THE CONSTRUCTION AND INSTRUMENTATION OF A PILOT TREATMENT SYSTEM AT THE STANDARD MINE SUPERFUND SITE, CRESTED BUTTE, CO[1]

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Abstract: A pilot biochemical reactor (BCR) was designed and constructed to treat mine-influenced water emanating from an adit at a remote site in southern Colorado which receives an average of 400 inches (10.2 m) of snowfall each season. The objective of the study is to operate and monitor a BCR on a year-round basis in a harsh mountain environment. There are several unique attributes of the treatment and monitoring system. It has been constructed at an elevation of 11,000 ft a.m.s.l. (3353 m), and is designed to operate year-round. Since the site has limited winter accessibility due to snowfall, a remote monitoring system was designed to collect samples and field parameters throughout winter months. An automated sampling system powered by solar cells is used to sample the system influent and effluent on a weekly basis and an elaborate Teledyne ISCO™ (ISCO) satellite monitoring system tracks data on an hourly basis with data being uploaded to a web site. Winter water samples will be gathered from the autosamplers in the spring and analyzed for metals. Fall influent and effluent water quality results from the treatment system are reviewed. These include field parameters reported via satellite and metal concentrations from water quality samples. Since there are limited data on biochemical and sulfate-reducing reactors operating in elevated and harsh winter locations, the acquired data are unique for mine-influenced water remediation.

Additional Key Words: ARD, MIW, biochemical reactor, BCR, sulfate reducing bioreactor, SRB, satellite data transmission, heavy metals remediation, passive treatment, Green Remediation

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Introduction

In 2007, the Engineering Technical Support Center (ETSC), Office of Research and Development (ORD) of the U.S. EPA and Golder Associates, Inc. with assistance from others designed and constructed a pilot scale treatment system to treat mine influenced water (MIW) from an adit draining the Standard Mine near Crested Butte, Colorado. Mining activity began at Standard Mine around 1874. However, the most significant operations began in 1931 with the mining of Pb, Zn, Ag, and Au. Operations ceased in 1966 and the mine was abandoned. Wastes at Standard Mine continue to impact surface water in the area. The adit chosen for the pilot project drains into Elk Creek, which is devoid of all aquatic life and feeds directly into Coal Creek. Crested Butte's drinking water supply is taken from Coal Creek four miles downstream from the former mine. The project presented several challenges since the mine adit was at an elevation of 11,000 ft a.m.s.l.(3353 m), had no available electric power, and limited access for 6 or more months during the winter season due to snowfall annual averages ranging from 400-700 inches (10.2 – 17.8 m). The EPA Region 8 project manager wanted a passive system that would operate year-round and reduce the concentrations of the site constituents of concern: Cd, Cu, Fe, Pb, Mn, and Zn. The adit concentrations of these metals exceed the applicable water quality standards.

During discussions by the design team, several objectives were developed. The system would operate 12 months of the year so it had to be insulated from the cold, harsh weather that would include many days considerably below freezing. In order to monitor the treatment process, an automated system with satellite reporting of influent and effluent measurements had to be included in the design. In addition, some method of capturing water samples for metals analyses throughout the year would be necessary as none of the researchers were in close proximity to the site, and access in the winter was difficult. Also, because of Mn and biological contaminants hypothesized to exit this BCR, some additional treatment had to be accomplished prior to discharge to Elk Creek.

Pilot System Overview

The main design elements of the system include the infiltration gallery, surge tank, BCR cell, sampling shed, aerobic polishing cell (APC), and Mn removal bed (MRB). The APC and MRB were not completed during the 2007 summer construction season and will be completed in 2008.

As a result, there are no data in this paper to document the performance of these treatment units. A description of each design element is given below. A schematic of the pilot system is shown as Fig. 1.

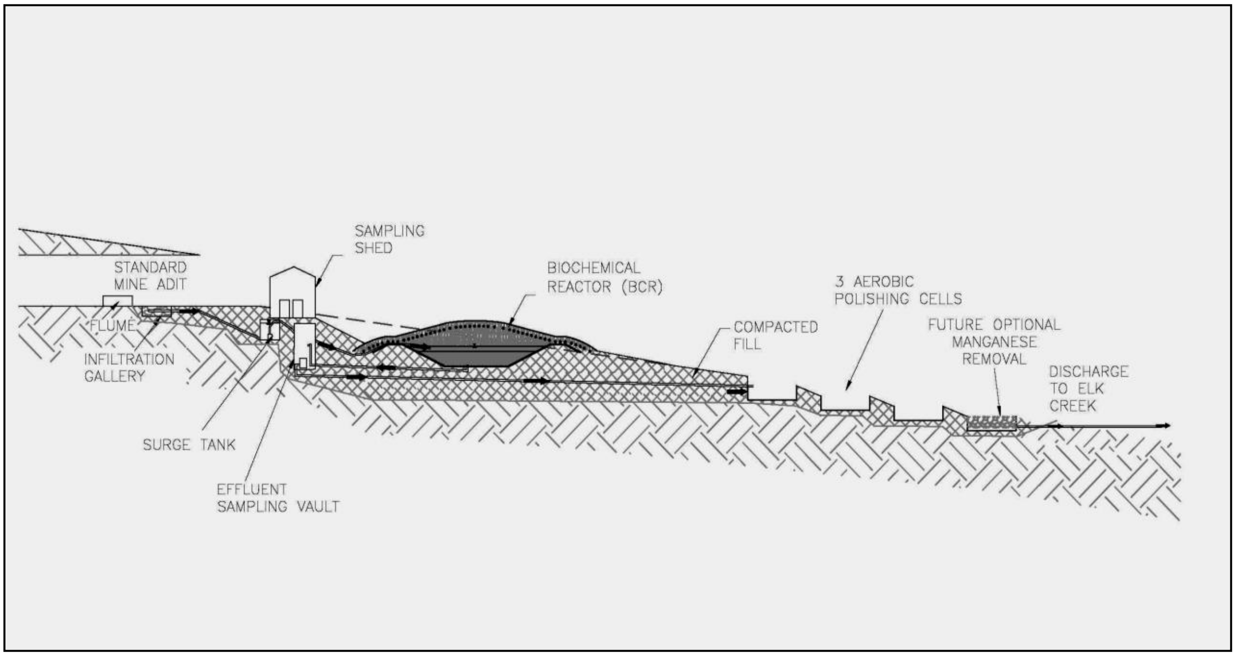

Figure 1 – Pilot System Schematic

Infiltration gallery

The purpose of the infiltration gallery is to capture flow from the adit and route the flow to the surge tank via parallel 2” HDPE pipes. The design goals include capture of a minimum of 4 gallons per minute (gpm) (15 liters per minute (Lpm)), prevention of freezing, and minimization of pipe sedimentation. The infiltration gallery is approximately 2 ft (0.6 m) long by 4 ft (1.2 m) wide by 2 ft (0.6 m) deep. The two intake pipes are perforated and buried towards the bottom of the gallery. The gallery is filled with pea gravel to reduce the freezing possibility, and partially filter sediment before it reaches the pipes.

Surge Tank

The surge tank provides a reservoir of influent water. The design flow rate for the BCR is 1 gpm (3.8 Lpm). Given the elevation of adit discharge and the shallow bedrock at the site, a gravity flow system to feed the BCR was not feasible. Therefore, a surge tank was included to provide a reservoir of influent water to pump from. The pump operates on a timer and pumps approximately 4 gpm (~15 Lpm). To achieve a one gpm (3.8 Lpm) flow rate over the course of a day (1440 gal or 5451 L) the pump operates at 4 gpm (~15 Lpm) for six hours per day. The surge tank has a spillway, which drains back to Elk Creek, in order to maintain a constant water level in the tank.

Figure 2 - Surge Tank Installation

BCR Cell

The downward-flow vertical reactor was built with a bottom footprint of 170 sq. ft (15.8 m^2) distinct zones: the bottom zone was a 6 in (15 cm)-thick limestone drainage layer, the middle zone was a 3 ft (91 cm)-thick organic substrate layer, and the top zone consisted of 6" (15 cm) of standing water. The cell was sized using an area-loading acidity rate and a volumetric molar metals loading rate. The detention time in the cell is approximately 31 hours. The BCR was filled with a substrate that included wood chips, dairy manure from a local farm, hay, and limestone fines, which was very similar to the pilot built at the Luttrell Repository near Helena, MT (Gusek et al. 2006). In addition, a bacterial inoculum was used from another EPA/Golder treatability study at the Elizabeth Mine site in Vermont. These bacteria were contained in a 55 gallon (208 L) non-metallic drum that treated two different MIWs at the Elizabeth Mine. At the completion of the Vermont study, the drum was drained and shipped to the Golder laboratory facilities in Lakewood, Colorado (Golder Lab). A new batch of substrate containing the same ingredients as the pilot BCR was mixed and placed in a 55-gal (208 L) non-metallic drum at the Golder Lab. This fresh batch of substrate was inoculated with Elizabeth Mine substrate. The new drums were filled with mine water from the Standard Mine, covered and incubated at the Golder Lab to allow the bacteria to adapt to the new MIW.

<u>BCR Cell Startup</u>

Upon completion of the BCR cell construction, it was filled with site water on 8/9/07 and allowed to incubate for two weeks. On 8/22/07, we began recirculating effluent water back into the BCR water at a rate of 1 gpm (3.8 Lpm). On 9/19/07, after two weeks of incubation, and four weeks of recirculation, the cell began treating 1 gpm (3.8 Lpm) of adit water.

Figure 3 - Addition of Bacterial Inoculum to Partially Filled BCR Cell

Figure 4 – Completed BCR Cell being filled with Incubation Water

APC and MRB Treatment Units

The APC and MRB units will be completed in 2008. The APC will consist of three treatment cells. One cell will be vegetated with native wetland species and the other two cells will be un-vegetated. The intent of the APC will be to decrease the biochemical oxygen demand (BOD), total suspended solids, nitrate, and coliform bacteria that are typically generated in a BCR. The APC influent and APC effluent concentrations of these parameters will be measured in 2008. In addition, the APC will be designed to increase the alkalinity and pH and provide a longer residence time prior to discharge.

The Mn removal bed (MRB) will be the third treatment unit and will be built at the end of the APC. The MRB will consist of a horizontal flow limestone reactor that relies on bacteria-mediated Mn removal at the site In the original design the MRB was going to be a separate unit, but because of the on-going tailings removal, there was a space limitation. Future planning includes additional wetlands between the discharge of the MRB and Elk Creek, thus allowing for additional residence time for Mn, BOD removal and any remaining bacteria from the BCR.

Pulles et al. (2001) showed that downstream from a BCR, additional sulfate-reduction will eventually occur from bacteria leaving the BCR in the effluent and colonizing other areas.

Automated Sampling Equipment and Satellite Communication

A sampling shed was constructed adjacent to the BCR to house electrical panels, ISCO™ samplers, and satellite communication equipment. The sampling shed (Tuff Shed™) was situated above both the surge tank and the BCR effluent line in order to provide sampling access to the influent and effluent water. The sampling shed was insulated with fiberglass and equipped with a unique solar-powered heat system. A sunroof-type window was installed in the roof in case winter access was necessary.

One of the key research areas that EPA ORD wanted to develop was the collection of winter samples with an automated, solar-powered system housed in an insulated, heated structure. In addition, because of the previous limitation of cellular coverage in the Luttrell EPA pilot project for transmitting data, as well as the lack of a cellular signal at the site, the project team decided that the transmission from the sampling shed would be by satellite, with the collected data then residing on an internet site. With the data being transmitted to a server, the EPA project manager and Golder project team would observe changes to certain parameters, and could determine if the equipment was operating properly, as well as assess the on-going BCR activity.

To accomplish this goal, the team installed two Hach Hydrolab MS5™ sondes to measure the pH, temperature, and ORP of the influent and the effluent. These field parameters were recorded every 15 minutes and transmitted by satellite to ISCO's Sampler Station Access™ webpage. The webpage allows influent and effluent field parameters to be viewed and downloaded, recorded when the samplers take a sample, and allowed the samplers to be enabled and disabled. In addition to field parameters monitoring equipment, the site was equipped with two ISCO samplers to allow collection of water quality samples and an ISCO 730 Bubbler Module™ (http://www.isco.com) to measure the influent flow rate. Beginning in mid-October 2007, the samplers were collecting influent and effluent samples once a week. Other sampling parameters were considered for the sonde measurements, but there were limitations. First, by design, the sonde is limited to collecting and transferring a maximum of 5 parameters each. Second, certain parameters could not be considered because of the inability to maintain proper calibration during the long winter sampling period. EPA ORD has begun another project looking at a method to do this type of calibration remotely.

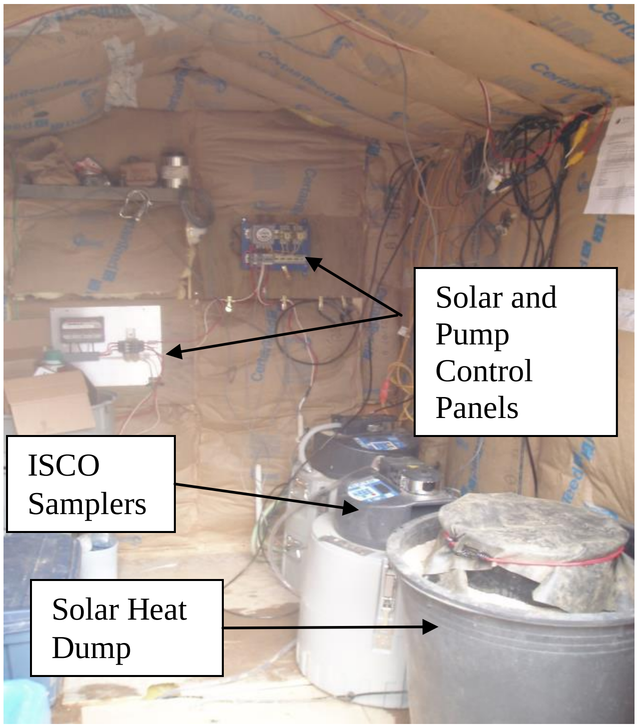

Figure 5 – Sampling Shed Interior

Figure 6 – Sample Shed and Solar Array

Methods

Ten sets of influent mine water samples were collected between 9/6/07 and 11/28/07 and twelve sets of effluent samples were collected between 9/6/07 and 12/12/07. The samples were analyzed in the EPA ORD Research Laboratory in Cincinnati, OH for metals (Al, Cd, Cu, Fe, Pb, Mn) (EPA Method 6010B), SO_4^{2-} (EPA Method 300 IC), pH, and alkalinity (EPA Method 310.1). Separate samples were submitted to ACZ Laboratories Inc. in Steamboat Springs, CO for sulfide analysis (EPA Method 376.2).

From the beginning of cell incubation (8/9/07) until to 10/4/07, sampling personnel took influent and effluent field measurements of pH, temperature, and oxidation-reduction potential (ORP) on a weekly basis. The sondes were deployed in early October and began recording the same parameters on 15 minute intervals. In addition, the influent sonde measured and transmitted flow data from the influent flume.

Results

Field Parameter Results

Temperature, pH, and ORP graphs are shown as Fig. 7 through 9. This period includes three different operating conditions: incubation (8/9/07-8/21/07), recirculation (8/22/07-9/19/07), and treatment (9/20/07-1/14/08). The different periods are distinguished on the graphs. Field parameter data for all three conditions are included in order to provide a complete picture of cell behavior from incubation through treatment.

The graphs include data collected manually (8/09/07 through 10/04/07) and data collected by the sondes (10/15/07 through 1/14/08). The bold, thick lines on the graphs represented data collected by the sondes and represented more continuous sampling. The lack of connected data lines were gaps due to equipment malfunction.

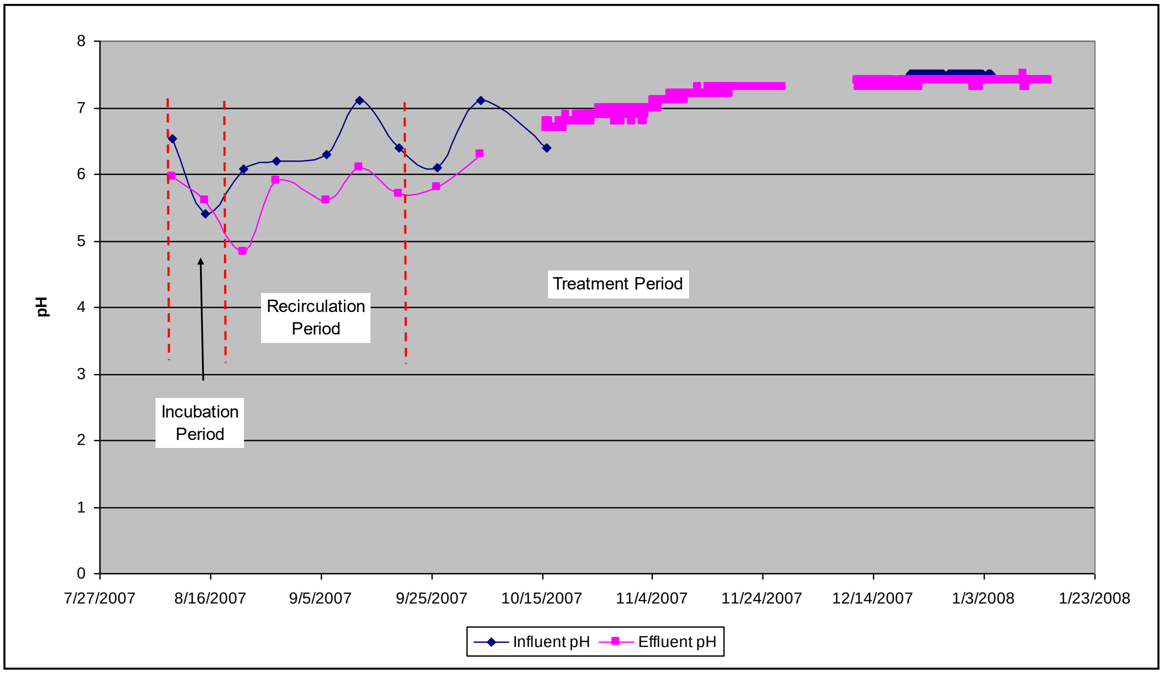

Figure 7 – Influent and Effluent Ph

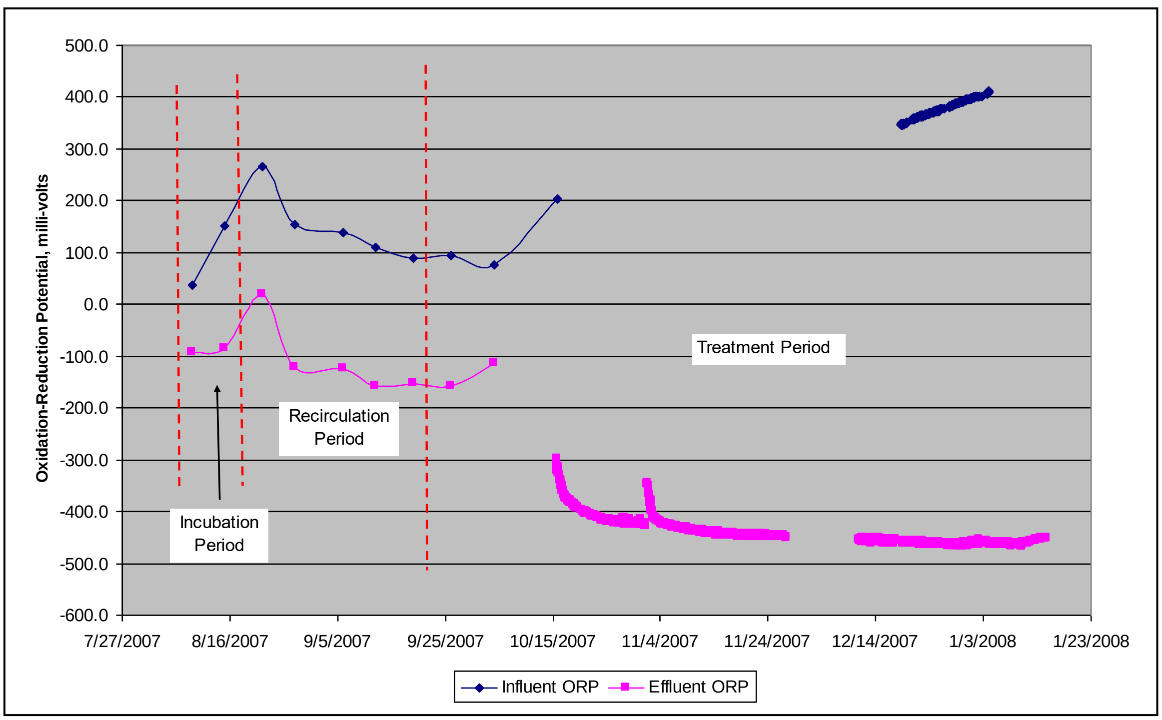

Figure 8 – Influent and Effluent ORP

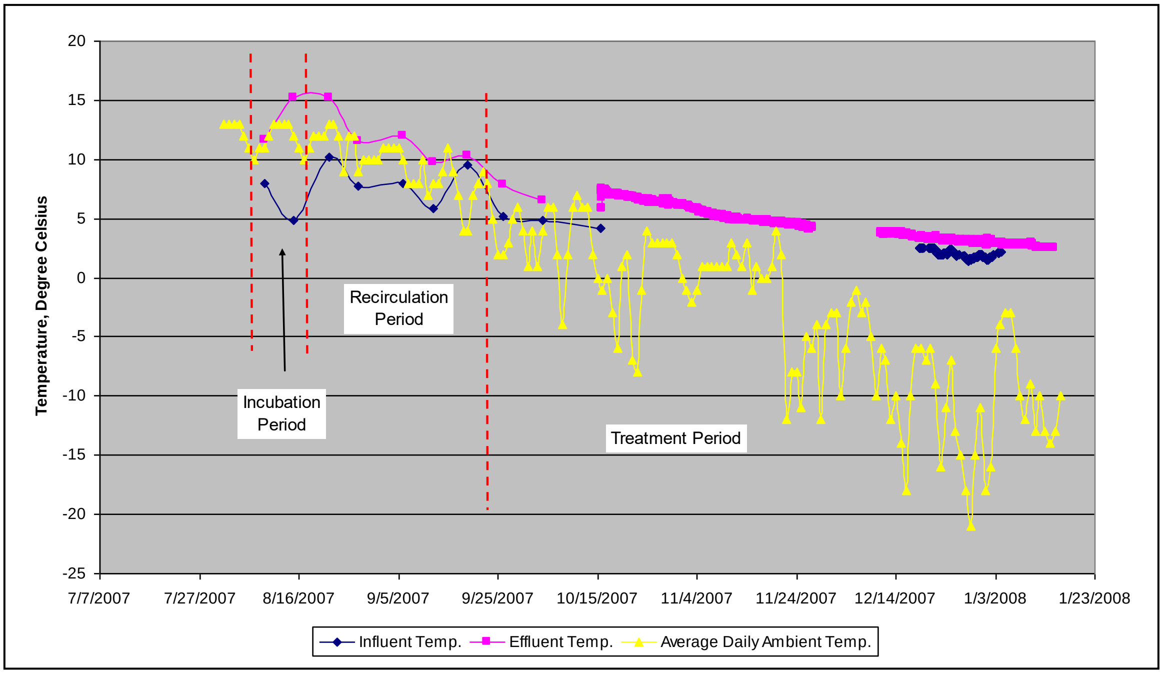

Figure 9 – Influent and Effluent Temperature

Summary statistics for the treatment period are provided in Table 1. The summary statistics are limited to treatment period data to provide the best indication of expected effluent field parameters for the lifetime of the BCR.

Table 1- Summary Statistics of Influent and Effluent Field Parameters for the Treatment Period (9/19/07-01/14/08)

Location Parameter	INFLUENT pH	EFFLUENT pH	INFLUENT ORP	EFFLUENT ORP	INFLUENT Temperature	EFFLUENT Temperature
Average	-	7.2	378.6	-439.3	2.0	4.4
Minimum	6.1	5.8	76.0	-468.0	1.4	2.5
Maxiimum	7.5	7.5	411.0	-114.0	5.2	7.9

Metals Removal Results

For the treatment period, the percent removal values for Cd, Cu, Pb, and Zn are > 95%. Summary statistics for the parameters of concern (Cd, Cu, Fe, Pb, Mn, Zn) for the treatment period as well as the applicable water quality standards are provided in Table 2. All concentrations are total metals.

Graphs of Cu and Zn removal are provided as Figs. 10 and 11. Similar to the presentation of field parameter data, the graphs include data collected during incubation and recirculation in addition to the treatment period. Effluent concentrations of Fe and Mn are greater than influent concentrations. On average, effluent Mn concentrations are 13% greater than influent concentrations and effluent iron concentrations are 206% greater than influent Fe concentrations.

Table 2 – Summary Statistics of Influent and Effluent Total Metals Concentrations for the Treatment Period (9/19/07-12/12/07)

Parameter	Detection Limit	2007 Segment 11 Chronic Stream Standard*	Influent Average	Influent Minimum	Influent Maximum	Effluent Average	Effluent Minimum	Effluent Maximum	Percent Removal[1]
Cadmium, Total (mg/L)	0.0024	0.0004	**0.132**	**0.120**	**0.138**	**0.003**	**0.001**	**0.013**	**98%**
Copper, Total (mg/L)	0.0036	0.009	**0.479**	**0.124**	**0.853**	**0.010**	0.001	**0.039**	**98%**
Iron, Total (mg/L)	0.021	1	**5.416**	0.165	**12.919**	**5.343**	0.359	**15.259**	**1%**
Lead, Total (mg/L)	0.008	0.0025	**2.101**	**0.225**	**4.136**	**0.031**	**0.004**	**0.102**	**99%**
Manganese, Total (mg/L)	0.0066	1.65	**11.275**	**9.871**	**11.881**	**9.962**	**8.109**	**12.652**	**12%**
Zinc, Total (mg/L)	0.0067	0.124	**25.945**	**22.637**	**27.233**	**1.043**	**0.422**	**2.127**	**96%**

* = Hardness = 100 mg/L

[1] - The percent removal was calculated with the average influent and the average effluent concentrations.

Values in with **BOLD** exceed the Chronic Stream Standard only.

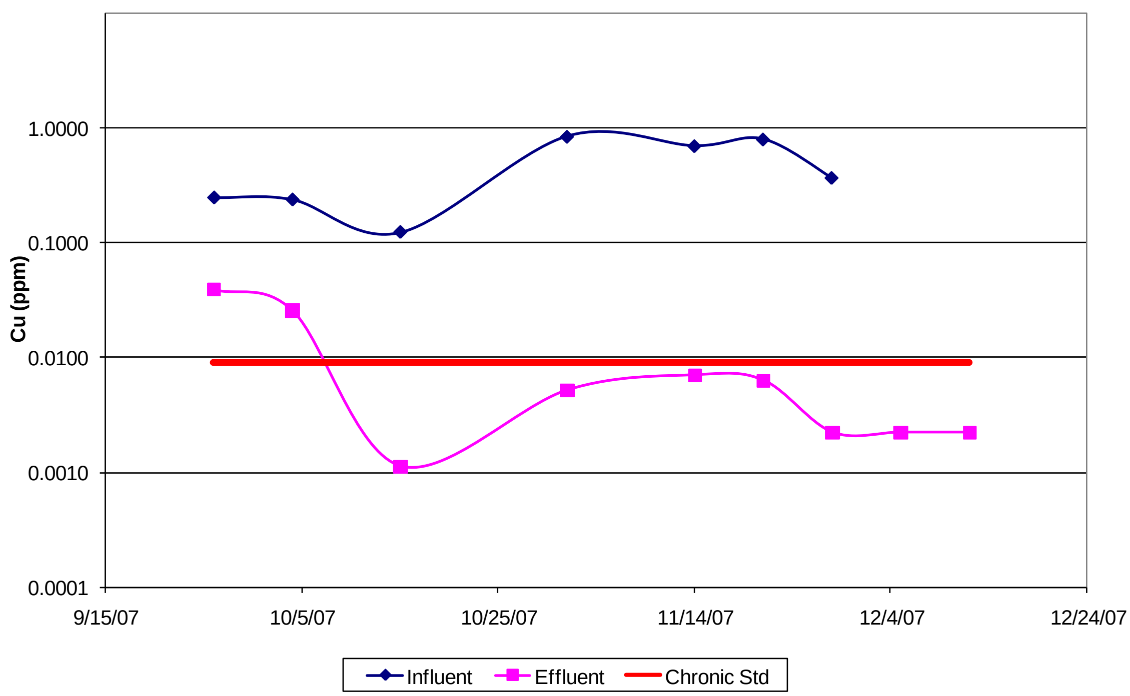

Figure 10 - Copper Removal

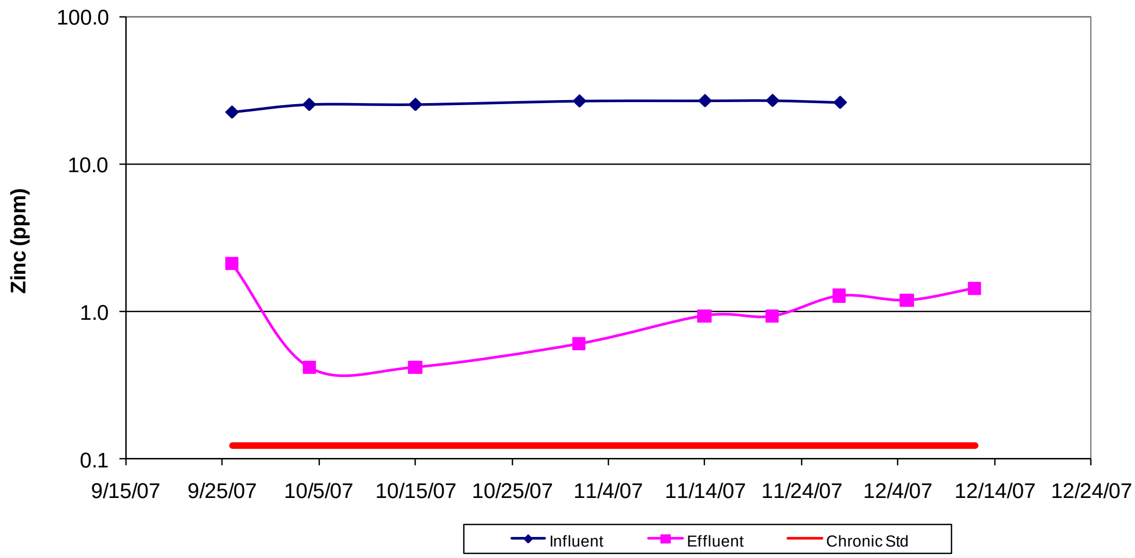

Figure 11 - Zinc Removal

A significant decrease in SO_4^{2-} was observed between the influent and effluent samples. Correspondingly, effluent samples consistently contained low levels of sulfide. Influent and effluent SO_4^{2-} and sulfide concentrations are provided in Table 3.

Table 3 – Influent and Effluent Sulfate and Sulfide Data

	Sulfate (mg/L)		Sulfide (mg/L)	
Sample Date	Influent	Effluent	Influent	Effluent
8/22/2007	NS	NS	BDL	1.470
8/28/2007	NS	NS	BDL	0.900
09/06/07	244.6	54.6	BDL	1.650
09/12/07	241.0	53.1	BDL	3.100
09/19/07	212.2	27.1	NS	NS
09/26/07	244.8	33.1	BDL	2.550
10/04/07	338.9	56.7	NS	NS
10/15/07	374.3	8.7	NS	NS
11/01/07	348.5	144.0	NS	NS

NS - not sampled.
BDL - Below the detection limit.
The sulfide MDL is 0.02 mg/L.

Discussion

The high level (> 95 %) of metals removal for Cd, Cu, Pb, and Zn is similar to the level of removal measured in other BCR cells (Gusek et al., 2008). In the initial phases of a BCR, several removal mechanisms occur. We believe that the first phase is mainly due to adsorption to surfaces within the substrates, followed by precipitation due to limestone alkalinity, and the beginning of bacteria-mediated SO_4^{2-} reduction, and subsequent metal sulfide precipitation. The consistent presence of sulfide in the BCR effluent is a direct indication that SO_4^{2-} reduction is occurring. The combination of metals removal and sulfide generation provide a strong indication that bacteria-mediated metal sulfide precipitation is occurring in the BCR.

The increase in Fe and Mn concentrations indicates that either the substrate or the limestone contained within the BCR is a source of these metals. From previous studies and chemistry principles, Mn does not precipitate as a metal sulfide in anaerobic cells at the effluent pH, and is therefore not removed well in BCR cells. When the system is completed, Mn removal will likely occur in the MRB. Similar to Mn, Fe removal will occur in the APC cells. Past experience has shown that metal sources of Fe and Mn within the BCR typically become depleted within months (Gusek, 2005). We expect BCR effluent Fe concentrations to decrease, and residual concentrations to be removed aerobically downstream from the BCR in the APC cells.

The cold climate at the site has not negatively affected the performance of the BCR cell. Given the short summer season at the site, it appears the startup method, which included bacterial inoculum from a prior BCR and a six week incubation/recirculation period, created favorable conditions for the bacteria-mediated treatment process. The first direct indication of sulfate reduction was observed on 8/22/07, two weeks after BCR incubation began, when sulfide was detected in the BCR effluent along with a decrease in metals concentration. As this was the first effluent water sampling event, it is possible that BCR sulfate reduction began immediately after adding the adapted bacteria to their new residence outside the incubation drum. Indirect indicators of SO_4^{2-} reduction included a negative ORP and removal of trace metals and SO_4^{2-} within days of incubation in the BCR. The authors believe that incubation and conditioning of the bacteria prior to subjecting the consortium to continuous loading of metal-laden influent water is a key to successful start-up, even in colder temperatures. Low temperatures have been shown to affect the SRBs' ability to acclimate, but once acclimated, SRB will still operate at lower temperatures (Tsukamoto et al., 2004). Since SRB have slow growth at lower temperatures, and this BCR was started just as the nights began to get colder, the laboratory acclimation regimen appears to help start the reactor and the SRB activity. In comparison, the Standard Mine BCR has increased metals removal compared to the Luttrell BCR, which had an even longer adaptation period, but the bacteria in the Luttrell BCR had never been subjected to MIW prior to construction. Since there are other factors, only further research can determine if creating new BCRs from inoculum taken from existing BCRs is advantageous to faster start-up and initial increases in metals removal.

The unique design of the system (infiltration gallery, surge tank, BCR, sampling shed) allowed the system to continue functioning through extremely cold ambient temperatures experienced in November and December 2007. The average minimum ambient temperature measured at the surrogate site (Schofield Pass NRCS weather station) was -15 ° Celsius (C) and the lowest minimum temperature was -28 ° C (12/28/07). Key design features that protected the system from sub-zero temperatures included:

- The BCR was operating successfully in this harsh environment largely because it was insulated with 140 cu yd (107 m^3) of wood chips mounded directly on top of the BCR. The wood chips were covered with a geomembrane liner. This design appeared to prevent BCR freezing, and allowed the continuation of treatment processes during the cold months; effluent temperatures remained consistently higher than influent temperatures. At the Luttrell BCR, residing in a similar climate, the BCR was equipped with temperature sensors buried at different depths within the substrate. The BCR appears to freeze down to about 2.5 ft (0.76 m), and the bottom temperatures of the Luttrell BCR on the same dates were approximately 3° C colder.

- The sampling shed allowed influent and effluent field parameter monitoring by the sondes and sampling by the ISCO samplers. The shed received heat from the unique solar-powered heat dump. Based on a reading of the maximum/minimum thermometer located within the shed on 12/18/07, the minimum temperature in the shed since the prior site visit (11/1/07) was about 20° F.

The automated sampling system (Hydrolab sondes, ISCO 730 Module Bubbler, ISCO samplers, ISCO satellite transmission, ISCO Sampler Station Access webpage) experienced some difficulties. A list of positive and negative attributes included:

- A Hach Hydrolab sonde ceased to function in the influent surge tank and needed to be replaced in October. Afterwards, the transmission of field parameters by satellite was relatively consistent from 10/15/07 through 1/04/08 for both effluent and influent devices. On 01/04/08, transmission of influent sonde data again ceased. At the time this paper was submitted (1/16/07), the influent sonde was still not transmitting. The effluent sonde was still operational.
- The transmission of flow data measured by the ISCO Bubbler Module has been successful. The ISCO webpage allows the user to enable and disable the ISCO sampler program. These functions have not worked properly throughout the project. ISCO personnel have worked with the team to determine the reasons for failure..
- The ISCO equipment sampled the influent and effluent waters successfully as programmed.
- The project team has spent significant effort troubleshooting the automated sampling system with ISCO technical personnel. This level of effort was not anticipated at the outset of the project, and has caused significant additional expenditures.
- In another project where different equipment was used for autonomous data collection, there were problems with the data transmissions through cellular lines in the initial year. The use of the ISCO satellite system for a remote area worked very well.

Conclusions

The Standard Mine pilot system is designed to operate year-round in a cold-weather alpine setting that receives significant snowfall. The BCR system is equipped with automated sampling equipment to allow remote monitoring of the treatment system. To date, the BCR system has operated as designed and achieved the treatment goals despite extremely cold temperatures. Furthermore, this is a passive treatment system that operates with solar power only and without chemical addition. The remote monitoring and sampling equipment has had limited success, and needs refinement before it is used at other remote sites. In addition, while we consider this remote data collection system a step forward, the capabilities of the system are still limited and cannot measure sulfide generation or metals concentrations in real-time.

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