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Appendix D

Solid-Reactant SRB Bioreactors

Papers by Jim Gusek et al.

THE CHALLENGES OF DESIGNING, PERMITTING AND BUILDING A 1,200 GPM PASSIVE BIOREACTOR FOR METAL MINE DRAINAGE WEST FORK MINE, MISSOURI [1]

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Abstract. An active underground lead mine produces water having a pH of 8.0 with 0.4 to 0.6 mg/L of Pb and 0.18 mg/L of Zn. A full-scale 1,200 gpm capacity bioreactor system was designed and permitted based on a phased program of laboratory, bench and pilot scale bioreactor testing; it was constructed in mid-1996. The gravity flow system, covering a total surface area of about five acres (2 ha), is composed of a settling basin followed by two anaerobic bioreactors arranged in parallel which discharge into a rock filter polishing cell that is followed by a final aeration polishing pond. The primary lead removal mechanism is sulfate reduction/sulfide precipitation. The discharge has met stringent in-stream water quality requirements since its commissioning. The system was designed to last about 12 years, but estimates suggest a much longer life based on anticipated carbon consumption in the anaerobic cells.

Key words: Metal Mine Drainage, Lead, Zinc, Passive Treatment, Anaerobic Bioreactors

Introduction

Asarco's West Fork Unit is an underground lead-zinc mine that discharges water from mine drainage to the West Fork of the Black River (West Fork) under an existing NPDES permit. The adoption of water quality based discharge limits in its NPDES permit issued in October, 1991, prompted Asarco to evaluate treatment methods for metal removal.

Evaluations of alternative treatment processes determined that biotreatment methods were feasible and cost less than half as much as sulfide precipitation. The goal of the water treatment project was to ensure that the stringent water quality based limits in the permit would be consistently met.

[1] To be presented at the 15th National Meeting of the American Society for Surface Mining and Reclamation, May 17-22, 1998 in St. Louis, MO.

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Location

The West Fork Unit is located in Reynolds County in central Missouri, about three hours from St. Louis (Figure 1). The mine is located in the New Missouri Lead Belt.

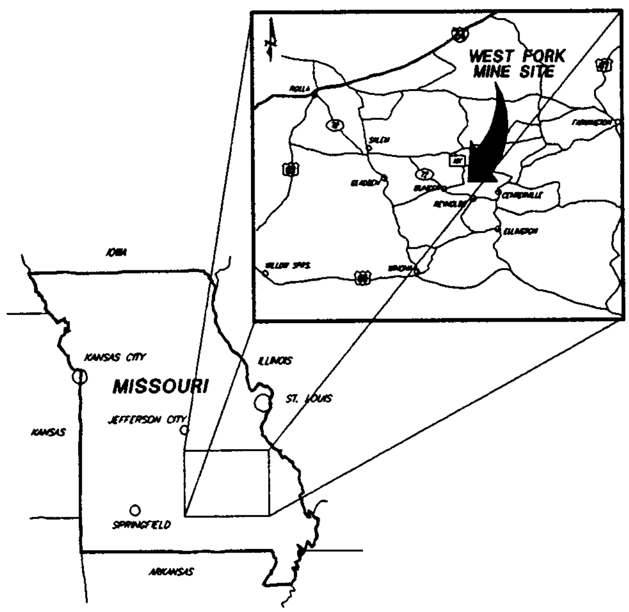

Figure 1, Site Location

Flow rates in West Fork vary from about 20 cubic feet per second (cfs) to more than 40 cfs; water quality is relatively good, despite being located in an area with naturally high background levels of lead due to the bedrock geology. The mine discharges about 1,200 gpm on the average (2.7 cfs) or about 10 percent of the total flow in West Fork.

Biotreatment

A Brief History of Biotreatment

Natural systems have been removing metals from water for eons; examples include pyrite fixed into coal beds and bog iron ore deposits. For the past 10 years, wetlands and bogs have been the natural method of choice for improving water quality. Contaminant reductions are being seen through the precipitation of hydroxides, precipitation of sulfides, and pH adjustments. Local conditions, oxidation state, and water and soil chemistries dictate whether such natural reactions occur under oxidizing (aerobic) or reducing (anaerobic) conditions. Man-made or constructed wetlands/ bioreactors employ the same principles as natural wetlands, but are designed to optimize processes occurring naturally in wetland ecosystems. Aerobic and anaerobic zones occur in natural wetlands (Figure 2) (Wildeman, et al., 1993). The key goal of bioreactors/ wetlands is the long term immobilization of metals in the substrate materials. Metals are precipitated as carbonates or sulfides in the bioreactor substrate (anaerobic cells) and as oxides in aerobic (rock filter) cells.

Anaerobic bioreactors have been successful at substantially reducing metal concentrations and favorably adjusting pH on metal mine drainages. It is generally recognized that the bacteria commonly found in cattle and other domestic animal intestinal tracts include sulfate reducers and a consortium of other beneficial bacteria. Hence, cow or other animal manures have been frequently used as bacterial inoculum for anaerobic biotreatment cells. These same bacteria are found in many natural wetlands and bogs, and in lakes and ocean water. Aerobic biotreatment systems are similar to "natural" wetlands in that they typically have shallow depths and support vegetation in the form of algae.

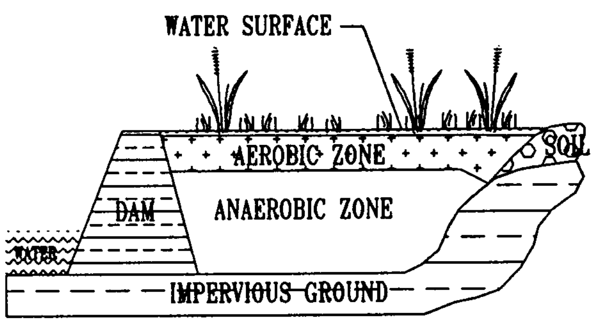

Figure 2, Natural Wetland Ecosystem Zones

Since the early 1980's, researchers have documented water quality improvements in natural wetland systems. The former US Bureau of Mines (USBM), Tennessee Valley Authority (TVA), and universities such as the Colorado School of Mines [CSM] and others focused on plant-based ecosystems for biotreatment. Many pilot scale systems were built but results were uneven.

In the interval from 1985 to 1988, Greg Brodie of TVA and Bob Kleinmann of the former USBM began to use influent water chemistry as part of the design for aerobic type systems for treating coal mine acid rock drainage (ARD) (Hammer, 1989). In 1987, CSM, Knight Piésold/Camp Dresser & McKee and the US EPA jointly developed a pilot system for metal mine ARD at the Big Five Tunnel in Colorado. At the Big Five Tunnel, anaerobic processes were found to be important in metals removal; macroscopic ecosystems were not needed because the cells worked fine without plants.

Since 1988, there have been rapid advancements in understanding the functioning of wetland/bioreactor systems. The first large scale aerobic system (2,000 gpm capacity) was built in 1992 by TVA; the West Fork Unit system (1,200 gpm capacity) is the first large-scale anaerobic biotreatment system. Aerobic "rock filter" treatment follows for polishing manganese and other parameters.

While the volumetric flow capacity of the West Fork system is a biotreatment milestone, the metal mass loading capacity has been surpassed by many other pilot scale systems which treated water with metal concentrations one thousand times more concentrated than those observed at West Fork. The innovative West Fork technology holds promise over typical chemical treatment methods because large volumes of sludge are not generated; in fact, sludge disposal may be delayed until the end of the project life. In situ reclamation may also be feasible.

Biotreatment Removal Mechanisms

Research has shown that microbial processes are a dominant removal mechanism in anaerobic type biotreatment systems. One prominent researcher calls these systems "bioreactors with green toupees," referring to the organic substrate where most of the bioreactions occur and the collection of plants that often grow on their surfaces.

Many physical, chemical and biological mechanisms are known to occur within biotreatment systems to reduce the metal concentrations and neutralize the acidity of the incoming flow streams. Notable mechanisms include:

- Sulfide or carbonate precipitation catalyzed by bacteria in anaerobic zones;
- Hydroxide or oxide precipitation catalyzed by bacteria in aerobic zones;
- Adsorption and exchange with plant, soil and other biological materials;
- Filtering of suspended material;
- Metal uptake into live roots and leaves; and
- Ammonia-generated neutralization and precipitation of hydroxides.

Remarkably, some studies have shown that plant uptake does not contribute significantly to water quality improvements in wetlands. This may be plant-species dependent. Plants can, however, replenish the anaerobic bioreactor with organic material and add aesthetic appeal. In aerobic biocells, plant-assisted reactions appear to aid the metal-removal performance of the system, perhaps by increasing oxygen and hydroxide concentrations in the surrounding water through photosynthesis-related reactions that use bicarbonate in the water.

Bacterial Reactions

Research testing showed that anaerobic reactions could provide the desired level of lead remediation at West Fork. In the anaerobic systems, sulfide precipitation assisted by sulfate-reducing bacteria thriving in the anaerobic zones has been demonstrated to be the most significant metal removal mechanism. The bacterial reactions involve the generation of

- sulfide ions ($S^=$), which combine with dissolved metals to precipitate sulfides, and

- bicarbonate, which has been shown to raise the pH or alkalinity of the effluent.

The sulfate reducing bacteria, which appear to function best above pH 5.5, are believed to produce sulfide ions which can in part volatize into hydrogen sulfide gas (H_2S) and bicarbonate (HCO_3^-) in accordance with the following reactions:

Hydrogen Sulfide:
$SO_4^{-2} + 2\,CH_2O + 2\,H^+ \dashrightarrow H_2S + 2\,H_2O + 2\,CO_2$,
[pH < 6.0]

Bicarbonate:
$SO_4^{-2} + 2\,CH_2O \dashrightarrow HS^- + 2\,HCO_3^- + H^+$,
[pH > 6.0]

At low pH, hydrogen sulfide gas bubbles up through the bioreactor substrate, precipitates metals as sulfides, and essentially reverses the reactions that produced the dissolved metals in the water. At higher pH values such as those observed at West Fork, the sulfide ion is in solution and available for precipitation of metals. In the case of dissolved lead, soluble sulfide ion combines to form the lead sulfide mineral galena (PbS):

$Pb^{+2} + HS^- \dashrightarrow PbS + H^+$

Testing had also shown that manganese in the anaerobic cell effluent was elevated during the startup period, but then it dropped below 1 mg/L after 40 days of operation. The results of testing also suggested that aerobic reactions would be required in order to polish the discharge from the proposed West Fork anaerobic cell for excess sulfide and for biological oxygen demand prior to discharge. Thus, a brief discussion of aerobic bacterial processes is appropriate.

The primary component of the West Fork aerobic biotreatment system, a "rock filter," re-oxygenates the anaerobic cell effluent as the water passes through the system and serves as a final aeration polishing pond. Excess dissolved sulfide is oxidized from the effluent solution ($S^{-2} + O_2 \Rightarrow SO_4$) in this step. Because the pH is above 7, the evolution of hydrogen sulfide gas is abated. The development of aerobic rock filters for removing dissolved organic matter that create biological oxygen demand (BOD) has been well established in municipal waste water treatment installations. The oxidizing of sulfide from anaerobic bioreactor effluent was documented from the West Fork Unit pilot scale biocell in a "sluice" installed downstream of the biocell. In the rock filter, photosynthesis reactions and open channel flows provide the oxygen needed to remove BOD and oxidize sulfide.

As the water passes through the rock filter, the combined effects of algal growth (especially in the zone surrounding the algae cell wall where pH is high) and the bacteria Leptothrix discophora (Robbins et al., 1997) probably precipitate most of the manganese as a black manganese oxide which coats the rocks in the rock filter. This coating is similar to the natural black coatings on rocks observed in many regional streams and ground water intersecting highway cuts throughout Reynolds County, Missouri.

Removal of manganese was projected to be required on a short term basis because its source was the substrate material in the anaerobic cells. The levels of manganese in the effluent of the pilot biocell appeared to approach influent levels after about five months of biocell operation. Removal of manganese in rock filter aerobic cells has been documented in many studies including Wildeman, et al., 1993 and Robbins, et al., 1997.

Test Methods

As with any water treatment facility, the West Fork Biotreatment system was designed by following a phased testing approach that begins in the laboratory and progresses through bench scale and pilot scale systems before sufficient data are gathered to design a full scale passive treatment system. This approach was eventually adopted after Asarco initially constructed and operated a bench scale reactor based on a preliminary design whose results showed promise. A brief history of the design process implemented at West Fork follows.

Asarco had initiated investigations into improving water quality from the West Fork Unit into the West Fork of the Black River as early as 1989. At that time, suspended solids concentrations were the prime concern and numerous test programs were undertaken to minimize suspended solids in the effluent. While improvements were realized through modifications of settling ponds prior to discharge, effluent limits on total lead in the NPDES permit issued in October, 1991 were decreased to levels below which primary settling would work. Asarco initiated investigations into biotreatment and other treatment options to meet lead limits in early 1993 (Knight Piésold, 1995).

The investigations revealed that the unique water chemistry at the West Fork site was not amenable to "standard" water treatment techniques such as pH adjustment, flocculation/settling or sodium sulfide precipitation (which should have worked) for the removal of lead to meet effluent limits. These standard treatment processes were found to be either impractical or too expensive or could not be made to work in field tests. As such, Asarco utilized its positive experiences with biotreatment at other metal mine sites to focus on a relatively new technology that was innovative and, most important, efficient, as demonstrated by two years of pilot plant performance data.

Water quality modeling using MINTEQAK software suggested that relatively small additions of sulfide under the anaerobic conditions of a biotreatment cell would achieve an effluent with acceptable limits for lead (less than 0.035 ppm). Other removal mechanisms such as lime or sodium carbonate additions did not meet the required treatment levels. Conversely, the biotreatment process is consistent with basic geochemical knowledge and was confirmed by positive pilot scale test results. It was found to be the appropriate process to use to treat West Fork's unique water quality.

Bench Scale and Laboratory Testing

Evolution of the Asarco West Fork biotreatment system design began with bench scale testing. Asarco initiated biotreatment investigations in January, 1993 with the commissioning of a bench scale "bio-tank" system that was operated until February, 1994. The bio-tank, about eight feet in diameter and four feet deep, was initially filled with "green" cow manure; this substrate material was replaced in June, 1993 with a mixture of aged cow manure and aged saw dust. The bio-tank treated up to eight liters per minute (about 2.1 gallons per minute [gpm]) of mine water until it was dismantled. The undepleted substrate was then used to inoculate a larger cell.

In anticipation of pilot scale design, laboratory testing to evaluate other substrate candidate materials was undertaken in August and September, 1993. From October through November, 1993, an evaluation of the laboratory and bio-tank performance results yielded a pilot scale system design which was approved by Asarco in November of 1993. Adverse weather prevented pilot scale construction until February, 1994.

Pilot Scale Field Testing

The pilot scale system was commissioned at an outdoor site adjacent to the mine in March, 1994; it reached design flow (20 gpm) and removal rates in about June, 1994 and operated successfully at a nominal rate of about 25 gpm with flows as high as 49 gpm providing high-end operating data until February, 1996. Several polishing-type aerobic cells were added in parallel to evaluate the removal of manganese, BOD, fecal coliforms, and sulfide removal and the enhancement of dissolved oxygen in the system effluent.

Interim bench scale studies were undertaken while the pilot system was operated. These studies evaluated startup procedures to minimize BOD, fecal coliform, color, and manganese concentrations and accelerate early removal of lead in the anaerobic cell effluent.

Data from the 24-month operation of the pilot scale bioreactor showed that the biotreatment system could consistently remove total and dissolved lead to concentrations less than 0.02 ppm, despite significant fluctuations in flow and metal loading and changes in climate (rainfall and temperature).

Large Scale Design

The large scale system was designed based on the performance of the pilot scale system and the interim bench scale studies. The large scale system was estimated to cost approximately $500,000 and require about two to three months of construction time, depending on the vagaries of weather and construction surprises. System operational costs include water quality monitoring as mandated by law. No additional costs for reagents are incurred; since the system uses gravity flow, moving parts are few and include valves, minor flow controls and monitoring devices. Based on carbon depletion rates observed in the pilot system, the anaerobic cell substrate life was projected to be greater than 30 years; the full scale biotreatment system should be virtually maintenance-free.

Should mine water quality deteriorate, the full scale design included a 50 percent safety factor. The pilot scale system was tested by operating for about 90 days at double the design capacity; compliance effluent with respect to total lead concentration and other key performance parameters resulted from this test.

Two construction sites were considered for the final system design. One site was located within the existing mine permit area, bounded by the mine/mill buildings, a pond at the toe of a tailings dam, a steep hillside, and the West Fork of the Black River, the receiving stream. This site had numerous other constraints including multiple buried utilities, a concrete-lined drainage structure which bisected the site and an above-ground liquid propane storage tank. Relocation of either of these structures was not allowed. An alternative site was located about 2,000 feet away, on the other side of the main access highway to the mine. This relatively uncluttered site consisted of open pasture land bounded by woodland on two sides, the highway, and the West Fork of the Black River. This area, while controlled by Asarco, was not within the mine permit area. Mine water to be treated would need to be pumped to this site; the pipeline would need to be bored through the highway embankment. A regional natural gas pipeline was located within the highway right of way.

After a preliminary design analysis revealed that the full scale system could fit barely within the land available adjacent to the mine/mill buildings even considering the various constraints, the alternative site was rejected to avoid additional land disturbance, permitting delays and pumping of mine effluent.

System Dimensions

The biotreatment system is composed of five major parts (Figure 3): a settling pond, two anaerobic cells, a rock filter, and an aeration pond (Knight Piésold, 1997). The system is fully lined. The design was also integrated into the mine's pre-existing fluid management system.

- A rectangular-shaped, 40 mil HDPE-lined **settling pond** has a top surface area of 32,626 square feet (0.75 acres) and a bottom surface area of 20,762 square feet (0.48 acres). The sides have slopes of 2 horizontal to 1 vertical (2H:1V). The settling pond is nominally 10 feet deep. It discharges through valves and parshall flumes into the two anaerobic cells.

- **Two anaerobic cells** are used, each with a total bottom area of about 14,935 square feet (0.34 acres) and a top area of about 20,600 square feet (0.47 acres). Each cell is lined with 40 mil HDPE and was fitted with four sets of fluid distribution pipes and three sets of fluid collection pipes, which were subsequently modified (see Start Up discussion). The distribution/collection pipes were connected to commonly-shared layers of perforated HDPE pipe and geonet materials sandwiched between layers of geofabric. This feature of the design was intended to allow control of sulfide production in hot weather by decreasing the retention time in the cell through intentional short circuiting.

  The spaces between the fluid distribution layers were filled with a mixture of composted cow manure, sawdust, inert limestone, and alfalfa, referred to hereafter as "substrate." The total thickness of substrate, piping, geonet and geofabric was about six feet. The surface of the anaerobic cells was covered with a layer of crushed limestone. Water treated in the anaerobic cells flows by gravity to a compartmentalized concrete mixing vault and thereafter to a rock filter cell. The gravity-driven flows can be directed upward or downward.

- The **rock filter** is an internally bermed, clay-lined shallow cell with a bottom area of about 63,000 square feet (1.4 acres) and a nominal depth of one foot. It is constructed on compacted fill that was

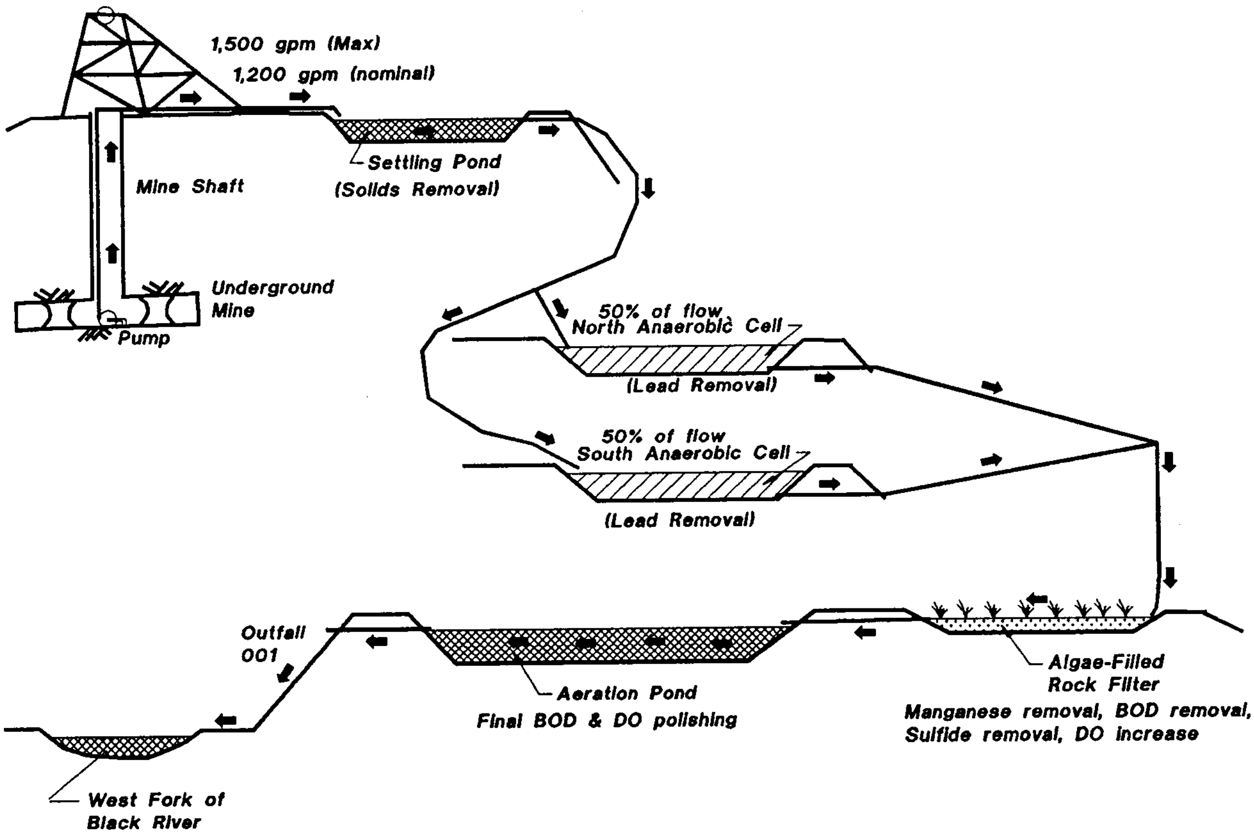

Figure 3, System Configuration

systematically placed on the west side of a pre-existing mine water settling pond. Limestone cobbles line the bottom of the cell and the cell is compartmentalized by limestone cobble berms.

- The discharge from the rock filter flows through a drop pipe spillway and buried pipe into a 40 mil HDPE lined **aeration pond**. The aeration pond surface covers approximately 85,920 square feet (2.0 acres). The aeration pond discharges through twin 12-inch HDPE pipes into a short channel that leads to monitoring outfall 001 and thence into West Fork.

After the water pumped from the underground mine enters the settling pond, all flows are by gravity.

Permitting Hurdles

The permitting aspects of the project were very complex. Regulators needed to be convinced that an organic-based wetland-type substrate could remove dissolved lead from mine effluent. Note: Missouri is known as the "Show Me" state and regulators were suspicious of a new and innovative technique that did not quite fit in established regulatory guidelines or statutes. However, regulators were willing to listen to facts and the flow of communications was good. Nevertheless, cow manure as an ingredient in the anaerobic cell substrates was a special regulatory hurdle because its use raised issues of BOD, fecal coliform bacteria and other organic-related water quality criteria problems from a non-degradation of West Fork perspective.

From a construction permit perspective, only one regulation was a problem. Missouri Department of Natural Resources (DNR) regulation 10 CSR 20-8.110 [Engineering - Reports, Plans and Specifications] is for conventional water treatment plants that remediate fecal-type wastes. This regulation was not promulgated with the concept of using manure as a construction material.

Education of permit document reviewers was a key aspect of the permitting effort, supported by the results of the two years of pilot scale test results. The original permitting application was made after gathering one year's worth of pilot data; data acquisition continued throughout the permitting process. Making the permit submittal fit the regulation requirements was somewhat akin to making a round peg fit into a square hole.

Missouri DNR raised useful and valid concerns which were addressed with additional testing, including monitoring for fecal coliform, color, BOD, and other minor constituents. This additional testing raised the level of knowledge of passive treatment performance in general and improved the database utilized in the final design.

The closure and reclamation of the biotreatment system after its scheduled decommissioning at the end of the West Fork facility life was also a DNR concern. The system was constructed within the boundaries of the waste management areas as defined by the Metallic Minerals Waste Management Act and was, by definition, a waste management structure. Therefore, closure and reclamation activities would adhere to Section 5 of the Metallic Minerals Waste Management Permit issued to Asarco's West Fork Unit in January, 1991.

The substrate material, made up primarily of sawdust, alfalfa hay, limestone and cow manure, was projected to accumulate metals over time through the operation of the water treatment system. Based on average flow and metal content of the mine water, it was estimated that the final metal loading in the substrate will be 1,866 mg/kg Pb as PbS. At the end of the active life of the biotreatment system, core samples of the substrate will be subjected to TCLP. If the substrate material fails TCLP, disposal will be in accordance with all applicable laws and regulations pertaining to characteristic hazardous waste. If the substrate passes TCLP, it will be used as an organic fertilizer to stimulate vegetation growth on the slope of a nearby tailings dam. Data from other sites have suggested that organic substrate containing metals will pass TCLP tests if it is allowed to oxidize first (McLain, 1995).

Odor control from the proposed facility was not expected to be a problem. Asarco personnel conducted a reconnaissance air quality screening study at the site with chemically activated sniffer sampling of air immediately adjacent to the operating pilot scale biotreatment plant. Hydrogen sulfide concentrations were the focus of the survey. Air quality modeling suggested that the facility would be in compliance with applicable standards.

Another point favoring its application at West Fork, the biotreatment method had been used at other Asarco facilities (in Colorado, Montana [which was issued an interim NPDES permit] and Canada) and it was accepted as a viable treatment method by agencies in other states and the USEPA. Some of the original research work into biotreatment was sponsored under the EPA's Emerging Technology Program. The following mine/mill sites are known to have included biotreatment in their record of decision:

- Clear Creek, Colorado
- Buckeye Landfill, Ohio
- Palmerton Site, Pennsylvania
- Bunker Hill, Idaho

In the cases listed above, biotreatment was the preferred alternative or a key component of the preferred alternative.

System Construction

Following permitting, the biotreatment system was constructed in accordance with plans and specifications as submitted to and approved by the Missouri Department of Natural Resources (MDNR) Water Pollution Control Program. The construction was authorized under the Construction Permit issued on March 12, 1996. Work commenced on March 13, 1996; as of July 10, 1996, the work was declared to be substantially complete in accordance with the Plans and Specifications. Wet weather delayed construction in situations requiring the installation of welded geomembrane materials. There were no change orders.

Construction management of an outside contractor was provided by an Asarco engineer and construction quality assurance was conducted by a Knight Piésold engineer. Minor field changes in the design typically improved the facility. Some of these are discussed below.

The original recipe for the substrate included aged sawdust, low-manganese limestone, aged cow manure, and alfalfa hay in decreasing proportions. As specified, the alfalfa hay was assumed to be baled. A readily-available source of slightly moldy alfalfa hay cubes was substituted as a field change. The volumetric proportions of the substrate components changed slightly (the substrate became denser) and additional sawdust was used to make up the total volumetric deficit. The addition of more organic carbon could increase projected cell life, already in excess of the required operational time.

As originally designed, the anaerobic cells would have discharged via flexible hoses into geomembrane-lined channels. These were replaced by a compartmentalized reinforced concrete vault with variable-height internal baffles. This structure in essence combined the features and intent of a specified "concrete mixing vault" with the level/flow control provided by the flexible hoses; it also took up far less space.

The construction was sequenced so that the settling pond was built and commissioned first so that the mine and mill could continue to operate during construction. Subsequently, the old settling pond was backfilled in part to become the foundation of the rock filter. The portion of the remaining settling pond was lined with HDPE geomembrane and became the aeration pond.

Start-Up Experience

Bench-scale test results suggested that the anaerobic cells be incubated with settled mine water for about 36 hours or less before fresh mine water was introduced at full flow to minimize initial levels of BOD, fecal coliform, color and manganese. For about two weeks, pumps recycled the water within the two anaerobic cells. Based on data collected in field, and subsequent laboratory confirmation, the water from the anaerobic cells was routed to the tailings pond for temporary storage. At that point, the rock filter and aeration ponds were brought on-line. In the meantime, the mine discharged according to plan through an overflow pipe from the settling pond as it had during construction of the other components. Plumbing was available to temporarily discharge to an adjacent tailings pond, if necessary, where it would be stored for later treatment and release.

After about six weeks of full scale operation, the apparent permeability of the substrate was found to be lower than expected and the system was operating nearly at capacity. The system had been designed so that either of the two anaerobic cells could accept the full flow amount on a temporary basis in case maintenance work required a complete cell shutdown.

Research found that H_2S gas, generated by the sulfate reducing bacteria, was being retained in the substrate in the anaerobic cells; this created a gas-lock situation that prevented full design flow. A temporary solution was obtained by periodic "burping" of the cells using the control valves. However, the "burping" had to be performed at 24-hour intervals and it was determined that this solution was too labor intensive.

The sulfide gas lock problem was investigated in December, 1996 by installing vent wells in the substrate and measuring the gas pressures. Observations indicated that the gas was a factor in apparent short circuiting of the water passing through the cell. The layered geotextiles, (geonet and geofabric) originally intended to promote horizontal flow, appeared to be trapping the sulfide gas beneath them and vertical flow was being restricted. The permeability of the substrate itself was for the most part unaffected. However, construction practices in the south anaerobic cell could have contributed to the situation. Here, a low ground bearing bulldozer was used to place substrate in nominal six-inch lifts. This could have created a layering effect that may have trapped gas as well. Substrate layers in the north anaerobic cell were placed in a single lift and no layering effect was observed during subsequent excavation. It is noteworthy that the mid-cell geotextiles had not been a feature of the pilot test cell design.

The first phase of a permanent solution was implemented with a trenching machine that ripped through the geonet/geofabric layers in the south anaerobic cell. This disrupted the gas-trapping situation. Subsequently, the substrate from the entire south anaerobic cell was excavated and the cell refilled without the geotextiles in June, 1997. Identical action was taken on the north anaerobic cell in September, 1997. These actions have apparently solved the gas lock problem.

Operational Results

The average influent water quality can be compared with discharge water quality (Table 1) during the June through November, 1997 period. Discharge levels of Pb and other metals were reduced substantially from average influent levels. For Pb, the level was reduced from a typical average of 0.40 mg/L to between 0.027 and 0.050 mg/L. Zn, Cd and Cu effluent concentrations were also reduced.

Conclusions

1) A practical design has been developed to bring Pb values down to stringent water quality standards.

2) Bacterial sulfate reduction is the major Pb removal process.

3) An aeration step is needed to polish for Mn, BOD, fecal coliforms removal and re-oxygenation.

4) Pilot testing should include as many features of the final design as possible to minimize start up difficulties.

5) Education of regulators on innovative water treatment techniques can facilitate permit approvals.

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Table 1. West Fork Water Quality Data

Parameter	Typical Average Influent Water Quality	Range of Water Quality Discharge (June - November 1997)
Pb	0.4	0.027 - 0.050
Zn	0.36	0.055 - 0.088
Cd	0.003	<0.002
Cu	0.037	<0.008
Oil and Grease	--	<5.0
H_2S	--	0.011 - 0.025
Total Phosphorus	--	<0.05 - 0.058
Ammonia as N	0.52	<0.050 - 0.37
Nitrate and Nitrite	2	<0.050 - 1.7
True Color	--	10 - 15
BOD	1.7	<1 - 3
Fecal Coliform	--	<1 - 2
pH	7.94	6.63 - 7.77
TSS	--	<1 - 4.2

Sources: Asarco, Inc., 1997, and Knight Piésold LLC, 1995.

Preprint 02-033

WHY DO SOME PASSIVE TREATMENT SYSTEMS FAIL WHILE OTHERS WORK?

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ABSTRACT

There are hundreds of passive treatment systems accepting mining influenced water (MIW) throughout the world. Some systems do not perform to design expectations while others, including volunteer systems, have successfully operated relatively unattended for decades. The primary reasons for this situation include the common misconceptions that (1) a "cookbook" approach to design is valid for a wide array of MIW chemistries and site conditions, and (2) low maintenance means "no maintenance." Passive treatment systems for MIW are typically manmade ecosystems that are designed to handle a specific range of metal loading conditions and MIW geochemistry. Thus, when design conditions are exceeded, the suite of microbial to macroscopic ecosystems may be slow to recover or mature. This should be no surprise to designers. But when a particular system fails, it may be inappropriately attributed to the technology, not the design. This paper presents a standard "phased" design protocol that appears to work and provides examples of sub-par performance of selected passive treatment systems.

INTRODUCTION AND BACKGROUND

Since about 1985, wetlands and bogs have been the natural method of choice of engineers for improving water quality at many mining sites, and the number of installations continues to grow. These systems rely on common geochemical reactions that result in metal and other parameter (e.g., nitrate and cyanide) reductions.

The goal of any passive treatment design is to:

- Utilize common geochemical reactions typically assisted by locally adapted microbes or plants
- Operate without power or the addition of chemical reagents, including short-term exchange of process media
- Function without human intervention for long periods (decades)

Gusek (2000) provides a more detailed background discussion on basic passive treatment system geochemistry as well as three case histories that illustrate the wide variety of conditions in which this technology has worked. For the sake of completeness, a brief discussion of how passive treatment systems immobilize dissolved metals in MIW follows.

METALS REMOVAL MECHANISMS IN PASSIVE TREATMENT SYSTEMS

Many physical, chemical, and biological mechanisms are known to occur within passive treatment systems to reduce the metal concentrations and neutralize the acidity of the incoming flow streams. Notable mechanisms include the following:

- Sulfide and carbonate precipitation catalyzed by sulfate reducing bacteria (SRB) in anaerobic zones
- Hydroxide and oxide precipitation catalyzed by bacteria in aerobic zones
- Acidity neutralization through alkaline material dissolution
- Filtering of suspended material and precipitates
- Metal uptake into live roots and leaves
- Adsorption and exchange with plant, soil, and other biological materials

Remarkably, some studies have shown that plant uptake does not contribute significantly to water quality improvements in passive treatment systems (Wildeman, et al., 1993). However, plants can replenish systems with organic material and add aesthetic appeal.

THE DESIGN PROCESS

The design of passive treatment systems is a somewhat inexact science due to the variety of water chemistries requiring treatment and the variety of materials that can be used in construction. For chemically simple coal drainage (relatively mild pH water containing iron and manganese and little or no aluminum), engineers and scientists at the former U.S. Bureau of Mines developed "cookbook" design criteria (Hedin, et al., 1994) for aerobic systems that are still being followed (sometimes inappropriately) today. Wildeman, et al., (1993) developed a phased design protocol that is appropriate for more complex acidic as well as neutral to net alkaline drainage chemistries.

These two approaches represent end points in a design philosophy continuum. The inherent danger in any "cookbook" design approach is a typical inability to properly address situations lying outside the range of conditions that were originally used to develop the standardized design criteria. The treatment of low pH water containing dissolved aluminum is especially problematic and outside the original U.S. Bureau of Mines design criteria, which addressed the issue by suggesting restrictions in the application of anoxic limestone drains (ALDs). A precise and reliable aluminum design guideline has yet to be developed for ALDs and probably should not even be considered. That is because of the complexity of aluminum chemistry. While iron can be more or less precipitated aerobically as ferric hydroxide or anaerobically as a sulfide or carbonate, the list of aluminum mineral species found in nature (and thereby possible in a passive treatment system) is extensive.

The "cookbook" design challenge represented by the individual case of aluminum is multiplied many fold when additional heavy metal contributions are considered, as may be the case for some MIW sources at metal mines. Adding the effects of varying anionic concentrations and water temperature further reinforces the futility of considering cookbook approaches to passive treatment design. Still, the design engineer must start somewhere.

The situation is not as bleak as it may sound. Mining, chemistry, and other industries have used a phased design process, probably since the dawn of engineering. The concept is simple: start small, learn from failures, and build on successes until the data required to properly design a full-scale treatment system are obtained. With that data, the risks of the full-scale system failure or less than optimum performance are significantly reduced. Wildeman, et al. (1993) proposed a design protocol that included laboratory-, bench- and pilot-scale phases. The approach has been used at over three dozen mine drainage sites.

A phased-approach design project typically begins in the laboratory with static tests, graduating to final testing phases (bench and pilot) performed at the site on the actual MIW. Bench-scale testing will determine if the treatment technology is a viable solution for the MIW and will narrow initial design variables for the field pilot. A proper bench-scale test will certainly reduce the duration of the more costly field pilot test. Field pilot test duration can range from days, to months, to years, depending on the nature of the technology. Depending on the nature of the equipment and personnel needed, significant costs may be incurred during the field pilot tests – about $500 to $1,000 per week – mostly for sampling and analysis. Compare this to $5,000-$10,000 per week for active treatment pilot tests. More detailed descriptions of testing phase activities follow.

TESTING PHASES

- Laboratory-scale Testing. This phase of testing is usually conducted in the laboratory. It might include:
  – Paste pH and redox testing of passive treatment material substrates
  – Static bottle tests to isolate and identify beneficial bacteria for a given cell type (aerobic or anaerobic)
  – Static limestone "cubitainer" tests for limestone consumption/alkalinity determination
- Bench-scale Testing. This phase of testing is typically performed in the controlled environment of a laboratory but can be conducted in the field. It is most appropriate for evaluating the dynamic response of different mixtures of organic substrates, system configurations, or metal loading rates. This level of testing should be relatively inexpensive to set up; most of the cost should be allocated to sampling and analysis. To keep costs down, bench-scale test units can be constructed with off-the-shelf items such as trash cans and kiddie wading pools, items typically found at do-it-yourself/home improvement stores and gardening centers. Once the range of dynamic variables has been narrowed, one should proceed to onsite pilot testing.
- Field Pilot-Scale Testing. This phase of testing is performed at the site, on the actual MIW. Information gathered during these tests should provide an accurate operating cost estimate as well as final capital cost data. If the field pilot study does not meet the necessary discharge standards, another treatment technology should be considered or added on. It is also important to determine the sludge characteristics during this phase. Will the sludge be hazardous or non-hazardous? Can the treatment sludge be disposed of on the mine site? Sludge management and organic substrate replacement may comprise the principle "operating" costs of a passive treatment system.

Upon completion of the field pilot test, full-scale design should take into consideration seasonal fluctuations in flow rate and seasonal fluctuations in chemical composition that may not have occurred during a shorter pilot test. Equalization ponds or tanks should be included in the design to handle these fluctuations.

It is important to note that there are two equally important aspects of full-scale passive treatment system design – bio-geochemistry and filtration. The bench and pilot test results should have yielded the conditions necessary to establish the proper bio-geochemistry or dominant geo-ecosystem in a given treatment cell to develop stable chemical precipitates. However, constructing an ideal bio-geochemical environment is a wasted effort if the metal precipitates formed are flushed out of the system because of inefficient filtration. Among other factors, this aspect of a proper system design is influenced by the grain-size distribution and compacted density of organic substrates, the settling and flocculating characteristics of the precipitates, and the retention times of the settling cells.

WHY SOME SYSTEMS FAIL

There are four major reasons why some passive treatment systems do not function as intended:

- No Design, e.g., "Just build a swamp here, fill that pond over there with manure and call it good."
- Inadequate Design. Undersized for load, applying the wrong geochemical approach, phased design lacking, complex geochemistry, improper startup and operational procedures.
- Inadequate Maintenance. (Low maintenance does not mean NO maintenance.)
- Last Minute Design Changes. Departure from well conceived construction specifications in response to field conditions can affect system performance – experience helps.

Brief discussions of these reasons follow.

Inadequate Designs

Given the wealth of technical information available in the scientific literature, it is rare to find a passive treatment system based on a "seat of the pants" design. However, without much design background, any person with a strong recollection of his or her high school chemistry can construct a system that will function successfully at some level and thus provide some proof that, yes, the concept can work in principle. This level of effort is insufficient, however, for designing a system that will work continuously for many years. Professional assistance should be sought from experienced engineers and academia to avoid frustrating failures.

Although they may be slow to admit it, professionals are not immune to failure. This is why it is prudent to:

- Experience failures and eliminate design uncertainties during laboratory, bench, and pilot testing (phased design)
- Clearly determine the range of expected metal loading (the product of flow times concentration) for the treatment situation to avoid under-sizing
- Evaluate startup procedures (being ecologically based, passive treatment systems typically should not be "turned on" at full flow; bacteria may need time to incubate or acclimate
- Develop clear operational plans and designs that allow future maintenance without total system shutdown

A success story worthy of note, the 1,200-gpm capacity West Fork system in Missouri (see Gusek, et al., 1998 and Gusek, 2000) has met stringent NPDES permit requirements for the last five years without a single violation despite experiencing minor problems. In this case, the heart of the system was two anaerobic sulfate reducing bacteria (SRB) bioreactors, plumbed in parallel (see Figure 1). Each cell was sized (based on the results of pilot testing) to accept the full flow from the mine for up to several months in case maintenance was required.

When suspended sediment from mine hoisting operations inadvertently choked the surface of the anaerobic cells (despite an intermediate settling pond), the mine elected to replace the organic substrate with fresh materials (Murphy, 2001). This was undertaken in the summer, when bacterial activity was high, by diverting all the mine flow through one of the SRB bioreactors while the other cell was being retrofitted. The mine personnel were supported in this endeavor by an "operator's manual" that accompanied the original plans and specifications; the original design consultant was not even contacted.

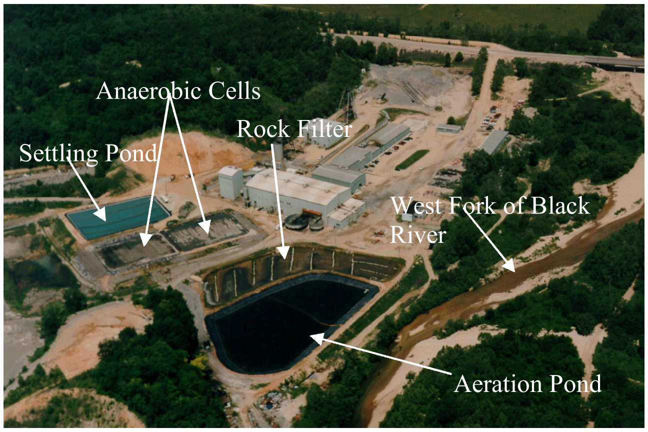

Figure 1. Aerial photo of West Fork mine passive treatment system, Missouri

Inadequate Maintenance

With minor exceptions, passive treatment systems consist of biological populations that include many suites of living things ranging from bacteria to plants. While somewhat resilient to minor, short lived changes, the biological populations in passive treatment systems cannot sustain overloading without suffering sometimes permanent damage. Overloading may not be apparent at startup. In concert with the definition of "loading" previously provided, the term "overloading" extends beyond the concept of excess flow rates (perhaps in response to storm events). It also applies to increases in metal concentration while flow remains fairly constant. Addressing this is a water management issue, solved by including surge/equalization capacity and flow controls in the system design.

Short-term changes in mineral acidity can be dealt with using limestone amendments that are periodically replenished as needed. This was a lesson that was learned at the Wheal Jane pilot system in Cornwall, England (unpublished data). An anaerobic SRB bioreactor was sized to receive flow from a series of aerobic cells (see Figure 2) that were designed based on USBM criteria to remove iron at low pH. These cells were also expected to and did remove arsenic. At the time, all flow from the aerobic cells was routed to the anaerobic cells, including direct precipitation. The prevailing thought (in 1993) was that rainfall would dilute the metals remaining and that, even at increased flow rates, the loading would stay constant. However, a number of conditions combined to overwhelm the SRB cell receiving the effluent from the aerobic cells. First, the aerobic cells were not as efficient as expected in neutralizing mineral acidity, and rainfall dilution did not significantly affect the mineral acidity of the water, a critical design parameter for SRB cells. Second, overloading occurred during the winter when SRB bacteria activity was stressed already due to the low water and air temperatures. Third, and lastly, the organic substrate did not contain any inherent buffering capacity (bench-scale tests had not been performed due to schedule restrictions). In summary, the stressed SRB were hit with an acidity overload, and there was no self-buffering component in the substrate to counter it. Consequently, the metal removal performance of the cell suffered. Fortunately, this was a pilot test, and the situation was corrected by excavating the anaerobic substrate, amending it with limestone, re-inoculating with manure, and installing a flow restriction device (orifice) on the aerobic cell outfall that helped to manage the flow peaks. The cell responded favorably and was subsequently more successful at zinc (and iron) removal.

Figure 2. Aerobic cell at the Wheal Jane Mine, Cornwall, UK

Another similar situation occurred at the Burleigh Tunnel in Colorado (EPA, 1999), but the outcome was different. This drainage typically has neutral pH and about 50 to 60 mg/L of dissolved zinc. Two pilot-scale cells, each capable of handling about 7 gpm (see Figure 3), were constructed in 1994. Like the Wheal Jane SRB cells, the Burleigh Tunnel SRB cells were exposed to a high flow/high concentration event (pH 4.1 [estimate], Zn at 109 mg/L, and flow at 20 gpm – loading was estimated to be three times the design rate) in 1995 in response to the spring snowmelt. The acidity loading also increased, and despite some self-buffering capacity of the substrate, the cells' performance suffered. Unlike the test protocol at Wheal Jane, there was no intervention response to the overloading event such as reducing the flow to allow the SRB to recover or re-inoculation with fresh SRB. Consequently, the cells limped along for another year before the test was terminated. In the view of this author, the results of this test could have been markedly different (and more positive) had some effort at system maintenance been made.

Figure 3. Burleigh Tunnel pilot-scale cell, Silver Plume, Colorado

Last Minute Design Changes

As stated earlier, a properly designed passive treatment system should be based on a phased testing program of laboratory-, bench-, and pilot-scale experiments. These experiments and the subsequent design must take into account the physical availability of some construction materials. Bench testing may have identified a superior type of organic component that the SRB favored, but it may not be available in sufficient quantities to warrant including it in the final design. Local farmers in particular are notorious for offering to give away animal manure during the testing phase of the project only to boost the price to capitalize on a captive market when large quantities need to be procured. Contractors and project owners seek relief from these situations by substituting "similar" but less expensive sources which are virtually the same. Again, the West Fork Project in Missouri provides a couple of instances where minor digression from the pilot design caused subsequent problems in the full-scale system.

As reported in more detail by Gusek (2000), the first problem related to the use of geotextile in the organic substrate column, which was 6 feet (2.9 meters) thick in both the pilot and final design. To allow better flow control/system throttling in the full-scale SRB cells during the summer, intermediate layers of perforated pipes were installed in the substrate at the 2-foot and 4-foot depths. To facilitate water collection/dispersion, the pipes were sandwiched between a layer of geonet and two layers of geotextile. Due to project scheduling, there was not time to test this concept on a pilot scale; the design change appeared to be minor. Another minor design change occurred during construction of the full-scale system. Alfalfa hay that was used in the construction of the pilot was in short supply; a source of spoiled alfalfa pellets was offered as a substitute and approved by the field engineer.

The two combined changes above had significant impacts on the ultimate hydraulic performance of the SRB cells. While the geochemical characteristics of the substrate mix met the design specifications, the physical situation caused by the changes was a significant departure from the pilot design. First, the geotextile trapped some of the gases evolved from the biological activity and created a "gas-lock" condition that restricted fluid flow through the cell. Second, the substitution of the alfalfa product in place of the baled source yielded a substrate with a slightly lower saturated permeability than that measured in the pilot. The net result was a system that was geochemically sized to temporarily treat elevated flows, but the flow restrictions prevented this design feature of the system from being used. The condition was ultimately fixed, but a valuable lesson was learned. Even minor deviations from bench- or pilot-scale configurations or design can result in major changes in system performance and should be avoided as much as possible.

SUMMARY

Passive treatment technology has been proven to be effective in a variety of geochemical, flow, and climatic situations (Gusek, 2000). However, "cookbook" design approaches should be implemented on a full-scale basis with caution; it would be more prudent to use cookbook designs as a starting point for bench- or pilot-scaled passive treatment systems. Conclusively, many system failures can be avoided by using phased testing of system designs and attention to detail during construction, operation, and maintenance.

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