4-AW-2/19/04-S7-W-C	2/19/2004	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	
4-AW-2/19/04-S7-W-C-F	2/19/2004	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
4-AW-3/24/04-S1-W-C	3/24/2004	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
4-AW-3/24/04-S1-W-C-F	3/24/2004	System Influent at Weir	Yes	P1, P2	X					
4-AW-3/24/04-S2-W-C	3/24/2004	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
4-AW-3/24/04-S2-W-C-F	3/24/2004	System Effluent	Yes	P1, P2	X					MS/MSD
4-AW-3/24/04-S3-W-C	3/24/2004	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	
4-AW-3/24/04-S3-W-C-F	3/24/2004	Bioreactor 1 Influent	Yes	SG1, SG6	X					
4-AW-3/24/04-S4-W-C	3/24/2004	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
4-AW-3/24/04-S4-W-C-F	3/24/2004	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
4-AW-3/24/04-S5-W-C	3/24/2004	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
4-AW-3/24/04-S5-W-C-F	3/24/2004	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
4-AW-3/24/04-S7-W-C	3/24/2004	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	
4-AW-3/24/04-S7-W-C-F	3/24/2004	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
4-AW-4/29/04-S1-W-C	4/29/2004	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
4-AW-4/29/04-S1-W-C-F	4/29/2004	System Influent at Weir	Yes	P1, P2	X					

Table A-1. Sample Register for the Compost-Free Bioreactor Treatment System, Gravity Flow Operations (continued)

Sample ID	Date	Location	Filtered?	Project Objective	Total Metals	Sulfate	Alkalinity	TSS	TDS	Comments
4-AW-4/29/04-S2-W-C	4/29/2004	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
4-AW-4/29/04-S2-W-C-F	4/29/2004	System Effluent	Yes	P1, P2	X					MS/MSD
4-AW-4/29/04-S3-W-C	4/29/2004	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	
4-AW-4/29/04-S3-W-C-F	4/29/2004	Bioreactor 1 Influent	Yes	SG1, SG6	X					
4-AW-4/29/04-S4-W-C	4/29/2004	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
4-AW-4/29/04-S4-W-C-F	4/29/2004	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
4-AW-4/29/04-S5-W-C	4/29/2004	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
4-AW-4/29/04-S5-W-C-F	4/29/2004	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
4-AW-4/29/04-S7-W-C	4/29/2004	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	
4-AW-4/29/04-S7-W-C-F	4/29/2004	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
MS/MSD=Matrix spike/matrix duplicate										
					TDS=Total dissolved solids			TSS=Total suspended solids		

Table A-2. Sample Register for the Compost-Free Bioreactor Treatment System, Recirculation Operations

Sample ID	Date	Location	Filtered?	Project Objective	Total Metals	Sulfate	Alkalinity	TSS	TDS	Comments
AW-6/14/04-S14-W-G	6/16/2004	Pond 3	No	SG2, SG3	X	X	X	X	X	
AW-6/14/04-S14-W-G-F	6/16/2004	Pond 3	Yes	SG2, SG3	X					
AW-6/14/04-S1-W-C	6/16/2004	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
AW-6/14/04-S1-W-C-F	6/16/2004	System Influent at Weir	Yes	P1, P2	X					
AW-6/14/04-S2-W-C	6/16/2004	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
AW-6/14/04-S2-W-C-F	6/16/2004	System Effluent	Yes	P1, P2	X					
AW-6/14/04-S3-W-C	6/16/2004	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	
AW-6/14/04-S3-W-C-F	6/16/2004	Bioreactor 1 Influent	Yes	SG1, SG6	X					
AW-6/14/04-S4-W-C	6/16/2004	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
AW-6/14/04-S4-W-C-F	6/16/2004	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
AW-6/14/04-S5-W-C	6/16/2004	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
AW-6/14/04-S5-W-C-F	6/16/2004	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
AW-6/14/04-S7-W-C	6/16/2004	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	MS/MSD
AW-6/14/04-S7-W-C-F	6/16/2004	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
AW-8/19/04-S1-W-C	8/19/2004	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
AW-8/19/04-S1-W-C-F	8/19/2004	System Influent at Weir	Yes	P1, P2	X					
AW-8/19/04-S2-W-C	8/19/2004	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	MS/MSD
AW-8/19/04-S2-W-C-F	8/19/2004	System Effluent	Yes	P1, P2	X					
AW-8/19/04-S3-W-C	8/19/2004	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	
AW-8/19/04-S3-W-C-F	8/19/2004	Bioreactor 1 Influent	Yes	SG1, SG6	X					
AW-8/19/04-S4-W-C	8/19/2004	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
AW-8/19/04-S4-W-C-F	8/19/2004	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
AW-8/19/04-S5-W-C	8/19/2004	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
AW-8/19/04-S5-W-C-F	8/19/2004	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
AW-8/19/04-S7-W-C	8/19/2004	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	
AW-8/19/04-S7-W-C-F	8/19/2004	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
AW-12/3/04-S1-W-C	12/3/2004	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
AW-12/3/04-S1-W-C-F	12/3/2004	System Influent at Weir	Yes	P1, P2	X					
AW-12/3/04-S2-W-C	12/3/2004	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
AW-12/3/04-S2-W-C-F	12/3/2004	System Effluent	Yes	P1, P2	X					
AW-12/3/04-S3-W-C	12/3/2004	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	

Table A-2. Sample Register for the Compost-Free Bioreactor Treatment System, Recirculation Operations (continued)

Sample ID	Date	Location	Filtered?	Project Objective	Total Metals	Sulfate	Alkalinity	TSS	TDS	Comments
AW-12/3/04-S3-W-C-F	12/3/2004	Bioreactor 1 Influent	Yes	SG1, SG6	X					
AW-12/3/04-S4-W-C	12/3/2004	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
AW-12/3/04-S4-W-C-F	12/3/2004	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
AW-12/3/04-S5-W-C	12/3/2004	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
AW-12/3/04-S5-W-C-F	12/3/2004	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
AW-12/3/04-S7-W-C	12/3/2004	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	MS/MSD
AW-12/3/04-S7-W-C-F	12/3/2004	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
AW-2/3/05-S1-W-C	2/3/2005	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
AW-2/3/05-S1-W-C-F	2/3/2005	System Influent at Weir	Yes	P1, P2	X					
AW-2/3/05-S3-W-C	2/3/2005	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	
AW-2/3/05-S3-W-C-F	2/3/2005	Bioreactor 1 Influent	Yes	SG1, SG6	X					
AW-2/3/05-S4-W-C	2/3/2005	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
AW-2/3/05-S4-W-C-F	2/3/2005	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
AW-2/3/05-S5-W-C	2/3/2005	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
AW-2/3/05-S5-W-C-F	2/3/2005	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
AW-2/3/05-S7-W-C	2/3/2005	Pond 4 Effluent Pipe	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	Effluent, S2 iced over, MS/MSD
AW-2/3/05-S7-W-C-F	2/3/2005	Pond 4 Effluent Pipe	Yes	P1, P2	X					
AW-3/17/05-S1-W-C	3/17/2005	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	MS/MSD
AW-3/17/05-S1-W-C-F	3/17/2005	System Influent at Weir	Yes	P1, P2	X					
AW-3/17/05-S2-W-C	3/17/2005	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
AW-3/17/05-S2-W-C-F	3/17/2005	System Effluent	Yes	P1, P2	X					
AW-3/17/05-S3-W-C	3/17/2005	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	
AW-3/17/05-S3-W-C-F	3/17/2005	Bioreactor 1 Influent	Yes	SG1, SG6	X					
AW-3/17/05-S4-W-C	3/17/2005	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
AW-3/17/05-S4-W-C-F	3/17/2005	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
AW-3/17/05-S5-W-C	3/17/2005	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
AW-3/17/05-S5-W-C-F	3/17/2005	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
AW-3/17/05-S7-W-C	3/17/2005	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	
AW-3/17/05-S7-W-C-F	3/17/2005	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
AW-4/27/05-S1-W-C	4/27/2005	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	MS/MSD

Table A-2. Sample Register for the Compost-Free Bioreactor Treatment System, Recirculation Operations (continued)

Sample ID	Date	Location	Filtered?	Project Objective	Total Metals	Sulfate	Alkalinity	TSS	TDS	Comments
AW-4/27/05-S1-W-C-F	4/27/2005	System Influent at Weir	Yes	P1, P2	X					
AW-4/27/05-S2-W-C	4/27/2005	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	
AW-4/27/05-S2-W-C-F	4/27/2005	System Effluent	Yes	P1, P2	X					
AW-4/27/05-S3-W-C	4/27/2005	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	
AW-4/27/05-S3-W-C-F	4/27/2005	Bioreactor 1 Influent	Yes	SG1, SG6	X					
AW-4/27/05-S4-W-C	4/27/2005	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
AW-4/27/05-S4-W-C-F	4/27/2005	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
AW-4/27/05-S5-W-C	4/27/2005	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
AW-4/27/05-S5-W-C-F	4/27/2005	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
AW-4/27/05-S7-W-C	4/27/2005	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	
AW-4/27/05-S7-W-C-F	4/27/2005	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
AW-6/2/05-S1-W-C	6/2/2005	System Influent at Weir	No	P1, P2, SG1, SG2, SG6	X	X	X	X	X	
AW-6/2/05-S1-W-C-F	6/2/2005	System Influent at Weir	Yes	P1, P2	X					
AW-6/2/05-S2-W-C	6/2/2005	System Effluent	No	P1, P2, SG1, SG2, SG3, SG6	X	X	X	X	X	MS/MSD
AW-6/2/05-S2-W-C-F	6/2/2005	System Effluent	Yes	P1, P2	X					
AW-6/2/05-S3-W-C	6/2/2005	Bioreactor 1 Influent	No	SG1, SG6	X	X	X	X	X	
AW-6/2/05-S3-W-C-F	6/2/2005	Bioreactor 1 Influent	Yes	SG1, SG6	X					
AW-6/2/05-S4-W-C	6/2/2005	Bioreactor 1 Effluent	No	SG1, SG6	X	X	X	X	X	
AW-6/2/05-S4-W-C-F	6/2/2005	Bioreactor 1 Effluent	Yes	SG1, SG6	X					
AW-6/2/05-S5-W-C	6/2/2005	Bioreactor 2 Effluent	No	SG1, SG3, SG6	X	X	X	X	X	
AW-6/2/05-S5-W-C-F	6/2/2005	Bioreactor 2 Effluent	Yes	SG1, SG3, SG6	X					
AW-6/2/05-S7-W-C	6/2/2005	Pond 4 Effluent Pipe	No	SG1, SG3, SG6	X	X	X	X	X	
AW-6/2/05-S7-W-C-F	6/2/2005	Pond 4 Effluent Pipe	Yes	SG1, SG3, SG6	X					
MS/MSD=Matrix spike/matrix duplicate										
TDS=Total dissolved solids										
TSS=Total suspended solids										

Table A-3. Sample Register for the Compost-Free Bioreactor Treatment System, Solids for Both Modes of Operation

Sample ID	Date	Location	Filtered?	Project Objective	SPLP Metals	TCLP Metals	WET Metals	Total Metals	Percent Moisture	Comments
AW-7/13/05-S10-S-C	7/13/2005	Pond 3 sludge	---	SG4	X	X	X	X	X	MS/MSD
AW-7/13/05-S11-S-C	7/13/2005	Pond 4 sludge	---	SG4	X	X	X	X	X	
AW-7/13/05-S12-S-C	7/13/2005	Aeration Channel sludge	---	SG4	X	X	X	X	X	
AW-7/13/05-S13-S-C	7/13/2005	Pretreatment Pond sludge	---	SG4	X	X	X	X	X	
AW-9/29/05-S15-S-G	9/29/2005	Bag Filter Solids	---	SG4	X	X	X	X	X	MS/MSD
MS/MSD=Matrix spike/matrix duplicate				TCLP=Toxicity characteristic leaching procedure						
SPLP=Synthetic precipitation and leaching procedure				WET=Waste extraction test						

APPENDIX B
DATA USED TO EVALUATE PROJECT PRIMARY OBJECTIVES

Table B-1. Data Used to Evaluate Project Objectives for the Bioreactor Treatment System, Gravity Flow Operations

Sample Number ⁽¹⁾	Sample Date	Composite or Grab?	Analyte	Filtered Influent Concentration (µg/L)	Filtered Effluent Concentration (µg/L)	4-Day Average Filtered Effluent Concentration ⁽²⁾ (µg/L)
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Aluminum	38,100	79.8	
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Aluminum	39,400	203 UJ	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Aluminum	35,200	160	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Aluminum	35,300	5 U	112
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Aluminum	36,900	144	128
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Aluminum	39,900	25.8	83.7
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Arsenic	1.5 U	12.5	
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Arsenic	2.5 U	3.8 UJ	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Arsenic	1.6 U	1.6 U	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Arsenic	1.6 U	3	5.2
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Arsenic	3.1	2.4	2.7
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Arsenic	2.3 U	5.1	3.0
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Cadmium	0.44 UJ	0.17 U	
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Cadmium	1	0.21 UJ	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Cadmium	0.88	0.32 U	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Cadmium	0.34	0.098 U	<0.20
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Cadmium	0.4	0.23 U	<0.21
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Cadmium	0.57	0.23 U	<0.22
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Chromium	20.8 J	16.3	
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Chromium	3.9	9.9	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Chromium	4.4	0.5 U	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Chromium	4.5	0.45 U	6.8
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Chromium	17.2	6.4	4.3
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Chromium	22.4	13.4	5.2
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Copper	701	4.5	
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Copper	732	1.9 U	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Copper	630	4.7	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Copper	661	5.6	4.2
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Copper	656	5.6	4.5
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Copper	765	6.5	5.6
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Iron	121,000	4,030	
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Iron	126,000	12,800	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Iron	114,000	39,200	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Iron	109,000	7,100	15,783
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Iron	113,000	389	14,873
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Iron	120,000	105	11,699
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Lead	0.88 UJ	0.88 U	
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Lead	0.65 U	4.2 UJ	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Lead	2.9	5.1	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Lead	5.4	9.8	5.0
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Lead	5.3	3.4	5.6
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Lead	6.7	4.8	5.8
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Nickel	484	41.7	

Table B-1. Data Used to Evaluate Project Objectives for the Bioreactor Treatment System, Gravity Flow Operations (continued)

Sample Number ⁽¹⁾	Sample Date	Composite or Grab?	Analyte	Filtered Influent Concentration (µg/L)	Filtered Effluent Concentration (µg/L)	4-Day Average Filtered Effluent Concentration ⁽²⁾ (µg/L)
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Nickel	493	36.7	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Nickel	448	125	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Nickel	467	42.3	61.4
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Nickel	481	53.1	64.3
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Nickel	547	94.2	78.7
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Selenium	12.8 UJ	13.9	
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Selenium	11.6	10 UJ	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Selenium	16.3	13.3	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Selenium	18	8	11.2
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Selenium	9.6	8.7	10.0
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Selenium	14.9	13.3	10.8
3-AW-01-5-S0X-W-C-F	11/14/2003	Composite	Zinc	701	29	
3-AW-03-2-S0X-W-C-F	11/25/2003	Composite	Zinc	732	14.2 J	
AW-1/29/04-SX-W-C-F	1/29/2004	Composite	Zinc	677	13.5	
4-AW-2/19/04-SX-W-C-F	2/19/2004	Composite	Zinc	677	16.2	18.2
4-AW-3/24/04-SX-W-C-F	3/24/2004	Composite	Zinc	702	10.3	13.6
4-AW-4/29/04-SX-W-C-F	4/29/2004	Composite	Zinc	802	11.5	12.9
1 - For the influent sample, X in the sample number = 1; for the effluent sample, X=2 2 - The data from four consecutive sampling events were used in the calculation of the average instead of four consecutive days						
µg/L - Micrograms per liter NC - Not calculated U - Non-detect						

Table B-2. Data Used to Evaluate Project Objectives for the Bioreactor Treatment System, Recirculation Operations

Sample Number ⁽¹⁾	Sample Data	Composite or Grab?	Analyte	Filtered Influent Concentration (µg/L)	Filtered Effluent Concentration (µg/L)	4-Day Average Filtered Effluent Concentration ⁽²⁾ (µg/L)
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Aluminum	38,700	31.2	
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Aluminum	40,400	105	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Aluminum	39,000	33.9	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Aluminum	38,400	39.4 UJ	52.4
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Aluminum	34,300	54.8 J	58.3
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Aluminum	39,300	63.1	47.8
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Aluminum	50,100	41.8	49.8
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Arsenic	10.2 UJ	11.2	
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Arsenic	2.1 U	14.7 UJ	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Arsenic	1.9 U	1.9 U	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Arsenic	1.9 U	2.4 J	7.6
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Arsenic	4.8	5.3 UJ	6.1
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Arsenic	18.7 J	2.9	3.1
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Arsenic	12.4	7.2	4.5
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Cadmium	1.1 UJ	0.28 U	
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Cadmium	0.94	0.16 UJ	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Cadmium	1.3	0.12 U	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Cadmium	0.12 U	0.12 U	<0.17
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Cadmium	0.3 U	0.3 U	<0.18
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Cadmium	0.12 U	0.12 U	<0.17
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Cadmium	0.3	0.28 U	<0.21
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Chromium	17.9 J	14.1	
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Chromium	19.3	11.6 J	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Chromium	4.8	2.7	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Chromium	4.6	1.2 UJ	7.4
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Chromium	14.9	6.7	5.6
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Chromium	5.8 J	0.88 U	2.9
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Chromium	10.6	7.5	4.1
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Copper	851	7.6	
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Copper	766	9.5 J	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Copper	702	1.7	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Copper	697	1.6 U	5.1
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Copper	598	5.4 UJ	4.6
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Copper	769	1.7 U	2.6
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Copper	1,180	4.6	3.3
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Iron	104,000	3,160	
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Iron	99,500	269	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Iron	126,000	9,060	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Iron	124,000	2,550	3,760
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Iron	111,000	635	3,129
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Iron	109,000	975	3,305
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Iron	137,000	2,280	1,610
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Lead	6.7 J	3.6	

Table B-2. Data Used to Evaluate Project Objectives for the Bioreactor Treatment System, Recirculation Operations (continued)

Sample Number ⁽¹⁾	Sample Data	Composite or Grab?	Analyte	Filtered Influent Concentration (µg/L)	Filtered Effluent Concentration (µg/L)	4-Day Average Filtered Effluent Concentration ⁽²⁾ (µg/L)
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Lead	5.9	3.1 UJ	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Lead	1.7	0.73	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Lead	1.4	0.72 U	2.0
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Lead	5.3	3.3 J	2.0
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Lead	2.3 J	1.1	1.5
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Lead	5.9	4.6	2.4
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Nickel	525	36.8	
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Nickel	531	18.9 J	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Nickel	531	154	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Nickel	551	50.5 J	65.1
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Nickel	481	59.1	70.6
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Nickel	497	79.4	85.8
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Nickel	585	89.5	69.6
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Selenium	17.7	12.3	
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Selenium	14.4	7.8 UJ	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Selenium	9.5	5.6	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Selenium	18	13.3 UJ	9.8
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Selenium	7	6.3 UJ	8.3
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Selenium	7.1 UJ	3.6	7.2
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Selenium	7	10.5	8.4
AW-6/14/04-SX-W-C-F	6/16/2004	Composite	Zinc	774	8.4	
AW-8/19/04-SX-W-C-F	8/19/2004	Composite	Zinc	755	4.5 UJ	
AW-12/3/04-SX-W-C-F	12/3/2004	Composite	Zinc	772	17.5	
AW-2/3/05-SX-W-C-F	2/3/2005	Composite	Zinc	780	0.97 UJ	7.8
AW-3/17/05-SX-W-C-F	3/17/2005	Composite	Zinc	709	0.92 U	6.0
AW-4/27/05-SX-W-C-F	4/27/2005	Composite	Zinc	761	11.3	7.7
AW-6/2/05-SX-W-C-F	6/2/2005	Composite	Zinc	880	18.8	8.0

1 - For the influent sample, X in the sample number = 1; for the effluent sample, X=2
2 - The data from four consecutive sampling events were used in the calculation of the average instead of four consecutive days

µg/L - Micrograms per liter NC - Not calculated U - Non-detect

APPENDIX C
DETAILED COST ELEMENT SPREADSHEETS

Table C-1. Cost Element Details for the Compost-Free Bioreactor Treatment System - Gravity Flow Operation

	Description	Quantity	Unit	Unit cost	Subtotal
I	Site Preparation				
	Design (20% of capital cost)	1	lump sum	\$109,686.20	\$109,686.20
	Construction Management (15% of capital cost)	1	lump sum	\$82,264.65	\$82,264.65
	Project Management (10% of capital cost)	1	lump sum	\$54,843.10	\$54,843.10
	Preconstruction Site Work (Clearing and Chipping, Topsoil Removal, and Debris Removal)	1	lump sum	\$41,392.00	\$41,392.00
	Subtotal				\$288,185.95
II	Permitting and Regulatory Requirements				
	Superfund Site, No Permitting Costs				\$0.00
	Subtotal				\$0.00
III	Capital and Equipment				
1	Compost-Free Bioreactor Treatment System				
<i>a</i>	<i>Equipment Mobilization/Demobilization</i>	1	lump sum	\$73,550.00	\$73,550.00
<i>b</i>	<i>Pond and Pipe Trench Earthwork</i>	1	lump sum	\$136,442.00	\$136,442.00
	Seep collection pond excavation, bioreactor ponds and settling ponds excavation, sloping/riprap, trench excavation and placement of bedding for piping				
<i>c</i>	<i>Installation of Pond Liners, Stairs, Decant Structures</i>	1	lump sum	\$63,756.00	\$63,756.00
	Placement and seaming of liners and installation of boots for piping in the pretreatment pond, the two bioreactor ponds, and the two settling ponds. Installation of settling pond stairs and decant structures. Placement of geotextile in the bottom of the aeration channel.				
<i>d</i>	<i>Installation of Distribution Piping and Valve Vaults</i>	1	lump sum	\$149,263.00	\$149,263.00
	Placement of 6-inch system main drain and valves, 4-inch distribution piping and valves, and 4-inch perforated influent and effluent loops in the two bioreactors; installation of two precast flushing vaults and ten 24-inch diameter HDPE standpipe vaults				
<i>e</i>	<i>Placement of Bioreactor Substrate</i>	1	lump sum	\$47,173.00	\$47,173.00
	Placement of manure layer, 3- to 6-inch cobble layer, and 6- to 9-inch round rock layer				
<i>f</i>	<i>Erosion Control and Revegetation/Reseeding</i>	1	lump sum	\$10,907.00	\$10,907.00
<i>g</i>	<i>Water Turbine and Storage Batteries</i>	1	lump sum	\$14,700.00	\$14,700.00
	4 KW turbine and 60 KW battery (48 volt)				
	Subtotal				\$495,791.00
2	Reagent Storage and Distribution				
<i>a</i>	<i>Ethanol Storage Tank and Delivery System</i>	1	lump sum	\$13,400.00	\$13,400.00
	Two 2,300 gallon bulk tanks, a reagent pump and viton tubing, and line containment pad				
<i>b</i>	<i>Sodium Hydroxide Storage Tank and Delivery System</i>	1	lump sum	\$15,800.00	\$15,800.00
	One 1,000 gallon bulk tank, a stainless steel transfer pump, a daily make up tank, a reagent pump and viton tubing, and line containment pad				
<i>c</i>	<i>Make up Water Storage Tank and Delivery System</i>	1	lump sum	\$2,000.00	\$2,000.00
	One 1,000 gallon bulk tank, a pump and delivery line. Assumes a make up water source is available, otherwise, use treated effluent				
<i>d</i>	<i>Reagent Storage Area Fencing</i>	1	lump sum	\$4,000.00	\$4,000.00
	200 feet of eight foot high fencing, double wide access gate, razor wire top.				
	Subtotal				35,200.00

Table C-1. Cost Element Details for the Compost-Free Bioreactor Treatment System - Gravity Flow Operation (continued)

	Description	Quantity	Unit	Unit cost	Subtotal
3	Automation				
<i>a</i>	<i>Remote Monitoring/Alarm System</i>				\$9,742.50
	Sensaphone SCADA 3000 (control system, logger, alarm)	1	lump sum	\$2,495.00	\$2,495.00
	Miscellaneous Accessories for SCADA 3000	1	lump sum	\$500.00	\$500.00
	Personal Computer	1	lump sum	\$2,000.00	\$2,000.00
	Professional Series 900 MHz Data Transceivers	1	lump sum	\$1,000.00	\$1,000.00
	Miscellaneous Accessories for Transceivers	1	lump sum	\$500.00	\$500.00
	Installation Cost (assumes 50% of equipment cost)	1	lump sum	\$3,247.50	\$3,247.50
<i>b</i>	<i>pH Controller System</i>				\$6,202.50
	Pulse Output Controller	2	each	\$1,160.00	\$2,320.00
	Electronic Diaphragm Pumps	2	each	\$826.00	\$1,652.00
	pH Probe and Cable	2	each	\$220.00	\$440.00
	Temperature Sensor and Cable	2	each	\$200.00	\$400.00
	Accessories (cables, calibration solution)	1	lump sum	\$150.00	\$150.00
	Installation Cost (assumes 25% of equipment cost)	1	lump sum	\$1,240.50	\$1,240.50
	Subtotal				\$15,945.00
4	Communications				
	Motorola 9505 Satellite Phone	1	lump sum	\$1,495.00	\$1,495.00
	Subtotal				\$1,495.00
	Total Fixed Costs				\$836,616.95
IV	System Start up and Acclimation (one time event)				
	System Start-up Labor (2 Field Technicians for 2 weeks)	160	hour	\$56.19	\$8,990.40
	Acclimation Period Labor (1 Field Technician for 2.5 months)	240	hour	\$56.19	\$13,485.60
	Subtotal				\$22,476.00
V	Consumables and Rentals (Yearly)				
	Ethanol	2,262	gallon	\$2.50	\$5,655.00
	Sodium Hydroxide	5,839	gallon	\$0.85	\$4,963.15
	Personal Protective Equipment (4 days/month)	12	month	\$28.00	\$336.00
	Hydrogen Sulfide Gas Meter (4 days/month)	12	month	\$300.00	\$3,600.00
	Water Quality Meter and Supplies (4 days/month)	12	month	\$700.00	\$8,400.00
	Storage Connex	12	month	\$325.00	\$3,900.00
	Subtotal				\$26,854.15
VI	Labor (Yearly)				
	Field Technicians (1 day per week)	416	hour	\$56.19	\$23,375.04
	Administrative Support (5% of field effort)	20	hour	\$61.16	\$1,223.20
	Project Management (10% of field effort)	40	hour	\$90.00	\$3,600.00
	Subtotal				\$28,198.24
VII	Utilities (Yearly)				
	Backup Generator (3 Kilowatt; assume required for 4 months)	4	month	\$800.00	\$3,200.00
	Backup Generator Fuel (105 gallon/month at \$2.50/gallon)	4	months	\$262.50	\$1,048.00
	SCADA Communication Service	12	month	\$75.00	\$900.00
	Satellite Phone Communications Service	12	month	\$50.00	\$600.00
	Portable Toilet	8	month	\$325.00	\$2,600.00
	Subtotal				\$8,348.00

Table C-1. Cost Element Details for the Compost-Free Bioreactor Treatment System - Gravity Flow Operation (continued)

VIII	Residual Waste Handling and Disposal (Yearly)				
	Off-Site Hazardous Sludge Disposal (80% moisture)	40	ton	\$263.00	\$10,520.00
	Sludge Pumping and Bag Filtration	1	lump sum	\$3,795.00	\$3,795.00
	Subtotal				\$14,315.00
IX	Analytical Services (Yearly)				
	Dissolved Metals (Effluent Discharge)	52	each	\$80.00	\$4,160.00
	Total and Leachable Metals (Waste Characterization)	1	each	\$280.00	\$280.00
	Subtotal				\$4,440.00
X	Maintenance and Modifications (as indicated)				
	Replace Storage Batteries (every 5 years)	1	each	\$5,200.00	\$5,200.00
	Replace Water Turbine (every 20 years)	1	each	\$9,000.00	\$9,000.00
	Replace Reagent Pumps (every 2 years)	2	each	\$1,000.00	\$2,000.00
	Subtotal				\$16,200.00
	Total 1st Year Variable Costs				\$104,613.39
	Recurring Variable Costs				\$82,155.39
	Periodic Costs				\$16,200.00

Description	Total
Total 1st Year Costs	\$941,248.34
Total 1st Year Costs/1000 gallons	\$189.54
Total Variable Costs/1000 gallons	\$16.54
Cumulative 5-Year Total Variable Costs (Present Worth at 7% Rate of Return)	\$343,834.00
Cumulative 15-Year Total Variable Costs (Present Worth at 7% Rate of Return)	\$764,950.00
Cumulative 30-Year Total Variable Costs (Present Worth at 7% Rate of Return)	\$1,045,005.00
% - Percent HDPE – High Density Polyethylene KW - Kilowatt MHz – Megahertz SCADA - Supervisory Control and Data Acquisition	

Table C-2. Cost Element Details for the Compost-Free Bioreactor Treatment System - Recirculation Operation

	Description	Quantity	Unit	Unit cost	Subtotal
I	Site Preparation				
	Design (20% of capital cost)	1	lump sum	\$119,189.00	\$119,189.00
	Construction Management (15% of capital cost)	1	lump sum	\$89,392.00	\$89,392.00
	Project Management (10% of capital cost)	1	lump sum	\$59,595.00	\$59,595.00
	Preconstruction Site Work (Clearing and Chipping, Topsoil Removal, and Debris Removal)	1	lump sum	\$41,392.00	\$41,392.00
	Subtotal				\$309,568.00
II	Permitting and Regulatory Requirements				
	Superfund Site, No Permitting Costs				\$0.00
	Subtotal				\$0.00
III	Capital and Equipment				
1	Compost-Free Bioreactor Treatment System				
<i>a</i>	<i>Equipment Mobilization/Demobilization</i>	1	lump sum	\$73,550.00	\$73,550.00
<i>b</i>	<i>Pond and Pipe Trench Earthwork</i>	1	lump sum	\$136,442.00	\$136,442.00
	Seep collection pond excavation, bioreactor ponds and settling ponds excavation, sloping/riprap, trench excavation and placement of bedding for piping				
<i>c</i>	<i>Installation of Pond Liners, Stairs, Decant Structures</i>	1	lump sum	\$63,756.00	\$63,756.00
	Placement and seaming of liners and installation of boots for piping in the pretreatment pond, the two bioreactor ponds, and the two settling ponds. Installation of settling pond stairs and decant structures. Placement of geotextile in the bottom of the aeration channel.				
<i>d</i>	<i>Installation of Distribution Piping and Valve Vaults</i>	1	lump sum	\$149,263.00	\$149,263.00
	Placement of 6-inch system main drain and valves, 4-inch distribution piping and valves, and 4-inch perforated influent and effluent loops in the two bioreactors; installation of two precast flushing vaults and ten 24-inch diameter HDPE standpipe vaults				
<i>e</i>	<i>Placement of Bioreactor Substrate</i>	1	lump sum	\$47,173.00	\$47,173.00
	Placement of manure layer, 3- to 6-inch cobble layer, and 6- to 9-inch round rock layer				
<i>f</i>	<i>Erosion Control and Revegetation/Reseeding</i>	1	lump sum	\$10,907.00	\$10,907.00
<i>g</i>	<i>Recirculation Pump and Piping</i>	1	lump sum	\$6,120.00	\$6,120.00
	(1) Stainless steel submersible pump; 200 feet of 3-inch HDPE piping; 900 feet of 2-inch HDPE piping; wiring				
<i>h</i>	<i>Water Turbine and Storage Batteries</i>	1	lump sum	\$14,700.00	\$14,700.00
	4 KW turbine and 60 KW battery (48 volt)				
	Subtotal				\$501,911.00
2	Reagent Storage and Distribution				
<i>a</i>	<i>Ethanol Storage Tank and Delivery System</i>	1	lump sum	\$13,400.00	\$13,400.00
	Two 2,300 gallon bulk tanks, a reagent pump and viton tubing, and line containment pad				
<i>b</i>	<i>Sodium Hydroxide Storage Tank and Delivery System</i>	1	lump sum	\$15,800.00	\$15,800.00
	One 1,000 gallon bulk tank, a stainless steel transfer pump, a daily make up tank, a reagent pump and viton tubing, and line containment pad				
<i>c</i>	<i>Make up Water Storage Tank and Delivery System</i>	1	lump sum	\$2,000.00	\$2,000.00
	One 1,000 gallon bulk tank, a pump and delivery line. Assumes a make up water source is available, otherwise, use treated effluent				
<i>d</i>	<i>Reagent Storage Area Fencing</i>	1	lump sum	\$4,000.00	\$4,000.00
	200 feet of eight foot high fencing, double wide access gate, razor wire top.				
	Subtotal				35,200.00

Table C-2. Cost Element Details for the Compost-Free Bioreactor Treatment System - Recirculation Operation (continued)

	Description	Quantity	Unit	Unit cost	Subtotal
3	Automation				
<i>a</i>	<i>Remote Monitoring/Alarm System</i>				\$9,742.50
	Sensaphone SCADA 3000 (control system, logger, alarm)	1	lump sum	\$2,495.00	\$2,495.00
	Miscellaneous Accessories for SCADA 3000	1	lump sum	\$500.00	\$500.00
	Personal Computer	1	lump sum	\$2,000.00	\$2,000.00
	Professional Series 900 MHz Data Transceivers	1	lump sum	\$1,000.00	\$1,000.00
	Miscellaneous Accessories for Transceivers	1	lump sum	\$500.00	\$500.00
	Installation Cost (assumes 50% of equipment cost)	1	lump sum	\$3,247.50	\$3,247.50
<i>b</i>	<i>pH Controller System</i>				\$6,202.50
	Pulse Output Controller	2	each	\$1,160.00	\$2,320.00
	Electronic Diaphragm Pumps	2	each	\$826.00	\$1,652.00
	pH Probe and Cable	2	each	\$220.00	\$440.00
	Temperature Sensor and Cable	2	each	\$200.00	\$400.00
	Accessories (cables, calibration solution)	1	lump sum	\$150.00	\$150.00
	Installation Cost (assumes 25% of equipment cost)	1	lump sum	\$1,240.50	\$1,240.50
	Subtotal				\$15,945.00
4	Communications				
	Motorola 9505 Satellite Phone	1	lump sum	\$1,495.00	\$1,495.00
	Subtotal				\$1,495.00
	Total Fixed Costs				\$864,119.00
IV	System Start up and Acclimation (one time event)				
	System Start-up Labor (2 Field Technicians for 2 weeks)	160	hour	\$56.19	\$8,990.40
	Acclimation Period Labor (1 Field Technician for 2.5 months)	240	hour	\$56.19	\$13,485.60
	Subtotal				\$22,476.00
V	Consumables and Rentals (Yearly)				
	Ethanol	2,630	gallon	\$2.50	\$6,575.00
	Sodium Hydroxide	2,651	gallon	\$0.85	\$2,235.35
	Personal Protective Equipment (4 days/month)	12	month	\$28.00	\$336.00
	Hydrogen Sulfide Gas Meter (4 days/month)	12	month	\$300.00	\$3,600.00
	Water Quality Meter and Supplies (4 days/month)	12	month	\$700.00	\$8,400.00
	Storage Connex	12	month	\$325.00	\$3,900.00
	Subtotal				\$25,046.35
VI	Labor (Yearly)				
	Field Technicians (1 day per week)	416	hour	\$56.19	\$23,375.04
	Administrative Support (5% of field effort)	20	hour	\$61.16	\$1,223.20
	Project Management (10% of field effort)	40	hour	\$90.00	\$3,600.00
	Subtotal				\$28,198.24
VII	Utilities (Yearly)				
	Backup Generator (3 Kilowatt; assume required for 4 months)	4	month	\$800.00	\$3,200.00
	Backup Generator Fuel (105 gallon/month at \$2.50/gallon)	4	months	\$262.50	\$1,048.00
	SCADA Communication Service	12	month	\$75.00	\$900.00
	Satellite Phone Communications Service	12	month	\$50.00	\$600.00
	Portable Toilet	8	month	\$325.00	\$2,600.00
	Subtotal				\$8,348.00

Table C-2. Cost Element Details for the Compost-Free Bioreactor Treatment System - Recirculation Operation (continued)

VIII	Residual Waste Handling and Disposal (Yearly)				
	Off-Site Hazardous Sludge Disposal (80% moisture)	23	ton	\$263.00	\$6,049.00
	Sludge Pumping and Bag Filtration	1	lump sum	\$3,795.00	\$3,795.00
	Subtotal				\$9,844.00
IX	Analytical Services (Yearly)				
	Dissolved Metals (Effluent Discharge)	52	each	\$80.00	\$4,160.00
	Total and Leachable Metals (Waste Characterization)	1	each	\$280.00	\$280.00
	Subtotal				\$4,440.00
X	Maintenance and Modifications (as indicated)				
	Replace Recirculation Pump (every 5 years)	1	each	\$5,000.00	\$5,000.00
	Replace Storage Batteries (every 5 years)	1	each	\$5,200.00	\$5,200.00
	Replace Water Turbine (every 20 years)	1	each	\$9,000.00	\$9,000.00
	Replace Reagent Pumps (every 2 years)	2	each	\$1,000.00	\$2,000.00
	Subtotal				\$21,200.00
	Total 1st Year Variable Costs				\$98,352.59
	Recurring Variable Costs				\$75,876.59
	Periodic Costs				\$21,200.00

Description	Total
Total 1st Year Costs	\$962,471.59
Total 1st Year Costs/1000 gallons	\$193.81
Total Variable Costs/1000 gallons	\$15.28
Cumulative 5-Year Total Variable Costs (Present Worth at 7% Rate of Return)	\$321,654.00
Cumulative 15-Year Total Variable Costs (Present Worth at 7% Rate of Return)	\$715,681.00
Cumulative 30-Year Total Variable Costs(Present Worth at 7% Rate of Return)	\$977,880.00

% - Percent
 HDPE – High Density Polyethylene
 KW - Kilowatt
 MHz – Megahertz
 SCADA - Supervisory Control and Data Acquisition