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Passive Biotreatment of Mining Impacted Water:

Process Fundamentals, Project Experience, and Candidate Sites in the Bonita Peak Superfund Site

Daniel Dean and James R. Fricke
Resource Environmental Management Consultants, Inc.

Abandoned mines and the mining-impacted water (MIW) associated with them have been ubiquitous in the North American landscape for the past 150 years. The health of downstream aquatic environments is often moderately to severely impacted by low pH and high concentrations of sulfate, iron, manganese, and trace metals (e.g., arsenic, copper, cadmium, lead, selenium, thallium, zinc). Most MIW will require treatment in perpetuity as the source minerals are often impossible to isolate from infiltration of precipitation.

Most abandoned mines requiring reclamation are not associated with corporate responsible parties that can pay for treatment; therefore, treatment costs must be carried by Federal and State agencies. Active treatment of these waters requires substantial initial capital expenditure and ongoing operations and maintenance costs, including chemical reagents, high electrical demand, and continuous staffing by trained personnel. There is an evident need to treat MIW discharges with cost-efficient technologies. Passive MIW treatment systems have great potential to be deployed to such ends. The technology is under-utilized and could be applied far more broadly to mitigate the widespread environmental impacts from inactive and abandoned mines.

Figure 1. Dolores River Canyon, Rico Argentine Mine visible in center, 2012.

The capital cost differential between active chemical mine water treatment and passive biotreatment is on the order of 3:1, and annual operating costs are reduced by a factor of 10:1 or more. Unlike active treatment plants which must be operated 365 days per year, biotreatment systems can operate for weeks or months with no active input from field personnel. These systems are gravity-driven and thus have minimal need for electricity and active chemical dosing, or can often function completely off-grid in locations where conventional lime treatment or high-density sludge (HDS) systems could never work.

Good passive system designs also minimize mechanical parts, thus routine maintenance is limited to periodic maintenance such as dredging of settling basins, hydraulic maintenance, and replenishment of the organic substrate at decade-scale intervals.

Design Methodology

Over the past thirty years passive technologies have developed from field observations of natural wetlands (Huntsman, et al. 1978; Wieder and Lang 1982), to small-scale laboratory and field experiments, and finally to full-scale systems treating water in excess of 1,000 gallons per minute (gpm). Passive treatment designs typically incorporate multiple unit processes, depending on the nature of the MIW being treated and discharge requirements. This allows passive systems to remove a variety of compounds from MIW impacted waters and meet stringent discharge limits.

Passive treatment processes can generally be divided into two categories: aerobic and anaerobic. Aerobic treatment uses the oxidation of soluble ions to insoluble valence states, and is the most common historical MIW treatment. Soluble Fe(II) is oxidized to insoluble Fe(III), and soluble Mn(II) is oxidized to insoluble Mn(IV). In aerobic systems, this change in valence state prefers iron oxidation but can also be driven by both physical and biological chemistry. For instance, manganese oxidation increases at high pH (pH >9) or at neutral pH where little soluble Fe(II) is present (Rose, et al., 2003.) The impact of pH on manganese oxidation is why limestone drains were one of the first passive treatments to gain widespread use. In our experience, Mn(II) oxidation to Mn(IV) at neutral pH is typically mediated by manganese-oxidizing bacteria and even fungi.

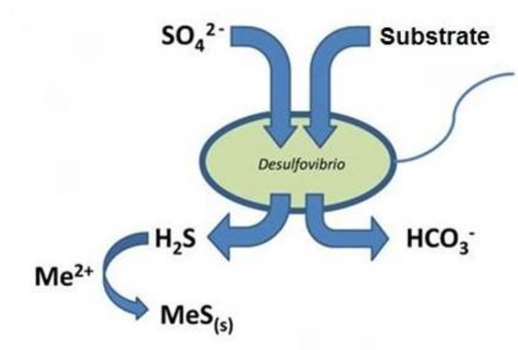

Figure 2. Metabolic pathways for anaerobic sulfate reduction and metal-sulfide precipitation (Me2+ refers to divalent metals, but monovalent metals, such as Thallium, may also be precipitated as $Me_2S_{(S)}$).

The primary anaerobic biotreatment mechanism is sulfate-reducing bacteria (SRB). SRB are obligate anaerobes whose metabolic process utilizes organic carbon and sulfate as electron donors and acceptors, respectively (Widdel 1988). The end products of this metabolic process are sulfide and bicarbonate, both of which are highly useful for treatment of contaminated mine drainage. Bicarbonate produced is capable of neutralizing moderate levels of acidity. Many heavy metals present in contaminated mine drainage readily combine with the aqueous sulfides produced by SRB to form insoluble metal sulfide precipitates, which are readily retained within a sulfate-reducing biocell and are highly stable long-term. The overall metabolic and physical-chemical processes that are used to achieve metals removal during passive MIW treatment by SRB are presented in Figure 2. In practice, sulfide production capacity has not been a limiting factor in performance of anaerobic biocells.

There are additional benefits to SRB mediated treatment of soluble metals in anaerobic treatment:

- ***Selenium Treatment*** - In cases where selenium must be removed from MIW sources, selenium may also be biologically reduced from soluble selenate ions to insoluble zero-valent selenium, and metal-selenide compounds with similar characteristics and removal rates as metal sulfides.

- ***Nitrate Removal*** - SRB biocells are also highly effective at removing nitrate.

Figure 3. SEM micrograph of sulfate-reducing bacterium.

At sites with complex water chemistry and multiple contaminants of concern, the following treatment sequence is typically employed:

Step 1 – Aeration, Iron Oxidation, and pH Adjustment
Where high Fe(II) is present, turbulent open channels or aeration cascades are effective for oxidizing Fe(II) to Fe(III). This will also strip excess CO_2 and raise pH which in turn improves Fe(II) oxidation. Where influent pH is below 5 SU, passive pH adjustment with alkaline materials (e.g., limestone, crushed concrete, steel slag) is beneficial. Stronger pH adjustment via lime dosing or similar means may also be employed, with water- and solar-powered systems available for off-grid sites.

Step 2 – Iron Precipitation and Solids Removal
Where high particulate loading is present, i.e. precipitated Fe(III) and other sources of TSS, pre-treatment via settling basins or vertical flow reactors (Blanco, et al. 2018) is required. Solids removal is critical to prevent pore clogging and loss of hydraulic conductivity in SRB biocell(s) and other downstream treatment components.

Step 3 – Anaerobic Biocell
In the anaerobic biocell, SRBs microbially reduce sulfate to sulfide, which forms insoluble metal precipitates. If selenium is present, the soluble selenate ions are reduced to selenide or elemental selenium. The biocell's organic matrix provides an organic carbon source for the SRBs and also acts as a filtration media for precipitated metals. Biocells are the main driver behind modern passive systems because they remove multiple trace metals including arsenic, cadmium, copper, lead, selenium and zinc.

Step 4 – Aeration and Polishing

An aeration cascade, aerobic wetland, or both are employed to remove residual sulfide, restore dissolved oxygen, and provide general effluent polishing prior to discharge.

Step 5 – Manganese Removal
Depending on site-specific factors, manganese removal may be accomplished in aerobic beds of solid media (limestone, other locally available rock, or plastic trickling filter media) downstream of either the settling basin or the sulfide polishing step.

Passive Treatment – Applied Knowledge

REMC has been developing passive MIW systems for over 20 years. REMC designed systems have effectively treated MIW across a range of water chemistry and flow rates, including multiple full-scale systems.

Rico Argentine Mine, Southwest Colorado

In southwest Colorado's Dolores River watershed, REMC designed a 30-gpm demonstration scale and full-scale 600 gpm hybrid aerobic-anaerobic biotreatment systems to treat drainage from the former St. Louis Tunnel. The site is located at an elevation of 8,800 feet above sea level and the two systems have

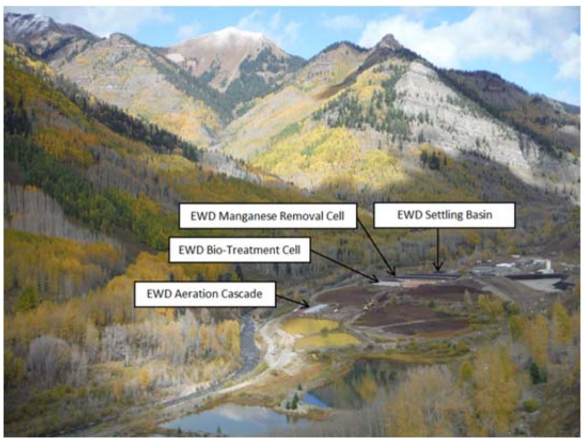

Figure 4. Annotated aerial photo of Rico Argentine EWD system, 2015.

Figure 5. Rico Argentine EWD system during construction. 2015.

been treating mine discharge water containing high concentrations of aluminum, cadmium, copper, iron, lead, nickel, manganese, and zinc since 2014 (30-gpm system, known as the CWD) and 2015 (600-gpm system, known as the EWD), respectively. The EWD system includes a settling basin, aerobic manganese removal cell, anaerobic SRB biocell, and an aeration cascade for sulfide removal and reoxygenation that encompass a total footprint of approximately 2.2 acres. The two systems have met applicable discharge standards during the vast majority of operation. In the next few years, this system is expected to be expanded significantly to accommodate the peak modeled discharge from the St. Louis Tunnel. The EWD and CWD systems combined have treated more than 750,000,000 gallons of water and the combined mass of metals removed from the St. Louis Tunnel discharge is more than 150,000 pounds.

Figure 6. Installing biocell substrate, Rico Argentine EWD system, 2015.

Viburnum Trend, Southeast Missouri

REMC's biotreatment experience began in Southeast Missouri's Viburnum Trend in the 1990's at the West Fork mine. Favorable results from laboratory-scale and pilot-scale systems culminated in construction of a 1,200 gpm full-scale system in 1996. The West Fork system was the first biotreatment system built in the United States with a design flow over 1,000 gpm. The West Fork system included a settling basin, two anaerobic SRB biocells and a polishing wetland that encompassed a total footprint of approximately 2.5 acres. The West Fork system operated until 2014 and would likely still be in operation today, but was forced to shut down when it was threatened by surface subsidence from underground mining operations. During its operation, the Missouri system was highly effective at treating high levels of cadmium, lead, nickel, zinc and nitrate with typical removal efficiencies exceeding 90%.

Figure 7. West Fork Biotreatment system, 2012.

REMC also conducted small-scale pilot testing at other Viburnum Trend facilities including the Buick mine, Viburnum 29 mine, Sweetwater mine, and Glover smelter. Flow rates for these various tests ranged from a low of thirty gallons per day to a high of ten gallons per minute. In all cases, results of these tests indicated that passive treatment systems could meet discharge criteria in the facilities' NPDES permits.

Figure 8. Buick Mine pilot testing, 2010.

Block P Mine Complex, Montana

REMC conducted a six-week off-site laboratory passive treatment test with water from the former Block P mine in Central Montana. The Block P drainage was the most challenging water REMC has attempted to treat. The water had a pH of approximately 2.5, and contained extremely high concentrations of aluminum (8,000 µg/L), copper (1,000 µg/L), cadmium (120 µg/L), iron (50,000 µg/L), lead (200 µg/L), manganese (50,000 µg/L), and zinc (30,000 µg/L). Despite the short duration, results from the Block P test indicated that passive treatment could meet applicable Montana water quality standards.

Figure 9. Block P column testing, 2013.

Pecos Mine, New Mexico

REMC conducted off-site laboratory passive treatment testing of water from low-flow seeps at the Pecos Mine in New Mexico. Results from the test indicated that passive treatment could effectively treat the seep discharge to below New Mexico water quality standards.

LESSONS LEARNED

During REMC's decades of experience with passive biotreatment we have learned several significant lessons:

- Biotreatment systems are low-maintenance compared to active treatment, ***but they are not maintenance-free***. Many well-designed biotreatment systems have failed unnecessarily due neglect.
- In REMC's experience, excess solids loading and subsequent pore clogging is the primary cause of system failure.
- Microbial ecosystems are complex. Not only are the SRB important; the system's capacity to hydrolyze cellulose is dependent on the health of fermentative microbes (Postgate 1984). SRB in typical sulfate-reducing bioreactors rely on other cellulolytic and fermenter microbes to degrade complex organic carbon compounds into simpler molecules, and SRB activity appears to be limited by the activity of these cellulose-degrading microflora (Neculita, et al. 2007).
- Sulfide production in SRB biocells remains viable at low water temperatures and at sites with severe winter weather.
- The presence of sufficient electron acceptors such as sulfate or selenate/selenite are also essential for treatment, though they are not commonly lacking in MIW.
- The functional life of the organic substrate can be extended by physically mixing it on 5-10 year intervals which restores hydraulic conductivity, disrupts preferential flow paths, and exposes unused organic carbon to the microbes.
- Regulatory acceptance of passive MIW systems has sometimes been challenging in the past, but agency attitudes have evolved considerably.
- A number of variables need to be considered before considering passive treatment for a MIW liability, including influent water quality characteristics, specific location of the discharge location or adit, hydraulic information regarding the discharge, budget and schedule requirements, regulatory requirements and responsible agencies' inputs, and others. It is important to note, however, that passive treatment systems are a viable option for many sites.

Figure 10. Buick Mine 10 gpm SRB pilot test, 2011. Note rock sitting on 2-inch ice layer. SRB biocell was producing 3 mg/L residual sulfide at water temperature of 4^{o} C and removing Zn to <100 µg/L.

Bonita Peak Candidate Sites

REMC has conducted a thorough review of MIW sources within the Bonita Peak Superfund Site. Our review indicates that the following sites are excellent candidates for installation of passive treatment systems. Candidate sites were selected based on favorable water chemistry, flow rates, and topography.

- Luck Jack Mine
- Vermillion Tunnel
- Frisco Tunnel
- Queen Ann Mine
- Tom Moore Mine
- Silver Wing Mine
- Elk Tunnel
- Mammoth Tunnel
- Big Colorado Mine
- Black Hawk Mine
- Senator Mine
- Anglo Saxon Mine
- Yukon Mine
- Auburn Mine
- Hamlet Mine
- Little Nation Mine
- Smuggler Mine
- Old Hundred Mine
- Mighty Monarch
- Green Mountain Mine
- Pride of the West Mine
- Oyama Tunnel
- Bandora
- Royal Tiger Mine

References

Blanco, I., Sapsford, D.J., Trumm, D., Pope, J., Kruse, N., Cheong, Y., MacLaughlan, H., Sinclair, E., Weber, P., Olds, W., 2018. International Trials of Vertical Flow Reactors for Coal Mine Water Treatment. Mine Water and the Environment, 37:4-17. DOI: 10.1007/s10230-017-0491-z

Huntsman, B. E., J. G. Solch, and M. D. Porter. "Utilization of Sphagnum species dominated bog for coal acid mine drainage abatement." *Abstracts, 91st Annual Meeting Geologic Society America, Ottawa, Ontario, Canada*. 1978.

Neculita, C., G. Zagury and B. Bussière. 2007. Passive Treatment of Acid Mine Drainage in Bioreactors using Sulphate-Reducing Bacteria: Critical Review and Research Needs. Journal of Environmental Quality, 36, 1-16.

Postgate, J.R. 1984. The sulfate-reducing bacteria. 2nd ed. Cambridge Univ. Press, Cambridge.

Rose, Arthur W., Brent Means, and P. J. Shah. "Methods for passive removal of manganese from acid mine drainage."*Procedings of the 24th West Virginia Surface Mine Drainage Task Force Symposium*. 2003.

Widdel, Friedrich. "Microbiology and ecology of sulfate-and sulfur-reducing bacteria." *Biology of Anaerobic Microorganisms.* (1988): 469-585.

Wieder, R. Kelman, and Gerald E. Lang. "Modification of acid mine drainage in a freshwater wetland." *Proceedings of the symposium on wetlands of the unglaciated Appalachian region*. Morgantown, WV: West Virginia University, 1982.