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SCALING UP DESIGN CHALLENGES FOR LARGE SCALE SULFATE REDUCING BIOREACTORS[1]

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Abstract: The first large scale, 1,200 gpm capacity, sulfate reducing bioreactor (SRBR) was constructed in 1996 to treat water from an underground lead mine in Missouri. Other large scale SRBR systems have been built elsewhere since then. This technology holds much promise for economically treating heavy metals and has progressed steadily from the laboratory to industrial applications. Scaling-up challenges from bench- and pilot-sized systems include designing for: seasonal temperature variations, minimizing short circuits, changes in metal loading rates, storm water impacts, and resistance to vandalism. However, the biggest challenge may be designing for the progressive biological degradation of the organic substrate and its effects on the hydraulics of the SRBR cells. Due to the wide variability of the organic materials that may be locally available at reasonable costs, the design of organic substrate SRBR systems is not and may never become a "cookbook" approach. Balancing substrate geochemical requirements with intuitive physical resistance to organic decay currently plays a large role in the large scale system design process.

Keywords: Passive Treatment, acid rock drainage, heavy metals, sulfate reducing bacteria

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Introduction

Among the growing list of generic design approaches, there are basically two kinds of *biologically*-driven passive treatment cells for treating mine drainage. ***Aerobic Cells*** containing cattails and other plants and algae are typically applicable to coal mine drainage where iron, manganese, and/or mild acidity are problematic. ***Anaerobic Cells*** or ***Sulfate-Reducing Bioreactors*** (see Figures 1 and 2) are typically applicable to metal mine drainage with low to high acidity and a wide range of metals. Most biologically-driven passive treatment systems employ one or both of these cell types. The track record of aerobic cells in treating coal mine drainage is impressive, especially in the eastern coalfields of the US. Sulfate-reducing bioreactors have tremendous potential at metal mines and coal mines but have not seen as wide an application.

Sulfate reduction has been shown to effectively treat mine drainage containing dissolved heavy metals, including aluminum, in a variety of situations (Gusek, 2002). The chemical reactions are facilitated by sulfate reducing bacteria, most commonly *Desulfovibrio*. The configuration is similar to that used in other similar systems such as SAPS, RAPS, and VFR's. An SRBR is defined here as a cell whose primary metal removal mechanism is sulfate reduction.

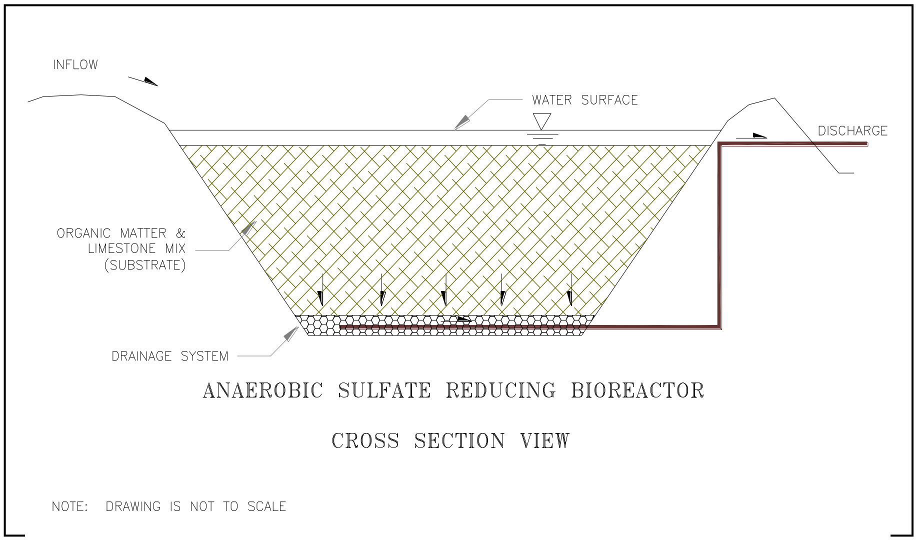

Figure 1 - Sulfate-Reducing Bioreactor Schematic Section

Figure 2 - A Typical Sulfate-Reducing Bioreactor

The sulfate reducing bacteria produce sulfide ion and bicarbonate (which has been shown to raise the pH of the cell effluent) in accordance with the following approximate reaction (Wildeman, et al., 1993):

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

The dissolved sulfide ion precipitates metals as sulfides, essentially reversing the reactions that occurred to produce AMD/ARD. For example, the following reaction occurs for dissolved zinc, typically forming amorphous zinc sulfide (ZnS):

$$Zn^{+2} + S^{-2} \rightarrow ZnS \qquad (2)$$

While aluminum does not form a sulfide, its removal in SRBR environments has been commonly observed. Instead of aluminum hydroxide typically formed in SAPS, Thomas and Romanek (2002) observed zones of insoluble aluminum hydroxysulfate precipitates in portions of their limestone buffered organic substrate (LBOS)-filled cells which were similar to SRBR's, perhaps in accordance with the following reaction which is one of many that are possible:

$$3Al_3^{+} + K^{+} + 6H_2O + 2SO_4^{-2} \rightarrow KAl3(OH)_6(SO_4)_2\ (Alunite) + 6H^{+} \qquad (3)$$

The key conditions for sulfate reducing bacteria health are:

- a pH of 5.0 or greater which can be maintained by the bacteria itself through the bicarbonate reaction in equation 1, and/or the presence of limestone sand,
- the presence of a source of sulfate (typically from the water being treated), and
- the organic matter (CH_2O) in the substrate.

SRBR's have been successful at substantially reducing metal concentrations and favorably adjusting the pH of metal mine drainages.

There are many advantages to sulfate-reducing bioreactors in treating mine drainage, including the ability to:

- work in cold, high altitude environments (Gusek, 2000);
- handle high flow rates of mildly affected mine drainage in moderate acreage footprints (Gusek et al., 2000);
- treat low pH acid drainage with a wide range of metals and anions including uranium, selenium, and sulfate (author's personal observation);
- accept acid drainage-containing dissolved aluminum without clogging with hydroxide sludge (Gusek and Wildeman, 2002);
- provide life-cycle costs on the order of \$0.50 per thousand gallons (author's estimate); and
- be integrated into "semi-passive" systems that might be powered by liquid organic wastes (Miller, 2000).

Sulfate reducing bioreactors might not be applicable in every abandoned or active mine situation. A phased design program of laboratory, bench, and pilot scale testing has been shown to increase the likelihood of a successful full scale design (Gusek, 2001).

It is relatively easy to construct and operate small scale SRBR's. Most of the construction materials are available off-the-shelf. The author has used 55-gallon drums or 40-gallon trash cans at numerous sites; these items can be easily retrofitted into SRBR bench scale cells using less than $10 worth of plumbing materials commonly found at local hardware stores. These sized cells might treat from one to tens of liters of water per day, depending on the drainage chemistry.

Children's swimming pools have been used to construct pilot scale SRBR's using less than $100 worth of common plumbing supplies. These sized cells might treat up to 30,000 liters per day (about five gpm).

Scaling up from pilot scale to full scale is no easy task. Now site-specific conditions become more important in design. This paper addresses some of the more common scale-up design challenges including:

- seasonal temperature variations,
- metal loading rate changes,
- short circuiting,
- gas lock-up,
- storm water impacts,
- resistance to vandalism,
- changing economics, and
- organic substrate biodegradation.

Seasonal Temperature Variations

In most bench and some pilot scale situations, the temperature of the mine drainage may be artificially controlled. This situation is somewhat necessary to minimize the number of experimental variables and frankly, it is the easiest thing to do, especially given the propensity of small plumbing fixtures to quickly freeze in the winter.

From a microbiological standpoint, it is well understood that depressed temperatures slow common mesophilic bacterial activity. This is why refrigeration is so popular in preserving food. Sulfate reducing bacteria activity is also sensitive to temperature; however, they have been found to adapt to very harsh environments, including super-cold (-40°C) water beneath the Antarctic ice cap (Postgate, 1979). In designed SRBR's, the limiting activity function may be the rate at which organic materials are decaying – this will be a function of the behavior of that whole suite of microbes that colonize SRBR's and break down the organic matter into simple compounds that become nutrients for the sulfate reducing bacteria.

Minor temperature fluctuations may not affect SRBR overall activity all that much once the microbial suite has established itself. In a pilot scale SRBR at the Ferris Haggarty Copper Mine/Osceola Tunnel in Wyoming, the mine effluent was typically less than 5°C. During the winter at this high altitude (9,500 ft elev.) site, the treated effluent temperature dropped to as low as 0.5°C. Yet the rate of sulfate reduction reduced to only about 80 percent of the 5°C benchmark rate (Gusek, 2000). This observation was incorporated into the design of a full-scale system to treat as much as 600 gpm.

A part of the temperature challenge at the Ferris Haggarty site was mitigated by a number of design features, including:

- collecting the mine water deeper in the mine and delivering it to the SRBR cells in insulated pipes to preserve some of its ambient in-ground temperature, and
- covering the SRBR's with an insulating layer of clean mine waste rock.

Covering/burying SRBR's (which do not need plants or sunshine to function) can be used to solve other full scale design challenges. Other design considerations, such as seasonal changes in metal loading rates, may further mitigate temperature effects on SRBR performance.

Metal Loading Rate Changes

SRBR cells are sized based on metal loading and can be resilient to metal loading variations *within reasonable limits*. Those limits are best determined in pilot scale tests where the expected operating ranges of flow and metal concentrations and the reactions of the SRBR cells to those varying conditions can be assessed. For example, a pilot SRBR cell at a lead mine in Missouri was sized for 25 gpm. Once steady state operation was observed for many months, the net alkaline flow was increased to nearly double the design rate. The SRBR cell began to show evidence of stress (i.e., decreased metal removal efficiency) after several months of exposure to the higher flow (Gusek et al., 1998). Not all SRBR cells might be this resilient, especially if the mine drainage is net acidic, but this observation allowed engineers to include a significant factor of safety in the design of the full-scale system (1,200 gpm capacity) at this site.

Overloading SRBR's with net acidic mine drainage can be catastrophic; sulfate reducing bacteria populations can be decimated by overexposure to low pH mine water with high concentrations of metal, particularly iron and aluminum. In this situation, the geochemistry of the SRBR might be significantly altered and while some metal removal may still occur, removal efficiencies may suffer and in certain cases even turn negative after the overloading situation has abated. In other words, some particularly unstable metal compounds that had been precipitated during the overloading event might actually be re-dissolved as the geochemistry of the SRBR cell recovers to the extent that the concentrations of metals in the SRBR cell effluent are greater than the influent.

SRBR's are typically sized to deliver treated water with low concentrations of metals and a near neutral pH. However, experience has shown that SRBR cell effluents typically contain excess alkalinity at reasonable concentrations that may be available to ameliorate acidity contributions that might be impacting the receiving stream far removed from the original passive treatment site. This operational by-product of metal removal in an SRBR may be used to lessen the impact of overloading conditions as suggested below.

In the full scale SRBR designs then, flow management will be a paramount concern to insure that the spikes in flow and/or concentration as defined in pilot testing are attenuated to the most practical extent. Alternatively overloads may even be temporarily diverted past the system in the hope that excess alkalinity and dilution by system-treated effluent will lessen the downstream impact as temporary as it may be. Overload mitigation may be practically accomplished in a full scale system design with a variety of methods that include using:

- properly sized holding/mixing ponds,
- flow-sensitive diversion ditches that are engaged only in overloading conditions, and
- underground mine workings that are configured as storage reservoirs.

Short Circuiting

SRBR's are typically designed as vertical flow systems with mine water traveling downward (or upward) through an organic substrate to be collected at the opposite end (bottom or top) of the cell. Early SRBR designs used organic substrate materials that had very low (on the order of 1×10^{-4} cm/sec) saturated hydraulic conductivity (K) values. Thus, minor changes in K values introduced by substrate heterogeneity offered a greater opportunity for short circuiting. Recent substrate mixes have measured K values several orders of magnitude less. However, as the capacities of systems have increased the opportunities for intra-cell short circuiting have increased as well. This is primarily due to the increasing cell surface area in larger capacity systems.

Busler, et al. (2002) studied this issue in vertical flow reactors (VFR's) which are similar to SRBR's. They documented significant short circuiting in a VFR that had been designed in accordance with accepted practice. Busler, et al. subsequently plumbed a VFR with multiple adjustable-head discharge points (each connected to a different zone of the VFR) and dramatically reduced short circuiting. Their design also evaluated the efficacy of variable spacing of solution collection pipe perforations to further minimize short circuiting.

The essence of large scale SRBR cell design that can be gleaned from field experience and Busler, et al. is to: "divide and conquer". That is, subdivide large flows into smaller flows that are equitably distributed to multiple cells of similar dimensions rather than construct one large SRBR cell. If intra-cell short circuiting is a concern, further subdivide the treated solution collection system into parallel flow nets with virtually identical pipeline headlosses. This approach may increase the cost of the system plumbing, but the design will be less likely to suffer the effects of short circuiting which are neither easily isolated nor rectified.

Gas Lock-up

The generation of sulfide ion (S^{-2}) and bicarbonate (HCO_3^-) as a result of the reaction cited in Equation 1 inevitably results in the formation of some hydrogen sulfide and carbon dioxide gases, respectively. Carbon dioxide may also form due to the dissolution of limestone typically included in the organic substrate mixture. These gases can collect within the pipe work and in other “traps” within the SRBR and cause gas lock-up conditions that may be manifested as apparent losses in organic substrate permeability or short circuiting. This was one of the scale-up problems reported at the West Fork site in Missouri (Gusek et al., 2000). In small-scale SRBR’s such as bench or pilot scale cells, the pipe used is typically made of rigid PVC or HDPE. It is difficult for gas to be trapped in these small systems; the short pipe lengths and the pipe’s rigidity combine to prevent unintentional gas trapping conditions. Some large scale SRBR’s have been constructed with flexible corrugated HDPE pipe that can easily bulge upward and form gas traps. This is a problem especially in the gravel-filled drainage layer at the bottom of a typical SRBR. The light-weight HDPE pipe has a tendency to “float” to the gravel surface during installation. Proper quality assurance/quality control during installation is required to correct or prevent this condition in the field. The use of more rigid pipe and including gas vent pipes in the SRBR cell design could also be used to avoid gas lock-up situations.

Storm Water Impacts

A properly-designed SRBR cell/system will need to survive the physical aspects of storm water impacts. This is accomplished with runoff diversion channels and other standard management practices which are not unique to SRBR cells or systems. However, in climates with high precipitation, storm water falling directly on to the SRBR can result in significant operational problems.

For example, an SRBR cell with an open water pond in South Carolina might be exposed to a 100 year, 24-hour rain storm event on the order of 7.5 inches. While the plumbing and hydrologic aspects of the cell can be easily designed to handle the additional influx of water, consideration needs to be given to the effects of the increased flow on the bacterial population and the physics of metal precipitate retention in the organic substrate. Assuming that the “solution to pollution is dilution” may be dangerous. It is unlikely that this situation would be naturally encountered during the operation of a pilot cell. Therefore, it may need to be artificially created to evaluate the short term effects on SRBR cell performance.

In the case of the South Carolina site, pilot test results and a parametric study revealed that the short term flow increases in response to rainfall events could result in unacceptable system performance. Several alternative SRBR cell designs were considered including adjustments of cell footprint (i.e., watershed area) and increasing the freeboard to temporarily store the 24-hour storm in the SRBR cell. The selected alternative to minimize storm water impacts was the burial of the cell beneath a light-weight fill/geomembrane/soil-vegetation cover. This approach offered significant resistance to long term vandalism at this site which was part of a permanent mine closure project.

Resistance to Vandalism

As distasteful the design consideration must be, any passive treatment system must be designed to resist vandalism by humans as well as animals. The larger the system is, the larger the vandalism target.

Camouflage is probably the best human vandalism deterrent; one cannot harm something that is not easily seen. This can best be accomplished by blending SRBR cells into the landscape by either burying them which can be used to solve other design issues or by creating visual footprints that look totally natural.

Again, because neither plants nor air are required for SRBR's to function, they can be buried beneath a veneer of rock and soil provided that the feed water plumbing to the cell is not compromised. Settlement of the organic substrate needs to be considered in the design if burial is being considered. However, most organic substrate designs typically include a large component of wood chips or sawdust, which do not readily compress under minor surcharge loads developed by soil/rock covers. This aspect of the design should ideally be evaluated at the pilot stage of the design effort.

The visual aspect of "natural-looking" SRBR cell design with open water ponded on the surface requires a step back from the rectangular or geometric shapes that seem to be the stamp of typical design engineers who may have difficulty drawing lines that are not straight. One way to hide a rectangular-shaped SRBR cell is to extend the ponded water surface beyond the rectangular footprint to a shallow water zone with a more natural-looking irregular shape. This design feature may add a little to the construction cost, but community acceptance and resistance to vandalism of exposed geomembrane liners may make it worth the extra expenditure.

While beavers are known as nature's "engineers", they can do more vandalism damage than humans to SRBR cells and other passive treatment system features on a pound-for-pound basis.

The larger the flow rate treated, the larger this problem can be. This is because beavers are naturally attracted to the sound of running water. This acoustical magnet triggers their digging and damming reflex and large scale SRBR cells become at risk.

To minimize this risk, large scale SRBR cells near beaver habitat can be designed with internal spillways or water level control structures that muffle the falling water noise. These reasonably-priced pre-fabricated structures are commercially available in a range of sizes. In addition, there are a number of websites that contain conceptual designs for "beaver-proof" spillways.

Changing Economics

Procuring the organic and inorganic components for bench and pilot scale SRBR's may involve several hundred kilograms to several thousand kilograms of various materials. Invariably, many businesses or individuals are initially more than willing to provide their waste materials such as manure, sawdust, green waste, or wood chips for free. This is probably done in the hope that they can save money by not having to pay to have their waste disposed in a landfill if it can be put to a beneficial use. Unfortunately, when it is revealed that a particular waste stream source is an integral component of the SRBR substrate, the price of procuring it inevitably goes up. The construction engineer is then faced with a dilemma: change the design and risk more uncertainty in the system's operation, or pay the higher price for the material.

The best solution to the dilemma may be to change the design by substituting similar materials if possible. Fortunately, the uncertainty of substitution can be minimized by a little extra effort in the bench scale phase of the full scale SRBR cell design. It is recommended that potential substitutions be anticipated in advance and tested on a bench scale. Thus, last-minute changes in material sources can be made with more peace of mind.

Organic Substrate Biodegradation

Organic materials are a key component in the formulation of the substrate of sulfate-reducing bioreactors. Often these materials are considered waste materials and can be obtained for little or no purchase cost. The only expense incurred might be in their transport to the treatment site. In many cases, the site is located in a remote forest environment. In this situation, some of the materials such as wood chips and sawdust might be generated onsite or from local sources. A short list of organic waste materials that might be candidates for use in a sulfate-reducing bioreactor is provided below. The list is not necessarily all inclusive as specialty wastes unique to different locales might be available.

- Wood chips
- Sawdust
- Rice Hulls
- Yard waste
- Mushroom compost
- Animal manure
- Hay and straw (spoiled)
- Cardboard?
- Soy bean hulls
- Waste alcohols including antifreeze
- Waste dairy products
- Sugar cane processing residue (Bagasse)

Early SRBR designs included large amounts of compost, manure, and easily degraded organic materials. Unfortunately, these systems were depleted of biologically-available carbon in a short time so cell longevities were short – on the order of several years. Subsequently, more-biologically durable materials such as sawdust and wood chips were used in substrate design to offer a better balance between short and long term sources of organic nutrients. To date, this author and others have relied on intuitive comparisons of the biodegradability of various solid organic materials that might be used in SRBR’s. Precisely estimating the progressive biological degradation of the organic substrate and its effects on the hydraulics of the SRBR cells is a significant design challenge.

However, some progress is being made on this front. Seyler et al. (2003) evaluated the effects of solid phase organic substrate characteristics on sulfate reducer activity and metal removal. The identification of a simple standardized analysis method for comparing the biodegradability of various organic materials is probably the most significant advance made by Seyler et al. The analysis method is tiered off of nutrient analysis of agricultural products. Their results conform to the intuitive observations of this author and could be the foundation of a better understanding of organic substrate design to maximize longevity.

Summary

Sulfate-reducing bioreactors are not the only type of passive treatment technique available to the design engineer, and they are not applicable in every situation. However, they can handle a wide variety of flows and AMD/ARD chemistries in hostile cold climates, and they can treat aluminum-bearing AMD/ARD without plugging. Furthermore, they can generate excess alkalinity in their effluent that further enhances the quality of the receiving stream.

Applying the results of laboratory, bench, and full scale tests to full scale designs is part common sense, part intuition. However, advancements in the discipline continue and a standardized design approach eventually may be realized.

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