WHERE DOES THE RECOVERY OF METAL RESOURCES FROM PASSIVE TREATMENT SYSTEMS FIT IN SUSTAINABLE DEVELOPMENT INITIATIVES ASSOCIATED WITH LARGE MINING PROJECTS? [1]

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Test Passive treatment systems for dealing with acid mine drainage/acid rock drainage (ARD) have been shown to be more economical than hydrated lime or similar neutralizing reagent methods. However, little effort has been focused on the beneficial use of precipitated metals in these systems. The metals are usually retained in passive systems as oxides, carbonates, or sulfides – probably forming a mineral suite similar to the deposit mined. Recovery of mineral resources retained in the passive systems will probably not be as profitable as the mine itself, primarily because of the typically slow kinetics of the process. However, a market for the minerals does exist; e.g., iron oxide recovered from passive systems associated with coal mines is being recovered and processed for paint pigment and similar uses. A similar effort may be possible for the recovery of sulfides or carbonates from sulfate reducing bioreactors, an alternative passive technology.

This passive treatment situation is an obvious opportunity for sustainable development at mines, whether currently operating or approaching closure. In many instances, some amount of ARD will result no matter what prevention measures are implemented. In many cases, treatment of ARD will be required in perpetuity, along with its long-term O & M responsibilities. Developing a sustainable cottage industry of metal recovery from these systems may effectively transfer these responsibilities to a local company. Opportunities for a metal recovery business may actually transform the treatment system liability cost into an asset. Benefits include enhancement of a given mining property's profitability and increased community acceptance of the operation because it will result in sustainable employment. The mine plan may even be altered to enhance the profitability of the metal recovery effort by selective placement of wastes containing desirable metals (e.g., leaching of copper waste dumps). The question is, what does the mining industry need to do to integrate this concept into its sustainable development initiatives?

Additional Keywords: recycling, metals, beneficial uses, sulfate reducing bioreactors

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Introduction

Mining companies are under intense pressure to conduct their operations in a socially responsible and environmental sustainable manner. All major mining companies now publish annual reports on sustainable development performance, and the definition and standards of best practice in this area are advancing rapidly. However, a major challenge for most companies is translating sustainability policy into practice at the facility level. One effective way to ”translate talk into action” is to examine all major mine process activities from a sustainability perspective. That is, to evaluate each process with consideration of economic, environmental, and social risks and opportunities.

To illustrate this point, treatment systems for acid mine drainage/acid rock drainage (ARD) are examined in greater detail to consider how they can be designed and operated to maximize sustainability. ARD is a significant environmental risk at many mine sites, and treatment costs can last in perpetuity. In recent years the development and use of passive treatment technology has proven to be an efficient, cost-effective, and environmentally sustainable solution for treatment of ARD at hundreds of installations at locations around the world. Within the context of a basic description of sustainability as it relates to the mining sector, the design, operation, and long-term maintenance of ARD passive treatment systems can be managed so as to optimize long-term economic, environmental and social benefit.

Sustainability Basics

Over the past twenty years, globalization fuelled by international media coverage, has raised many questions concerning business behavior and responsibility. Today, investors, regulators, and society at large expect businesses to be managed not only for economic benefit, but also to protect the environment and to benefit the communities in which they operate. Table 1 shows some common performance measures that can now be found in annual reports of most trans-national companies.

This consideration of economics, environment (health and safety), and social performance in business is known as the “triple bottom line.”

The global mining industry suffers from a historical legacy of poor environmental performance and unfair distribution of benefits to host governments and local communities. As a consequence, the ability to gain and maintain public acceptance of a project, known as the “social license to operate,” represents one of the highest risks to project success and company reputation. This risk is greatest in economically-deprived areas, aboriginal territories, and developing countries. However modern mine developments, especially large mines, generally have good environmental performance. They can also bring significant economic benefit to their host communities through direct and indirect employment, opportunities for local suppliers, and provision of physical infrastructure. The current challenge is to ensure that economic benefits are sustainable – and last well beyond the life of the mine.

Table 1. Examples of Performance Indicators

• Market Demand • Material Quantity • Materials Pricing • Local Jobs Created • Decommissioning Cost • Net Economic Benefit	• Community Health & Safety • Local Stakeholder Engagement • Transparency, Trust • Social Acceptability • Product Stewardship	• Worker Health & Safety • Legislation • Waste Minimisation • Site Emissions • Transport • Raw Materials Use • Future Land Use • Residual Contamination

The Problem of Acid Mine/Rock Drainage

The formation of ARD is a natural process. In the presence of air, water and bacteria, sulfide minerals such as pyrite oxidize and produce sulfuric acid; concurrently, iron and other metals are released into the water. The problem can be associated with both coal and hard rock operations where previously-buried sulfide minerals are exposed to oxygen and water. There are four generally-accepted chemical reactions that drive the production of acid drainage whereby pyrite (FeS_2) is oxidized in a step-wise fashion:

1) $FeS_2\ (\text{Solid}) + 7/2\ O_2 + H_2O \rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+$
2) $Fe^{2+} + 1/4\ O_2 + H^+ \rightarrow Fe^{3+} + ½\ H_2O$
3) $Fe^{3+} + 3\ H_2O \rightarrow Fe(OH)_3 + 3\ H^+$
4) $FeS_2 + 14\ Fe^{3+} + 8\ H_2O \rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+$

Below a pH of 4.5, reaction numbers one, two and four appear to be catalyzed by the action of natural bacteria, *Thiobacillus ferrooxidans* or similar bacteria, which accelerates the pyrite oxidation process and lowers the pH even further.

Hydrogen and ferric ions catalyze the oxidation of other metal sulfides that may be present, releasing additional metals such as copper, lead, zinc and manganese into contacting waters. It appears that if the other sulfides are present and pyrite is absent, the predominance of bacteria-assisted oxidation may be usurped by chemical oxidation which may be slower, depending on the oxidation conditions present.

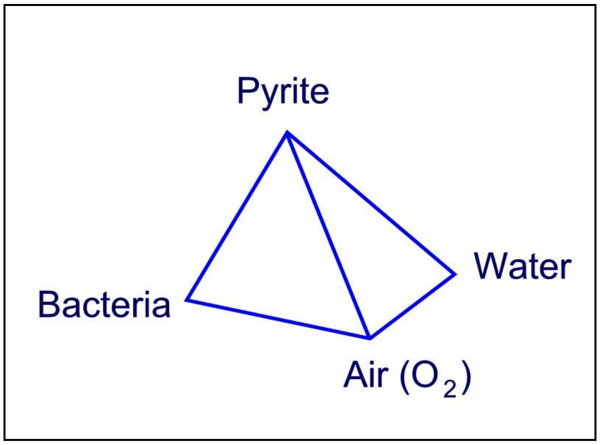

Figure 1. ARD Tetrahedron

Considered simplistically, the elementary ingredients for the formation of ARD are analogous to the components needed for the burning of combustible materials. To have a fire, one must have air, heat and a fuel source. To have ARD, one needs air, water and a pyrite source and the bacteria to speed reactions that would otherwise occur slowly: consider a "ARD Tetrahedron" concept, with each requirement at a corner (see Fig. 1). If any of the primary ingredients are missing, fire/ARD will not form. ARD prevention technology has matured in past decade through the disruption of the ARD Tetrahedron relationships (e.g., bactericides, encapsulating covers, etc.); however, despite all the ARD preventive actions implemented at a given mine site with pyrite, it is possible that some residual ARD will require long term management. This situation is ideal for implementing low-maintenance technology such as passive treatment. However, passive treatment systems are rarely "walk-away"; they typically require periodic maintenance (Gusek, 2001).

Passive Treatment Process Basics

There are many technologies for treating ARD. To properly focus the discussion, the following definition of passive treatment was proposed by Gusek (2001) :

> *Passive treatment is a process of sequentially removing metals and/or acidity in a natural-looking, man-made bio-system that capitalizes on ecological and geochemical reactions. The process requires no power and no chemicals after construction and lasts for decades with minimal human help.*

Passive treatment is typically a *sequential* process because no single treatment cell type works in every situation or with every ARD geochemistry. It is an *ecological/geochemical* process because most of the reactions (with the exception of limestone dissolution) that occur in passive treatment systems are biologically assisted. Lastly, it is a *removal* process because the system must involve the filtration or immobilization of the metal precipitates that are formed. Otherwise, they would be flushed out of the system as total suspended solids (TSS), and the degree of water quality improvement would be compromised.

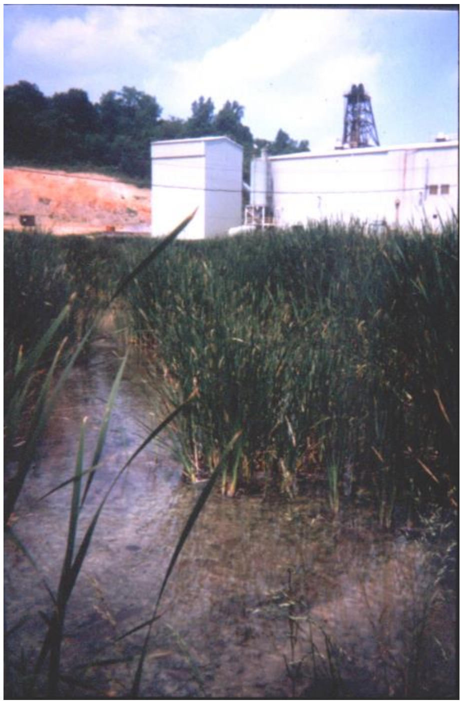

Figure 2. Aerobic Cell

There are basically two kinds of biological passive treatment cells for treating mine drainage. Aerobic cells (see Fig. 2) containing cattails and other plants are typically applicable to coal mine drainage where iron and manganese and mild acidity are problematic. Anaerobic cells or sulfate reducing bioreactors (SRBR's) (see Fig. 3) are typically applicable to metal mine drainage with high acidity and a wide range of metals. Most 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 United States. Sulfate-reducing bioreactors have tremendous potential at metal mines and coal mines but have not seen as wide an application. Other passive treatment techniques that are dominated by limestone application include (Gusek and Wildeman, 2002):

- successive alkalinity producing systems (SAPS),
- open limestone channels,
- limestone upflow ponds,
- anoxic limestone drains, and
- limestone sand placement.

The selection of a given passive treatment component will be primarily driven by the geochemistry of the ARD which often mimics the mineralogy of the mine's ore and/or waste rock suite. That is, if accessory minerals containing copper, lead, or zinc are present in the local geological formations, it is very likely that these constituents will be present in the ARD from the site. Since iron-containing pyrite is the ARD driver, dissolved iron is usually present in most ARD.

Figure 3. Sulfate Reducing Bioreactor

Metal Recovery Opportunity

Passive treatment systems are designed to accumulate metal compounds as oxides, sulfides, hydroxides, carbonates, hydroxy-sulfates, and native elements. In aerobic systems, metals (primarily iron) will typically accumulate in the intake end of the cells or whenever localized conditions favor the rapid formation of iron oxyhydroxides (see Equation 4). For example, as ARD exits an anoxic limestone drain or a SAPS and is subsequently aerated, the conditions for iron oxyhydroxide formation are satisfied. Given enough opportunity to settle and consolidate, these precipitates can be separated from the water and a clean effluent should result. As demonstrated by Hedin (2002), these iron precipitates have a beneficial use as a paint pigment reportedly superior to the iron oxides created using conventional manufacturing processes. Unfortunately, iron precipitates developed using conventional lime precipitation methods do not have a similar beneficial use because of the overabundance of gypsum in the precipitates. This problem might be surmounted if neutralizing agents other than lime were used; however, the economics of this substitution would need to be evaluated on a case by case basis.

In contrast, recovery of metals from SRBR systems does not appear to have been attempted. This is probably due to several factors, including:

- SRBR-based systems are relatively new (the oldest large-scale system at a lead mine in Missouri is less than a decade old),
- Most SRBR systems are designed to last decades before their organic substrate is depleted and needs replacement,
- Base metal prices have been relatively low, providing little economic incentive,
- The metallurgical technologies for recovering metallic compounds from organic-rich SRBR substrate have not been developed, and
- ARD prevention methods at the mine should curtail the metal loading and therefore the size of the SRBR cells.

These conditions may not always prevail at large mines. For example, base metal prices have increased lately, particularly the copper price which was $1.44 per pound ($3.17 per kg) as of early 2005. Also, SRBR cells at certain sites could also efficiently accumulate metals that might command premium prices. While not standard practice, SRBR cells are capable of accumulating silver and gold. This might provide a very economical way of handling heap leach drain-down solutions containing trace concentrations of precious metals. Metallurgical research efforts may reveal that metal recovery from SRBR substrate may be as simple as a vat-leaching process since most SRBR cells are lined with impervious geomembrane.

One design feature of SRBR cells may facilitate shorter-term recovery of metals, perhaps on a decade-long schedule. Most SRBR cells are configured as vertical flow reactors; ARD enters the cell on the top and treated water is collected from the bottom (see Fig. 4). Work by Thomas and Romanek (2002) with their limestone buffered organic substrate (LBOS) revealed that the entire organic substrate mass in a vertical flow reactor does not uniformly participate in the sulfate reduction process. Rather, a "reaction front" of metal precipitation forms at the top of the cell and migrates toward the bottom as the organic content of the substrate is consumed (see

Fig. 4). This author observed a similar phenomenon in "biopsy" data collected in several SRBR bench and pilot scale test cells.

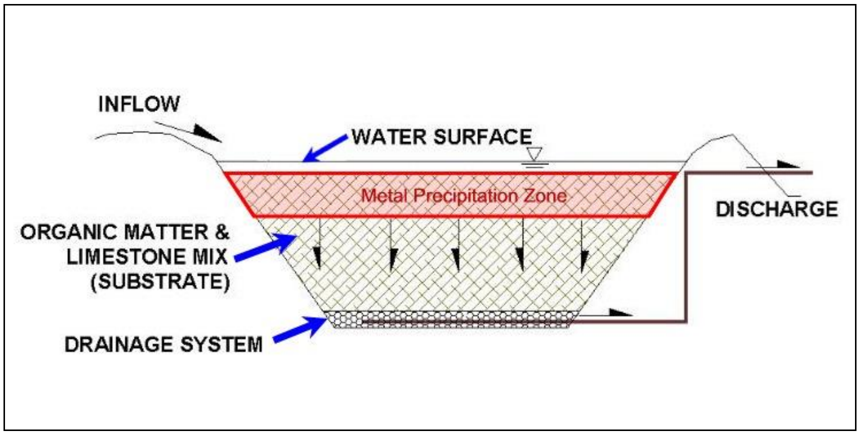

Figure 4. Schematic SRBR cross section and metal precipitation zone (which will advance downward over time)

This observation suggests that the upper zone of an SRBR cell might contain elevated elemental metal or metal sulfide concentrations to the extent that they might be economically "harvested" after only a decade of ARD processing. What this means for sustainable metal recovery operations is that multiple SRBR cell modules might be staggered operationally so that metal recovery might be less episodic.

While not unique to SRBR cells, the rate at which the mass of metal-bearing precipitates accumulate in a passive treatment system will be a direct function of the rate at which the metals are liberated from the mine waste or local geological formation. From an environmental protection perspective, mining companies typically try to reduce the metal liberation rate through ARD prevention measures that focus on the disruption of the ARD Tetrahedron (Figure 1). However, future ARD prevention policies may need to be relaxed in response to a possible economic demand for ARD "by-product resources" that could be recovered with passive treatment technology, especially if the land surface and other resources are available for passive treatment units.

The Triple Bottom Line

As previously discussed, the consideration of environment (health and safety), economics, and social performance in business is known as the "triple bottom line."

Reduced Environmental Risk

Conventional ARD treatment methods typically require the use of neutralizing agents that include caustic soda/sodium hydroxide, hydrated lime, and ammonium hydroxide. The transport, storage and use of these corrosive chemicals at a closed mine site whose infrastructure has been down-sized presents an increased environmental risk. Site access roads may not receive the maintenance they traditionally received while the mine was open; site remoteness may preclude delivery of neutralizing chemicals as frequently needed, and highly-trained personnel may no longer be living in the vicinity. Passive treatment systems by their nature reduce environmental risk; they are designed to operate unattended for long periods. Properly designed systems can achieve metal removal efficiencies above 99 percent, similar to conventional water treatment systems, without the hazardous chemicals.

This aspect of passive ARD treatment lends itself well to reduced environmental risk to workers who might be involved in metal recovery as part of a sustainable business, within limits. If the untreated ARD contains parameters that might be hazardous to human health, e.g., arsenic, cadmium, uranium, chromium, lead, mercury, selenium, then the metal precipitates in the passive treatment system will also contain these elements. However, the metallic *species* that are precipitated are more likely to be chemically stable and less biologically available. For example, lead would probably precipitate as the relatively insoluble sulfide, the mineral *galena*. Mercury would probably form as the sulfide HgS, the mineral *cinnabar*. These solid mineral phases are less geochemically mobile and are less likely to be toxic to workers in casual contact with the precipitates. However, these metals will certainly restrict the metallurgical processes employed in sustainable resource recovery.

In a third world country, incineration of copper-bearing organic substrate might be a "low-tech" recovery method of high grade native copper. However, if the substrate contained mercury or arsenic, such a process would be unthinkable because of volatizing of these elements at incineration temperatures. It will be important for metal recovery workers to understand the hazards (if any); sustainable metal recovery may not be practical in every situation.

Indeed, the long term sustainable business at a given closed site might not be metal recovery for recycling purposes per se, but the proper management of the relatively benign metallic residues from passive treatment that need to be isolated from the environment.

Economic Benefits

Passive treatment has been shown to be more economical than typical active treatment approaches that use hydrated lime or other neutralizing agents. Passive treatment capital costs are approximately the same or less than conventional treatment but operating/maintenance costs are a fraction of conventional treatment. These factors combine to yield life-cycle passive costs of about half that estimated for conventional treatment (Gusek, 1995).

Furthermore, studies suggest that a significant amount of resource will be retained within mature treatment system systems over time. To date, little effort has been directed to the economic value associated with recovery of the metals. Mature passive systems could have metal concentrations many times the original ore grade at the mine. While the quantity of metals may not be attractive to a large mining company, a small local company might find the steady accumulation of metals to be a reliable and sustainable source of income. Thus, metals recovery transforms the treatment system liability cost into an asset.

The authors are aware of a commercial enterprise that recovers and processes iron oxide from ARD passive treatment systems and sells the product as a pigment stock for use in paints and coatings, cement-based products, plastics, paper, and mulch. (see www.environoxide.com). A similar effort may be possible for the recovery of sulfides or carbonates from sulfate-reducing bioreactors as previously discussed. While the base metals retained within the bioreactors may not generate attractive returns, precious and rare trace metals might find competitive local markets.

For example, a passive treatment system that receives a flow of 100 US gallons per minute (0.38 cubic meters per minute) of water containing 21 mg/L of dissolved copper would accumulate 138 short tons (125,400 kg) of copper over a span of 30 years. At 2005 metals prices, this is a revenue of about US$ 400,000 or $ US 13,240 per annum. This would just be from copper recovery; if additional metals such as gold, silver, iron, and zinc were recovered, the estimate would be higher. In a third world country, this kind of revenue might be a substantial sum. However, the organic substrate replacement and processing costs would need to be deducted from the revenue to get a clearer indication of the metal recovery process economics. Several economic examples are subsequently discussed.

Social Benefit

Sustainable community benefits are greatest where the mine and the community work together from the earliest stages of the project to promote planned community development. Mining companies can provide not only capital for physical development, but also knowledge and skills to promote development of local 'social capital'. This knowledge transfer can apply to technical training and business management. Successful community development may begin with direct employment, and develop through provision of goods and services by local companies, to outsourcing. Numerous economic studies, including one by the World Bank & IFC (2002), have shown that non-mine employment generated through multiplier effects is often much higher than direct mine employment.

So how can this be applied to development and operation of passive treatment systems? If we assume, as described above that a passive treatment system is being designed with a view to its potential for long-term metals recovery, then this can form a component of a community development program. Such a program might have an objective of developing a community-based company to which the construction, monitoring and maintenance, and metals recovery could be outsourced. Financial agreements for metals recovery are logically agreed to as part of the initial negotiations concerning revenue sharing. Similarly, funding arrangements for seed capital and asset purchase should also be considered at this early stage.

During the design stage of the project, community input could be sought, as appropriate, concerning beneficial placement, configuration and access to cells for long-term use, as well as local source(s) suppliers and compensation for organic matter. The mine plan may be altered to enhance the profitability of the metal recovery effort by selective placement of wastes containing desirable metals (e.g., copper) than might normally be dispersed. Many operations already follow this approach with the creation of "low-grade" dumps that might be leached at some future date.

Construction, operation and monitoring of the system then forms the basis of the "apprenticeship" for key technical skills and for selection and training of future business managers. The business model encompassed in the community plan will dictate the method by which this occurs. For example, this training may be provided to employees who will eventually transition out of the company. Alternatively, the plan may call for a joint venture arrangement from the initial stages of development. In some cases, there may be a tri-partite agreement between the mine, the community, and local government. There are many possible configurations. However the objective of the plan is to see the transition of skills, knowledge, and responsibility over the active period of the mining operation.

During post-closure there will be revenues generated through ongoing monitoring and maintenance of the treatment facility, and ultimately metals recovery and re-configuration of the cells. In many parts of the world, there is a clustering of mine sites around a deposit. Consequently there is the potential for growth of locally owned and managed companies to service mines on a regional basis.

Hypothetical Sustainable Passive Treatment Scenarios

For the purposes of discussion, two hypothetical passive treatment scenarios are considered. One is a hypothetical coal mine with typical acidic drainage from an adit, the other is a metal mine with drainage from a reclaimed mine waste dump. The baseline economics assume 2005 prices and USA construction costs without inflation effects.

High labor costs can be an economic deterrent to implementing metal recovery projects. Because passive treatment technology can be considered “low-tech”, a skilled labor pool is not necessary for metal recovery projects. Indeed, the chances of successfully implementing this technology in a world-wide setting are improved by assuming that a pool of inexperienced labor is available either from:

- a depressed local economy,
- a nearby prison facility with low security risk inmates, or
- social programs supported by local government(s).

For the purposes of the following economic analyses, it is assumed that inexperienced laborers are available within a reasonable distance of the ARD sources.

Coal Mine Setting

This underground coal mine was described in detail by Hedin in 2002 and it is used as an example where iron oxide might be economically recovered. The abandoned mine is completely flooded and is discharging about 1,550 to 1,850 gallons per minute (6 to 7 cubic meters per minute) of acidic drainage with the characteristics show in Table 2.

Table 2. Average characteristics of the coal mine discharge

Period	Flow (gpm [m^3/min])	pH (su)	Alkalinity (mg/L $CaCO_3$)	Net Acidity (mg/L $CaCO_3$)	Fe (mg/L)	Sulfate (mg/L)
1973-75	1,849 [7.0]	5.7	185	108	196	2,425
2001	1,554 [5.9]	6.3	320	-176	79	1,410

The alkalinity of the mine drainage is high enough to provide net alkalinity so an anoxic limestone drain or other alkalinity-enhancing cell is not required. Manganese removal is not an issue. According to Hedin (2002), the predominant iron mineral precipitated is *Goethite* (FeOOH).

Under these conditions, an average 600,000 pounds (272,230 kg) of dissolved iron will precipitate annually. The construction cost of an aerobic passive system to remedy this situation (assuming the 2001 chemistry) is about US$ 677,000 using the baseline economics in the computer software program AMD Treat (OSMRE, 2002) with the one modification of assuming that "organic matter" is replaced by salvaged topsoil for the same cost as "excavation". The total footprint of the passive system would be about 23.6 acres (9.6 ha) based on an iron removal rate of 11 grams per day per square meter of aerobic wetland surface area and a 24-hour detention pond. Conservatively assuming a 30-year system lifespan, the unamortized cost of the iron is about US$ 75.22 per short ton of iron recovered or US$ 46.15 per short ton of *Goethite*. This value does not include the cost of recovering and processing the *Goethite*-iron precipitate.

Hedin (2002) describes the challenges met in processing the raw iron precipitate; 2,000 tons of iron bearing sludge were removed and processed in a demonstration project. Hedin reported that:

> The sludge was pumped to screens where large debris were removed and then dewatered using two frame filter presses. Screening removed vegetative debris, litter, and coal refuse. Dewatering increased the solids content of the product from 25-30% (in place sludge) to 48-52%. A total of 1,000 tons of product were trucked to a pigment manufacturer where it was further dried, calcined, and milled.

The drying and processing reduced the precipitate mass to about half of its natural state. Hedin (2002) further reported that processing costs in the demonstration was about US$ 500 per dry ton while the market for mined Goethite cited prices in the range of US$ 100 to US$ 300 per dry ton. Hedin suggests that passively-recovered Goethite could be recovered in the range on from US$200 to US$300 per short ton (US$ 0.22 to 0.33 per kg) if the passive system was designed to facilitate metal recovery operations and an effective method of removing organic detritus from the final product was developed.

In the hypothetical case study, it is assumed that the ferric hydroxide would accumulate in a settling pond that is cleaned out every two years to yield 600 dry tons (545,500 kg) of iron sludge. This requires further processing to remove detritus and to produce a saleable product as a natural dye for a local fabric mill. This application is not far-fetched; attendees at a recent ASMR conference were able to purchase T-shirts dyed with "yellow boy". The site is assumed to be located in a third-world country. Processing is accomplished by mostly unskilled manual labor (in drying beds, homemade kilns, and primitive processing) reducing the processing cost to 25% of that suggested by Hedin (2002). This also results in some losses; it is assumed that about 80 percent of the original precipitate mass is recovered.

Local markets will naturally drive the market price of the dye, but for the sake of simplicity, it is assumed that the price is on the low end (US$100 per dry ton or US$ 0.11 per kg) of the range reported by Hedin.

At the values shown in Table 3, the profit expected every two years from an episodic metal recovery event depends on whether or not amortization of the passive treatment system is included in the calculation. Assuming that the mining company originally responsible for the mine's operation paid for constructing the passive treatment system and it provides a nominal fund for periodic maintenance, a local company could theoretically return a modest profit and the treatment system's function could probably be maintained indefinitely. Considering current US economic conditions, US$ 9,000 in annual profit may be little incentive to support such an operation. However, in many foreign economies, this could represent a significant cash flow as well as providing a local source steady employment.

Table 3. Iron precipitate unit recovery economics

Economic Parameter	**Per Dry Short Ton of *Goethite* Recovered**	**Per Kilogram**	**Per Cleanout Event (80% recovered)**
System Amortization	US$ 57.70	US$ 0.063	US$ 27,700
Processing Costs by Hedin (2002)	US$ 250 (avg)	US$ 0.275	-
Hypothetical Processing Cost with Inexpensive Labor (25% of Hedin)	US$ 62.50	US$ 0.069	US$ 30,000
Total Cost – Processing & Amort.	US$ 120.20	US$ 0.132	US$ 57,700
Sale Price	US$ 100.00	US$ 0.11	US$ 48,000
Profit with amortization cost	(US$ 20.20)		(US$ 9,700)
Profit without amortization cost	**US$ 37.50**		**US$ 18,000**

Metal Mine Setting

This hypothetical surface copper mine is located in a rainy climate that receives 2.0 meters (6.5 feet) of rainfall per annum. It was closed decades ago; waste rock dumps cover about 300 acres (121 ha) with enough of a soil cover to support healthy vegetation. About 50 percent of the rainfall runs off but the remaining 50 percent infiltrates into the mine waste, recreating ARD that reports to a pre-existing under-drainage system. The flow from the toe of the waste dumps is collected at a single point and routed through one of the mine's solution holding ponds, a remnant of a dump leaching operation.

The average discharge rate from the holding pond is about 583 gallons per minute (2.2 cubic meters per minute) of acidic drainage with the characteristics show in Table 4.

Table 4. Average characteristics of the metal mine discharge

Flow (gpm [m^3/min])	**pH (su)**	**Fe (mg/L)**	**Cu (mg/L)**	**Zn (mg/L)**	**Ag (mg/L)**	**Sulfate (mg/L)**
583 [2.2]	3.0	188	21	69	0.005	1,425

Fortunately, there is no arsenic, mercury, or other hazardous constituent in the metal mine drainage. Mass calculations suggest that this condition could persist for centuries.

Under these conditions, a sulfate reducing bioreactor (SRBR) passive treatment system would be the most appropriate method of remedying the situation since the mine infrastructure (including the electric power grid) will be dismantled.

The construction cost of an SRBR passive system at this site is about US$ 5 million using typical economics suggested by Gusek (1995) with adjustments to 2005 unit prices of construction. The total footprint of the passive system would be about 23.5 acres (9.5 ha) of which 92 percent would be occupied by the SRBR cells (three planned) and the remainder of the land would be used for an aerobic polishing wetland. A sketch of the layout is shown in Fig. 5.

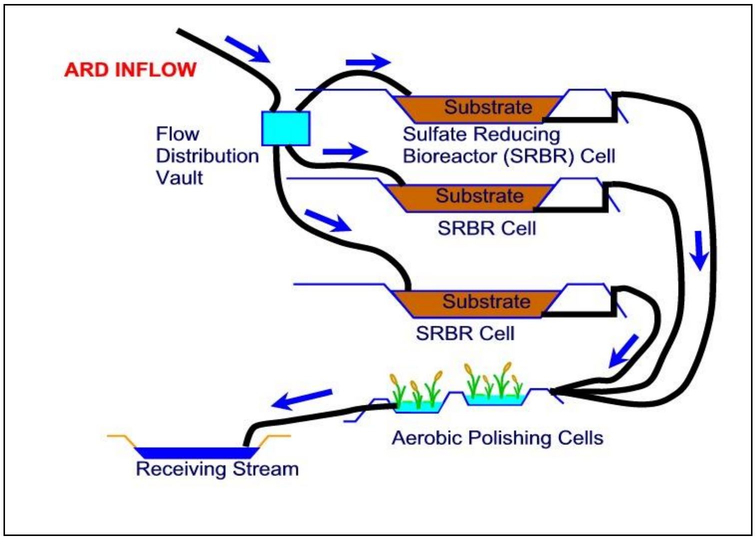

Figure 5. Sulfate reducing bioreactor system layout

The organic substrate in the three SRBR cells would be a homogeneous mixture composed of wood chips, rice straw, sugar cane processing waste, with crushed limestone or coral. The sulfate reducing bacteria would be manure obtained from local dairy farmers. All of these materials are available locally and are part of the sustainable local economy. Based on data from bench and pilot system tests conducted at the end of the mine's productive life, the substrate is projected to have a longevity of about 30 years before it organic and limestone fractions are completely consumed. The three cells were sequentially commissioned in a way that allowed each to be decommissioned and the metals recovered on a ten-year cycle; one of the cells was started a decade before the mine officially closed. In addition to the bench and pilot testing, the metallurgists at the mine developed a simple site-specific process flow sheet for recovering the metals from the organic substrate.

The metallurgists determined that with the addition of fresh limestone and organic matter, the metal-rich substrate could be roasted in a simple furnace arrangement. The fine limestone would scrub the sulfur from the stack gas similar to fluidized bed reactor behavior in coal-fired power plants. This process would produce a metal-oxide-rich concentrate suitable for shipment to a smelter. This roaster concentrate might be further processed, perhaps using simple wet gravity separation methods, to produce an enriched product. *(Author's note: it is emphasized that metal recovery from SRBR substrate has not apparently been attempted; the hypothetical process cited above is only conjecture at this time).*

To simplify the forthcoming economic analysis, it is assumed that the roaster concentrate would be commingled with concentrates from active mining and milling operations controlled by the same company that originally owned the closed mine being considered in this example. As such, it is assumed that smelter penalties and other fees would be waived and the sustainable metal recovery company would receive the current market prices for the metals in their typically traded forms.

It is assumed that the metal "harvesting" process implemented every ten years in a rotating fashion recovers 90 percent of the dissolved metal load that the passive treatment system receives. Table 6 below summarizes these amounts that are subsequently used in the economic analysis. No revenue is derived from the iron recovered.

Table 6. Metal mine recovery amounts and revenue

Metal Recovered	**Total 30 Yr. Load (1)**	**Recovered @90% Per Cleanout Event(1)**	**Price Per Short Ton (2) or Per Gram(3)**	**Revenue Per Cleanout**
Iron	7,200 (6.5 MM)	2,160 (2.0 MM)	$0.00	-
Copper	724 (0.7 MM)	241 (0.22 MM)	$2,900(2)	US$ 700,000
Zinc	2,380 (2.2 MM)	793 (0.72 MM)	$1,200(2)	US$ 950,000
Silver	0.172 (157)	0.06 (52)	$211.50 (3)	US$ 11,050,000
Total				**$12,700,000**

[1] short tons (kg)

A typical cleanout event would only involve replacement of the organic substrate which comprises about 18 percent of the total construction cost. Liners, piping, earthwork, and other system components should last indefinitely. It is assumed that excavating and processing of the organic substrate to recover the metals is equal to the cost of replacing it. Thus, the cost of every cleanout event every ten years (only 33% of the substrate would be processed) would be 12 percent (18% x 2 x 0.33) of the total construction cost of US$ 5 million or US$ 600,000. Due to the economic uncertainty of metal recovery costs, no discounting for labor in foreign economies is included. However, similar to the coal mine example, it is assumed that 33 percent of the total system construction is amortized per cleanout event.

As shown in Table 7, the profit potential is very sensitive to silver recovery even with silver concentrations in the ARD of only 5 parts per billion. This suggests that this technology might be more appropriate at closed precious metal operations than base metal operations. Regardless, the economics are more favorable than those shown for the coal mine example and should be a clear incentive to mining companies to investigate this technology.

Table 7. Metal mine unit recovery economics

Economic Parameter	Per Cleanout Event
System Amortization	US$ 1,665,000
Processing Costs	US$ 600,000
Total Cost – Processing & Amort.	US$ 2,265,000
Revenue without silver	US$ 1,650,000
Revenue with silver	US$ 12,700,000
Profit with system amortization & silver revenue	**US$ 10.435 million**
Profit without system amortization and without silver	**US$ 1.05 million**

Closing Remarks

It appears that the triple bottom line of mining companies has the potential to be markedly improved by recovering metals from passive treatment systems at closed mines. This assertion is especially applicable to mining companies with trace amounts of precious metals in the final drainage solutions. One could even envision the long-term management of mine wastes to preserve the chemistry of the ARD to sustain the metal recovery operations. This technical avenue is a real opportunity to become a positive agent of change in developing areas through contribution of skills, knowledge, and capital to sustainable community development. The cases presented in this paper are hypothetical but there are analogous success stories in other industries where embracing sustainable situations has resulted in a win-win for communities and companies alike.

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