ADVANCES IN DEVELOPMENT OF BIOREACTORS APPLICATIONS FOR THE TREATMENT OF ACID MINE WATERS[1]

Diana Bless[2], Marek Zaluski, Suzzann Nordwick, Brian Park, and Helen Joyce

Abstract. Demonstrations and technology development conducted under the Mine Waste Technology Program (MWTP) have lead to significant improvements of sulfate-reducing bacteria (SRB) bioreactors used to treat acid rock drainage (ARD). Benefits of this technology include the reduction of dissolved metal ions to insoluble metal sulfides and the neutralization of the acid rock drainage resulting from the production of bicarbonate from the oxidation of organic nutrients by the sulfate-reducing bacteria. Over the past 15 years, MSE has conducted many bench-scale and design tests along with several pilot-scale field demonstrations. This paper addresses engineering design criteria including the selection of organic media, maintenance of system permeability, and strategies for mitigation of ARD at remote sites with relatively small discharge.

Specific applications and results from field SRB bioreactors and associated research are presented. They include: (1) An in situ bioreactor in flooded subsurface mine workings where the bioreactor was operated from 1993 to 2005. (2) A set of field bioreactors that allowed various operational attributes to be evaluated including pretreatment and operational temperature. This demonstration was conducted over a three-year period. (3) A set of both anaerobic and aerobic field bioreactors that operated in staged fashion to show the comprehensiveness of bioreactor applications for acid rock drainage treatment. (4) A bench-test study that focused on the effectiveness of SRB to reduce dissolved sulfate and heavy metals. (5) A bench test and field verification of the advantages of horizontal flow configuration in SRB bioreactors. (6) A reactive cartridge, a component of a modular SRB bioreactor that can be easily transported to remote sites.

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Introduction

Demonstrations conducted under the Mine Waste Technology Program (MWTP) have lead to technical advances in the development of bioreactor application of sulfate-reducing bacteria (SRB) technology to treat acid rock drainage (ARD). Benefits of this technology include the reduction of dissolved metal ions to insoluble metal sulfides and the neutralization of the ARD resulting from the production of bicarbonate from the oxidation of organic nutrients by the SRB. Over the past 15 years, MSE has conducted many bench-scale and design tests along with several pilot-scale field demonstrations. Using examples from MWTP projects, this paper addresses engineering design criteria including the selection of organic media, maintenance of system permeability, and strategies for complete mitigation of acid drainage.

Specific field applications of SRB bioreactors and associated laboratory research are presented in this paper. They include: (1) An in situ bioreactor in flooded subsurface mine workings where the bioreactor was operated from 1993 to 2005. (2) A set of field bioreactors that allowed various operational attributes to be evaluated including pretreatment and operational temperature. This demonstration was conducted over a three-year period. (3) A set of both anaerobic and aerobic field bioreactors that operated in staged fashion to show the comprehensiveness of bioreactor applications for acid rock drainage treatment. (4) A bench-test study that focused on the effectiveness of SRB to reduce dissolved sulfate and heavy metals. (5) A bench test and field verification of the advantages of horizontal flow configuration in SRB bioreactors. 6) A reactive cartridge, a component of a modular SRB bioreactor that can be easily transported to remote sites.

Background

Acid rock drainage (ARD) results when metal sulfide minerals, particularly iron pyrite, come in contact with oxygen and water. The metal sulfide minerals are oxidized and then dissolved into the water. ARD emanates from many abandoned mines, which then results in environmental problems by contaminating surface waters and groundwater with dissolved metals, raising their acidity. Conventional treatment of ARD is often not feasible due to the remoteness of the site, the lack of power, and limited site accessibility. To immobilize metals and increase the pH at these sites, passive remedial technologies are needed.

Over the past decade, the MWTP, which is funded by the United States Environmental Protection Agency, has been demonstrating the use of SRB to treat ARD. As shown in Reaction 1, the SRB biological metabolism process uses organic carbon as an electron donor to reduce sulfate to sulfide in the form of hydrogen sulfide. Bicarbonate ions are also produced. As shown in Reaction 2, hydrogen sulfide reacts with most dissolved metal ions to precipitate stable metal sulfides. Besides lowering the concentrations of sulfate and dissolved metals, the SRB process also produces alkalinity in the form of bicarbonate. This acts to buffer and decrease the acidity of the ARD.

$$SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2HCO_3^- \qquad (1)$$

$$H_2S + M^{+2} \rightarrow MS + 2H^+, \text{ where } M = \text{metal} \qquad (2)$$

Biological sulfate reduction, with the subsequent precipitation of metal sulfides, is not the only metal removal mechanism associated with an organic-based system. Other possible treatment processes include ion exchange of metals by an organic-rich substrate, precipitation of metal hydroxides, and the sequential adsorption of metals by precipitated ferric hydroxide. The adsorption of metals by the organic substrate takes place as metal ions are bonded onto organic matter in the substrate. Along with SRB activities, this mechanism plays an initial metal removal role. However, in most cases, the ion exchange of metals only works as a temporary retention of metals, as the mechanisms are pH-dependent and different metals have different adsorption affinities. Over time, more poorly adsorbed metals such as manganese may be released back into solution in exchange for better adsorbed metals. Additionally, adsorption of metals by organic materials is a process limited by and dependent on the amount of organic material present.

Several MWTP SRB-based research demonstration projects involved constructing, operating, and designing bioreactors for ARD treatment. The following six sections contain summaries of individual MWTP projects.

SRB Subsurface Bioreactor

From 1994 to 2005, the MWTP demonstrated an innovative, in situ biological technology to treat and control ARD emanating from the abandoned and remote Lilly/Orphan Boy Mine near Helena, Montana. Cables suspend platforms about 9 meters below the static water level in the mineshaft. Organic matter, a mix of cow manure and straw, was placed on the platforms directly in the shaft, forcing the ARD (upwelling in the shaft) to pass through the organic matter. A cross-sectional view of the underground configuration is shown in Fig. 1. The biological reaction takes place in the substrate regions, and the treated water subsequently flows out of the mine through the portal. Because the technology causes the shaft water pH to rise and the E_H to fall, the amount of acid leaving the mine is decreased. The bioreactor was activated in August 1994 and analytical data taken since has shown a significant and continuous reduction in metals concentrations. Also, the discharge pH has been effectively lowered from a historic level of near 3 to a more neutral pH of near 6.

The main purpose of conducting this field demonstration is to evaluate the use of SRB to mitigate metal-contaminated ARD in situ. The performance of the SRB system was monitored through the collection and analysis of samples at multiple locations within the mine tunnel. Principally, dissolved metals concentrations were collected from the mine tunnel using monitoring wells and at the portal. Data collection also included total metals, alkalinity, temperature, dissolved oxygen, pH, E_H, sulfate, sulfide, biochemical oxygen demand, chemical oxygen demand, and volatile fatty acids. Nearly all of the analytical parameters showed positive trends toward the treatment of ARD. However, more desirable results were observed in the tunnel than at the portal. An in-depth discussion of the project has been the subject of previous publications (Canty, 1999; Canty, 2000; and Nordwick et al., 2003).

The chemical parameters typical to untreated Lilly/Orphan Boy Mine water are shown in Table 1 along with laboratory-obtained typical dissolved metals and post treatment water chemistries for the tunnel water and mine portal effluent.

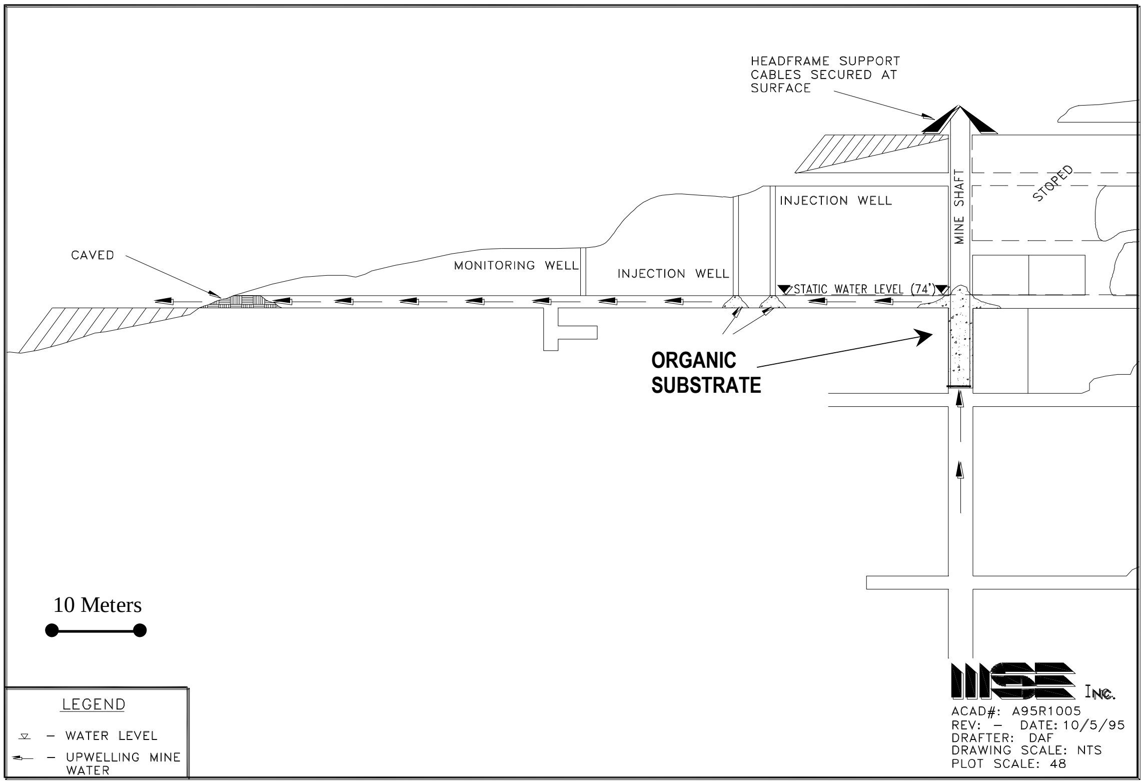

Figure 1. Cross-section of underground mine subsurface SRB bioreactor.

Table 1. Typical Lilly/Orphan Boy ARD and SRB treated water chemistries.

	Iron (mg/L)	Zinc (mg/L)	Aluminum (mg/L)	Manganese (mg/L)	Arsenic (mg/L)	Cadmium (mg/L)	Copper (mg/L)	Sulfate (mg/L)	pH
ARD	27.7	26.1	9.69	6.21	1.07	0.33	0.32	277	3.0
Tunnel	9.7	<0.01	<0.02	1.51	0.04	<0.005	<0.002	21.0	6.6
Portal	28.4	12.5	0.51	5.44	3.66	0.064	0.041	223	5.2

The data shows that the portal effluent removal efficiencies are greatly affected by spring runoff and that the overall metal removal is extremely high for aluminum, cadmium, copper, and zinc, but lower for arsenic and iron. The data also indicates that higher metal removals were obtained within the tunnel than at the portal. This phenomenon is attributed to the treated water being recontaminated with historic metal precipitates in the tunnel and by additional ARD infiltration from fractures within the tunnel as it travels through the section of tunnel beyond the organic substrate to the portal.

The pH of the mine water increased almost immediately after the implementation of the technology. This initial increase in pH was attributed to the buffering capacity of the organic substrate. During spring runoffs, the pH and water quality are lower in the portal than in the tunnel where the pH stays near neutral. This could be due to oxygenated surface water runoff penetrating through the ground above the portal, flowing into the tunnel, and then solubilizing historic metal precipitates and becoming contaminated as it passed through the tunnel. Also, the spring water quality may decrease at the portal due to a greater amount of ARD infiltration from fractures within the tunnel walls and a greater amount of recontamination resulting from water flow over the historic metal precipitates within the tunnel.

On-Site SRB Bioreactor

The primary objective of this project was to assess various configurations of bioreactors and monitor their ability to produce a high-quality effluent. This project was preformed to demonstrate that passive SRB technology could be used for remediation of thousands of abandoned mine sites that emanate ARD. A total of three SRB bioreactors were configured for horizontal flow and designed to evaluate the SRB technology applied in different conditions, and were constructed at the Calliope Mine site in the vicinity of Butte, Montana. Two underground bioreactors were built. One of these had a limestone cobble pretreatment section that was added to evaluate its efficiency effect on SRB to induce an improved pH and oxidation-reduction potential. However, conclusions on the pretreatment section could not be made as weather changes caused a significant improvement of the ARD quality. The third bioreactor had a pretreatment section and was built aboveground to evaluate the effect of cold weather and freezing on the system. Results did demonstrate that winter freezing of a well-established SRB population has little or no effect on SRB activity during the rest of the year.

Each bioreactor was filled with a combination of organic matter, limestone, and cobbles placed in two or four chambers. A simplified bioreactor cross-section is shown in Fig. 2.

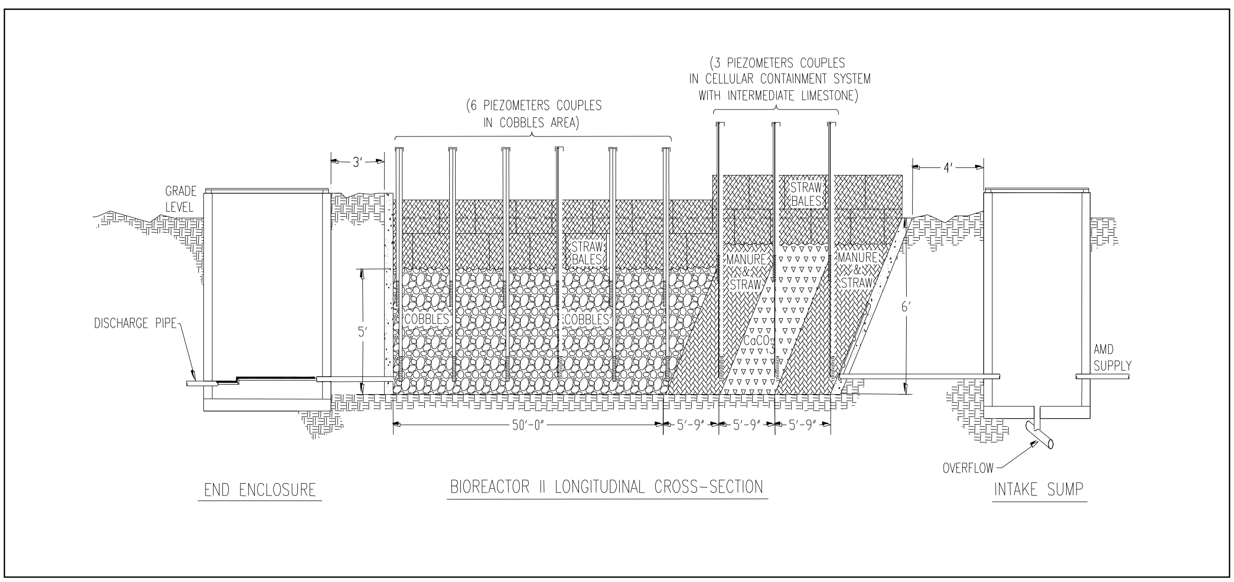

Figure 2. Cross-section of SRB bioreactor to treat ARD.

The belowground bioreactor with the pretreatment section was 21.8 meters (71.5 feet) in length and the other was 18.6 meters (61 feet). Both were constructed in 4.3-meter (14-foot) top-wide with 1.2-meter (4-foot) bottom-wide trapezoidal trenches. The aboveground bioreactor was 22.1 meters (72.5 feet) in length and constructed in a 3.7-meter (12-foot) wide metal half-culvert.

The chambers filled with organic matter or limestone were each 1.5 meters (5 feet) in length. The operation flow rate was 3.785 liters (1 gallon) per minute and corresponded to a calculated 5-½ day residence time for the ARD in the bioreactors with the pretreatment section and a 4-½ day residence time for the other bioreactor.

The organic matter was provided as an 80% to 20% by volume mixture of cow manure and cut straw. The cut straw was added to provide secondary porosity to the mix. TerraCell™ material, commonly used in landscaping for slope stabilization and made of high-density polyethylene, was used to form a cellular containment system (CCS) to house the organic matter (Zaluski et al., 2001, and Zaluski and Manchester, 2001). The CCS prevented the organic matter from settling to the bottom of the bioreactor, thus fostering the flow of ARD through the entire cross-sectional area without channeling. Each layer (lift) of TerraCell™ was positioned at 60 degrees off the horizontal plane so that the cells of each lift would be partially offset with respect to the cells of adjacent lifts. Each lift was 15.2 centimeters (6 inches) thick and contained 27.9-centimeter (11-inch) by 21.6-centimeter (8.5-inch) rhombohedral-shaped cells.

The bioreactors operated from December 1998 to July 2001. Previous publications have included a more in-depth discussion of the project details (Zaluski et al., 1999; Zaluski et al., 2000; Zaluski et al., 2001; and Zaluski et al., 2003). Bioreactor performance was monitored monthly by recording dissolved metals, pH, E_H, dissolved oxygen, and temperature measurements of both the influent and effluents. Analysis included SRB population, alkalinity, sulfate, sulfide, and dissolved metals concentrations.

Results showed that SRB performed best on zinc, cadmium, and copper. At the end of the project, the bioreactors were decommissioned and the site was restored to nearly original condition. Autopsy sampling included collection of solid matrix samples for chemical analyses to determine concentrations of total metals, sulfate, sulfide, nitrogen, phosphorous, and total organic carbon (TOC) in the chambers of organic matter and limestone. Bacteriological analyses were also conducted to determine SRB population in the organic substrate and in the limestone. Aqueous samples also were collected from the previously inaccessible bottom of the crushed limestone and cobble chambers and analyzed for total and dissolved metals.

The autopsy on the bioreactors revealed a convoluted biochemical environment that was probably caused by the dramatic change in the ARD chemistry after the first 10 months of operation. The material examined during the autopsy showed the mixed results of processes that were occurring at low pH and a reasonably high load of metals with the subsequent reactions that were characteristic for water of neutral pH laden with much less of the dissolved metals (Zaluski et al., 2003). The abundance of TOC present (20% by weight) in the organic matter chamber at the end of the project demonstrated that the bioreactors would have worked equally efficiently with a much smaller supply of organic carbon, provided the same residence time of ARD was maintained. Since the organic matter mass inhibits permeability, it is prudent to reduce the ratio of organic carbon to the permeability enhancing component and have a more permeable medium.

Interpretation of monthly monitoring results combined with the autopsy findings allowed for the formulation of a number of conclusions and recommendations. First, the CCS worked very well in preventing settling of the organic matter and ensuring uniform flow of ARD throughout the entire cross-section of the organic carbon with no preferential flow paths or channeling. Second, the configuring of the bioreactors to accommodate flow in a horizontal plane (rather than in the vertical direction) was successful. Third, time is required for an SRB population to be established in the bioreactors. Once established and supplied with organic matter, SRB can maintain an active population at temperatures ranging from 2 °C to 16 °C.

Results showed that only zinc, copper, and cadmium were being removed as sulfides due to SRB activities. Changes in concentrations of iron, manganese, aluminum, and arsenic, which do not necessarily precipitate as sulfide, seemed to be affected by SRB only in an indirect manner by responding to increased pH caused by SRB activity. Most of the metal sulfides that were formed due to the SRB activity precipitated within the organic matter. The same seems to be true for the rest of the metals that must have formed hydroxides and carbonate compounds.

Integrated Biological Treatment

This passive biological treatment process utilizes SRB along with manganese-oxidizing bacteria (MOB) to neutralize ARD and remove contained dissolved metals. Bench-scale testing was preformed to develop an integrated anaerobic with aerobic system parameters. Anaerobic treatment with SRB is used for arsenic, cadmium, copper, iron, lead, and zinc removal. An aerobic treatment is used for manganese oxidation/removal and polishing to remove organics. Figure 3 is a schematic of the process flows through the designed treatment system.

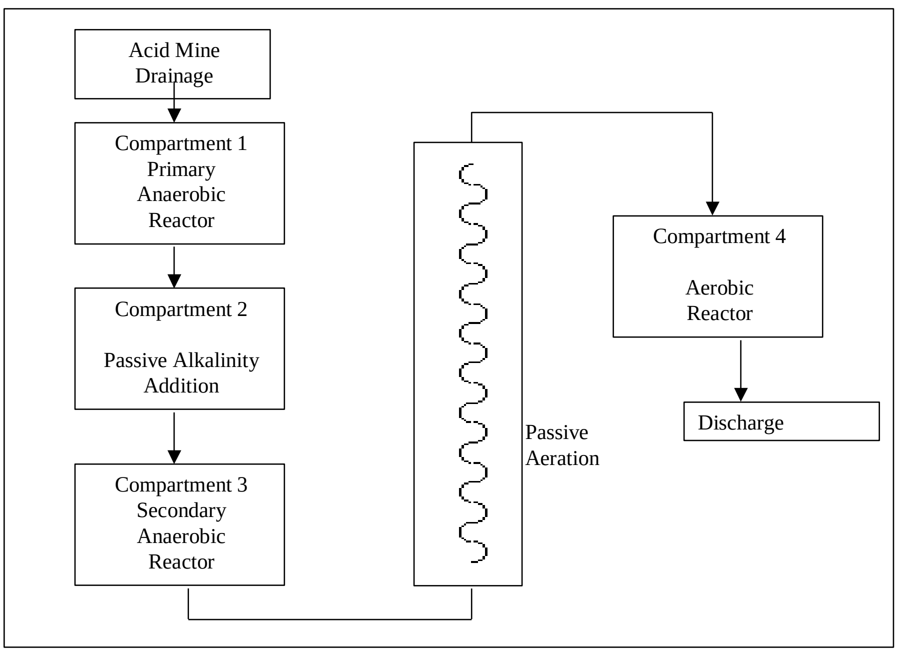

Figure 3. Block-flow of treatment system.

A pilot-scale system of this innovative passive treatment process was installed by MSE to treat ARD at the Surething Mine in Montana. At the demonstration site the bacteria live within a series of pit-type reactors constructed within the waste-rock pad located outside of the mine adit. Flow through the bioreactors is gravity dependent. The goal of this demonstration is to prove that this technology offers a comprehensive passive cleanup method for numerous remote or abandoned mines that discharge acidic metal-contaminated water (Nordwick and Bless, 2002).

The chemical parameters typical to untreated Surething Mine water are shown in Table 2 along with the dissolved metals and the effluent water chemistry for the initial effluent.

Table 2. Typical Surething Mine influent and effluent dissolved metals and pH.

	Iron (mg/L)	Zinc (mg/L)	Aluminum (mg/L)	Manganese (mg/L)	Arsenic (mg/L)	Cadmium (mg/L)	Copper (mg/L)	pH
Feed	15.0	22.7	29.5	26.7	0.13	0.21	2.35	2.5
Effluent	U	U	U	0.04	0.01	U	U	6.9

Note: U is undetected.

Evaluation of the data shows that overall metal removal was extremely high. This is attributed to slow self-establishment of an indigenous MOB population in the final reactor. As the demonstration progressed, design improvements were made and the removal of manganese was increased to present levels.

<u>Laboratory Experiments for Sulfate Reduction Rate</u>

As indicated by Reactions 1 and 2 the efficiency of SRB bioreactor depends on the sulfate-reduction rate (SRR). This important parameter can be determined in a laboratory using the organic matter selected for the given bioreactor. Synopsis of such an experiment conducted by MSE (MSE, 2004) is presented in this section.

The lab experiment focused on SRR of the organic matter composed of walnut shells and manure (W/M) mixed at the one to one ratio (by volume). This substrate was placed in six 5-gallon bucket bioreactors identified by numbers I, II, III, IV, V, and VI. The bioreactors were fed with the synthetic ARD, delivered to the test system by peristaltic pumps, at the rate of 2.7 mL/min to each bioreactor, which corresponds to an approximately 1-day residence time. The laboratory work was conducted using two synthetic compositions of ARD at three temperatures, 44 °F (6.7 °C), 58 °F (14.5 °C), and 77 °F (25 °C). The composition of synthetic ARD, referred to in this section as medium ARD (pH 4.2), and strong ARD (pH 2.6), replicate the ARD that once fed the bioreactors at the Calliope site (see section On-Site SRB Bioreactor). The medium ARD emulates the Calliope ARD composition the summer of 1999, and the strong ARD duplicates the ARD of the lowest pH and highest metal concentration during the time when the Calliope bioreactors were in operation.

All bucket bioreactors were sealed from atmosphere and configured for vertical upward flow Four bucket bioreactors were fed by the medium strength ARD with two of them operated at 58 °F (bioreactors II and IV) and the other two at 44 °F (bioreactor I) and 77 °F (bioreactor III). Two remaining bucket bioreactors that were fed by the strong ARD operated at 58 °F (bioreactors V and VI). The bucket bioreactors operated for 5 months and sulfur concentrations in the influent and effluent were monitored monthly.

Assuming that all aqueous sulfur was in the form of sulfate, the calculation of SRR was based on the difference (DS) in the sulfate concentrations in the influent and the effluent of the bucket bioreactors. Disregarding the first set of measurements, the decrease in the DS was from 18.6 mg/L to 87 mg/L (Fig. 4). Negative or abnormally high values of DS that occurred mostly during the first month of the operation are attributed to unstable conditions in the initial period.

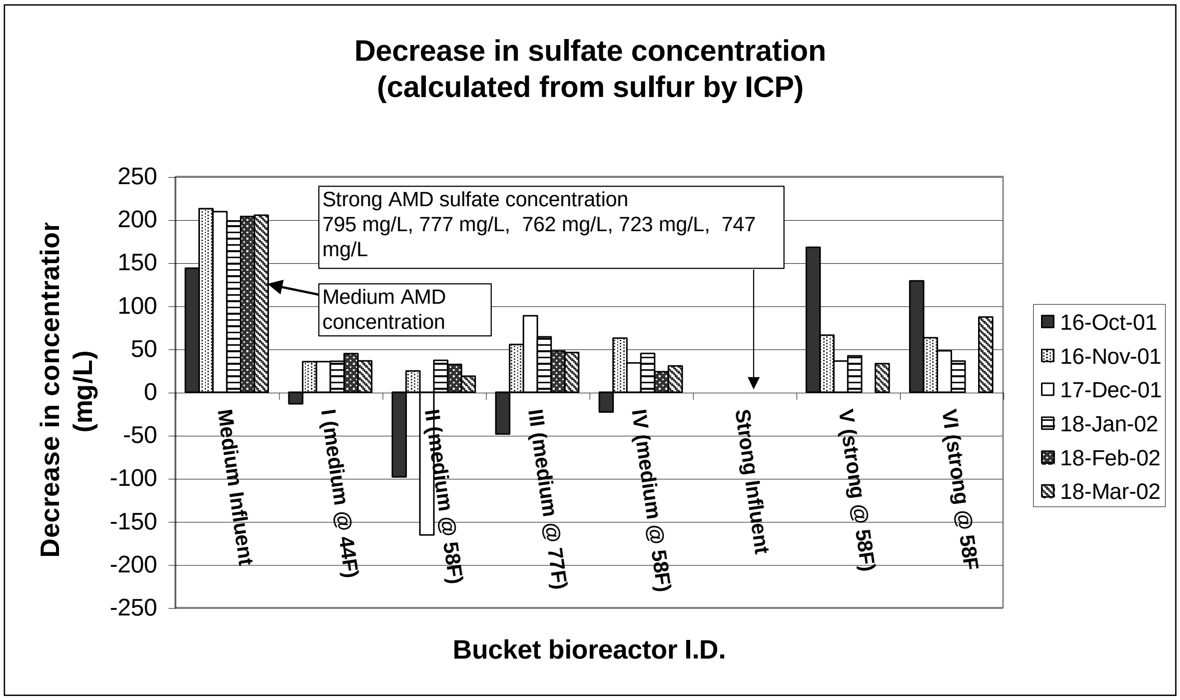

Figure 4. Decrease in sulfate concentration for bucket bioreactors

The SRR values, calculated using Equation 3 and shown in Fig. 5, ranged from 0.17 mole per day per cubic meter [mol/(d*m3)] to 0.79 mol/(d*m3) with the overall mean value of 0.40 mol/(d*m3). The mean value was calculated disregarding negative SRR values that occurred mostly during the first month of the experiment. The SRR values acquired from the laboratory experiment seemed to be independent of the strength of the influent and the temperature at which the experiment was conducted. The large range for SRR values indicates the need for conducting the experiment at least in triplicates.

$$SRR = \frac{DS * Q}{V * p} \qquad (3)$$

Where Q is flow rate in L/d, V is volume of the reactor, and p is porosity of the medium.

Flow Configuration

The life span of an SRB bioreactor depends not only on the availability of organic carbon, but also on the permeability of the organic matter. A decrease of the permeability of the organic matter during the bioreactor operation time may not only limit the flow rate for the treated ARD, but also may cause physical encapsulation of organic carbon, thus making it unavailable for the sulfate reduction process.

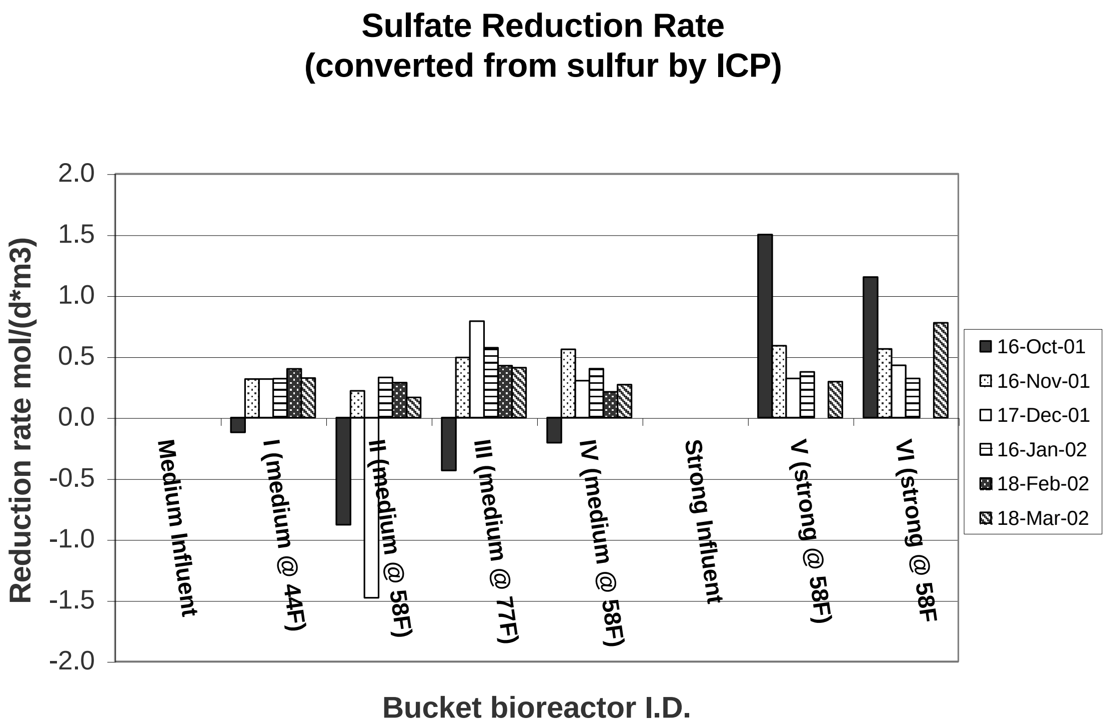

Figure 5. Sulfate reduction rates

Field bioreactors are designed and constructed with ARD flow configured either in horizontal or vertical direction. Selection of the flow direction depends primarily on the structure and the composition of the reactive medium used, and secondary on the filed conditions and limitations. In general, bioreactors that use a reactive medium containing a low ratio of organic matter to the inert material can be configured for either a horizontal or a vertical direction of flow. Such mixes are usually very stable, i.e. they do not settle or deform during the bioreactor operation time (Smyth at al 2001) because the inert material, usually gravel, supports the structure of the mix. While such feature of the medium is certainly desirable from the engineering point of view, its drawback is a relatively small supply of organic carbon that may affect the life span of the bioreactor. On the other hand, if the reactive medium contains a mix with high ratio of organic matter to the inert material it provides ample supply of organic carbon, but may settle for a lack of supportive structure.

Based on the results of the previous research and the technology demonstrations as described earlier in this paper, a new organic mix consisting of English walnut shells and cow manure (W/M) was developed by MSE (MSE, 2004). In this organic mix walnut shells substitute gravel in its role to provide structural support for the organic medium, but as being not inert, also provide a source of organic carbon; the feature unmatchable by gravel. Moreover, because walnut shells biodegrade slowly they would provide organic carbon in the latter stage of the bioreactor life, while easily biodegradable manure ensures a quick start of the bioreactor and deliver organic carbon in the early stage of its operation.

The W/M organic matter was tested (MSE, 2004) by investigating the time related changes of its permeability as a function of the flow orientation and the ratio of walnut shells and manure in the mix. This study included several long-duration permeability tests conducted for an upward vertical flow and a horizontal flow to determine the adequacy of each flow configuration. Results of these tests indicated that though there was no difference in the initial permeability of the medium for each configuration, the long-term permeability of the medium is significantly higher for flow in a horizontal plane. This phenomenon is attributed to the deformation of the W/M organic medium in which the finest particles are mobilized by the flowing ARD and migrate downward by gravity to settle at a certain level, usually at the bottom of the container, blocking the flow. In the case of a horizontal configuration, the migrating particles also settle in the bottom of the container; however, they do not block the entry of water that flows above them as it is fed laterally. Consequently, the bioreactors, which are designed to contain organic-carbon rich reactive matter of walnut shells and manure, need to be configured for the horizontal flow.

The experiments conducted showed that for a horizontal flow configuration the sustainable hydraulic conductivity (K) of the W/M mixture is 0.01 cm/s or higher. In general, the hydraulic conductivity value of the medium composed of 50% of walnut shells and 50 % of manure was one order of magnitude smaller than the K value for the medium composed of 80% of walnut shells and 20 % of manure.

Reactive Cartridge

The remoteness of ARD sites, their abundance, and economic aspects require that the design of a bioreactor be simple and inexpensive and that the bioreactor be capable of treating the anticipated ARD flow rate and associated dissolved metals loading. Therefore, it is preferred that bioreactors are prefabricated and designed to a size allowing for transportation using primitive and narrow roads in mountainous regions. These conditions are met by bioreactors consisting of a number of modules or reactive cartridges (RC) that are assembled into one SRB treatment system at the mine site.

A modular SRB treatment system (MSE, 2004) consists of a number of RCs that are configured in parallel or in series, depending on the ARD flow rate and its quality (metal load and pH), cleanup objectives, and space available at the given mine site. These RCs are filled with the W/M organic medium of the selected volumetric ratio for each component. The number of the RCs in the treatment system is determined using the BEST (bioreactor economics, size and time of operation) simulator (Zaluski et al., 2005). This simulator has been developed and tailored for designing such a treatment system based on the ARD chemistry and flow rate, and the reactivity of the organic matter that is used as the organic carbon source – the electron donor for the sulfate reduction process.

Reactive cartridges can be built using commercially available cylindrical or cuboidal high-density polyethylene (HDPE) or polypropylene tanks. Such a tank is equipped with necessary features to accommodate the W/C organic medium and serve as an RC. These modifications are made in a machine shop and then the tank is transported to a mine site. While at the mine site, the tank can be installed either aboveground or belowground as required by the site conditions. An appropriate piping system can convey the ARD into the RC.

Any tank of a suitable size and shape can be adapted for the RC; its suitability is determined by the mine site conditions, transportation restrictions, availability, price, etc. The RC design presented in this paper includes a 2.44-meter diameter, 2.44-meter tall polypropylene tank of the nominal size of 9.5 m^3. The 2.44-meter diameter tank was selected for the design because U.S. Department of Transportation regulations limit the width of the standard load to 8 feet (2.44 m).

Figure 5 and Figure 6 are conceptual drawings showing main components of the RC.

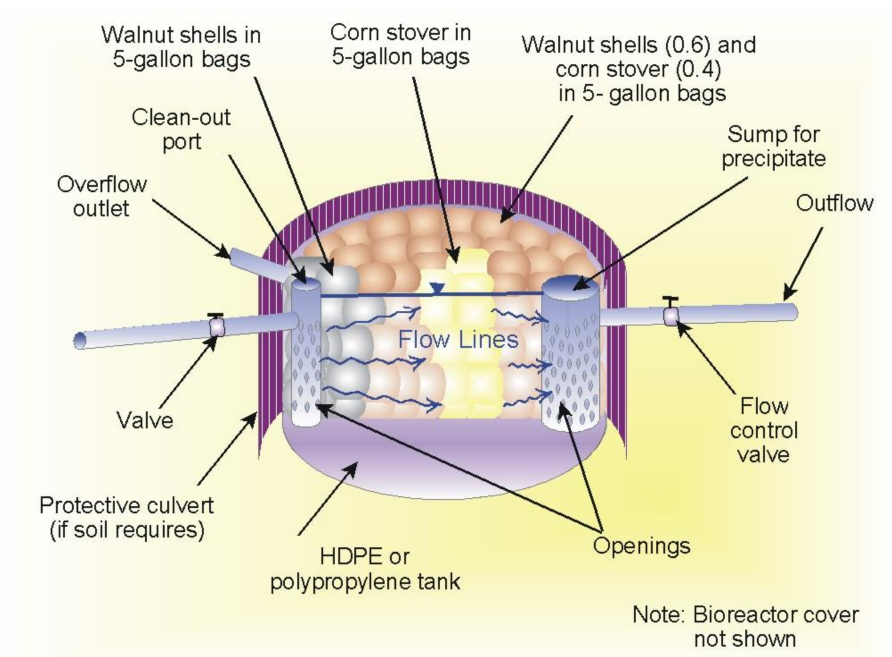

Figure 5. Conceptual 3-dimensional drawing showing main components of the RC.

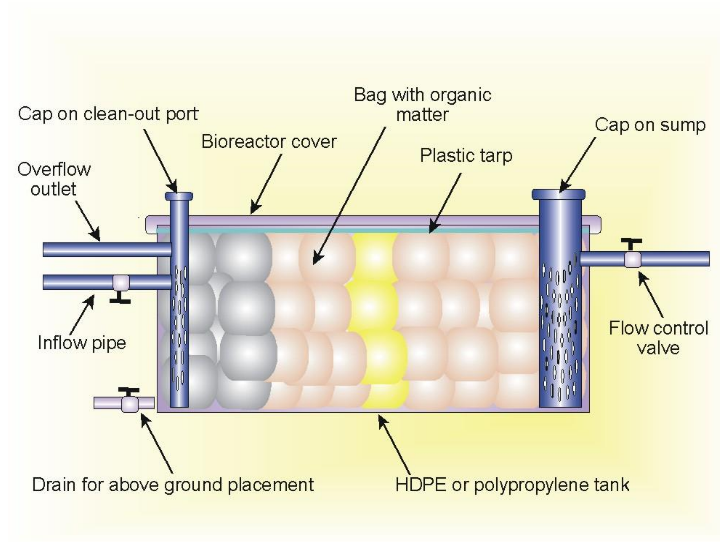

Figure 6. Conceptual cross sectional picture of RC with respective details

The reactive medium that fills the RC shown in Figures 5 and 6 is a mix of walnut shells and corn stover rather than walnut shells and cow manure. This new organic matter, has recently been developed through the combine research of MSE and Colorado School of Mines. For the ease of its placing, and replacing if needed, the organic matter is bagged (Fig. 7) in a plastic net with 1 cm (3/8-inch) openings. Such a netting material is commercially available in the form of a sleeve, and is commonly used for packaging produce.

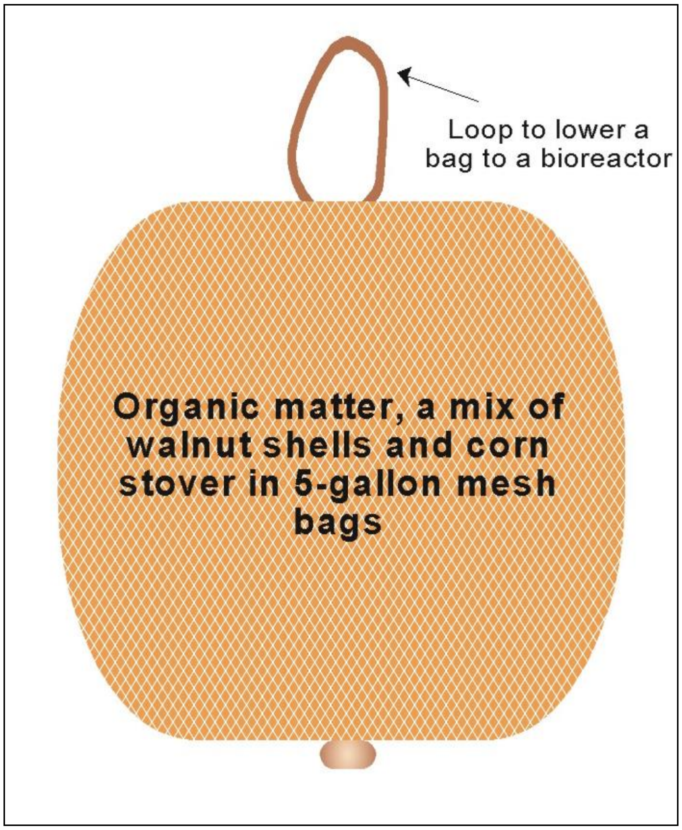

Figure 7. Bag with organic matter (walnut shells and corn stover).

Summary

The MWTP has worked to advance the development of SRB technologies to treat ARD. As part of this work, MSE has conducted both bench-scale testing and field demonstrations to demonstrate the benefits of employing SRB technologies to mitigate ARD. The advantages of SRB bioreactors include: the reduction of dissolved metal ions by formation of insoluble metal sulfides, and the neutralization of the ARD from the resultant production of bicarbonate generated by the oxidation of organic nutrients.

This paper presented summaries of selected MWTP projects and described the developed designs that have been employed such as the submerged in situ bioreactor at the Lilly Orphan Boy Mine, the SRB on-site bioreactor installed at the Calliope Mine, the integrated biological reactors built at the Surething Mine, and the ongoing development of a replaceable cartridge system. These MWTP demonstrations show that SRB bioreactors are very effective for passive ARD treatment.

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