PASSIVE MANAGEMENT OF MINING INFLUENCED WATER AT THE HAILE GOLD MINE, SC[1]

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Abstract: An engineered passive system was constructed to address the long-term post closure management of mining influenced water (MIW) from a backfilled open pit and two capped heap leach pads. The system design includes a sulfate reducing bioreactor (SRBR) which uses natural microbial processes to remove heavy metals and adjust pH. The MIW is first routed through two SRBRs, plumbed in parallel; the flow from the two SRBRs is subsequently polished in an aerobic free water surface wetland. The system was designed based on experience gained from operating a pilot-scale system and bench tests.

Since its completion in 2005, the system is working as designed and its effluent is meeting design goals. However, one of the SRBR cells is behaving differently from the other. The difference is suspected to be the proliferation of willow vegetation on the surface of one cell. With the recent spike in precious metals prices, plans to reopen the Haile Gold Mine are moving forward. If this occurs, the SRBRs would be decommissioned to allow the mining of ground beneath them. The unit cost of treating MIW at this site for 4.5 years was about \$3.71/m^3 and it continues to drop as maintenance is virtually nil.

Additional Key Words: precious metals, heavy metals, biochemical reactors, sulfate reduction, case history

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Introduction

The Haile Mine site is located in Lancaster County, South Carolina, approximately three miles north of Kershaw in the north central part of the state (Fig. 1). Gold has been mined in the region since the early 1800s. With its history dating back to 1827, the Haile Mine is the second oldest significant gold mine in the southeastern United States. Historic mining began with the recovery of placer gold from the gravel deposits of Haile Gold Mine Creek and advanced into small open pits during the 1830s and 1840s. Haile produced sulfur for explosives and medicines during the civil war until portions of the mine buildings were burned to the ground in 1865 by Union forces under General Sherman's command. Intermittent gold mining continued from 1870 through 1942, at which time open pits were expanded and localized underground workings were developed. (Golder, 2004).

Figure 1. Location of Haile Mine, South Carolina, USA

Modern open pit mining and heap leach gold recovery resumed in 1984 and ceased in 1992. Since then, various site reclamation activities have successfully reclaimed both modern facilities and historic mining features that predate the first modern-day production in 1985. These reclamation/closure activities include backfilling depleted open pits and capping rock dumps. However, the mine may yet re-open in response to a spike in metals prices and the results of an on-going exploration program undertaken by its current owner, Romarco Minerals Inc. (Romarco) based in Toronto, Canada. Current mining plans include developing potential gold reserves directly beneath the passive treatment system which would result in its decommissioning and dismantling.

Following the latest episode of site closure work, mining influenced water (MIW) requiring treatment originated from three sources (see Fig. 2):

- A backfilled and capped Chase Hill open pit with drainage of about 19 liters per minute (L/min) [5 gpm],
- The closed South Heap Leach Pad (South Pad), which was capped in 2000, with an MIW flow ranging from 0.15 L/m (0.04 gpm) to about 1.9 L/m (0.5 gpm), and
- The closed Chase Hill Pad was re-graded and capped with compacted clay in 1999 which was upgraded to a geomembrane system in 2005. A peak MIW flow of 0.76 L/min (0.2 gpm) or less and periods of near zero flow associated with dry periods is expected.

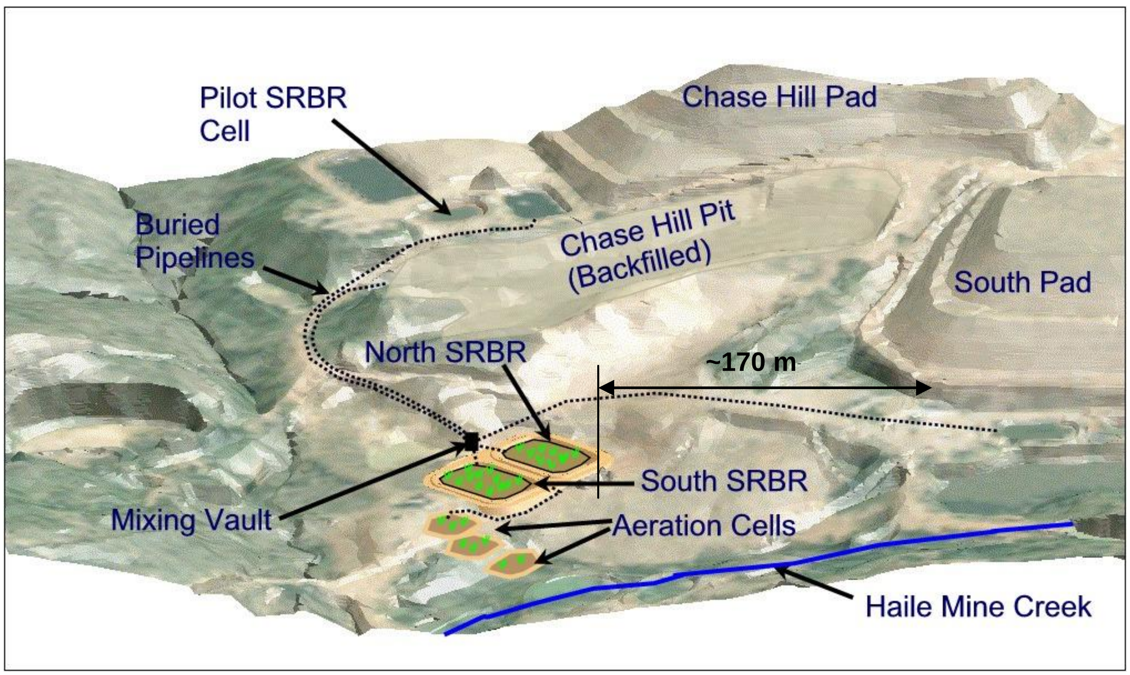

Figure 2. Proximity of Reclaimed Mining Areas in Relation to As-built SRBR System Layout

The MIW from these three closed facilities drains by gravity through buried pipelines and commingles prior to entering an engineered passive sulfate reducing bioreactor (SRBR) system whose design was based on bench and pilot scale tests. The peak MIW flow rate from the three closed facilities was expected to be approximately 23 L/min (6 gpm). The actual combined flow rates for the past five years have varied from 12.1 to28.4 L/min, averaging 21.2 L/min (5.6 gpm).

The passive SRBR system was designed to produce water that is consistent with overall site closure plans. Note that the passive SRBR system is not a "stand-alone" closure technique, but rather an integral component of the overall site closure water management plan to achieve minimized flows from capped and closed facilities.

Water Quality and Quantity

The water quality of flows from the Chase Hill Pit, Chase Hill Pad, and South Pad is shown in Table 1; flow rates vary among the water sources. Table 1 also presents the projected values for selected water quality parameters after mixing the three sources into a combined water sample. These estimated values were based on a weighted-average calculation. The individual weighting was proportional to the projected flow rate from the given MIW source. The actual combined concentrations of the various parameters in Table 1 reflect the beneficial effects of implementing acidic MIW prevention measures such as capping of net acidic mine wastes and

Table 1. Individual and Combined Chemistry of Closed Haile Site MIW– Projected & Actual

Parameter	Closed South Pad	Closed Chase Hill Pit	Closed Chase Hill Pad	Estimated Combined Flow into SRBR System	Actual Combined Influent Chemistry (4.5 yr average)
Flow, L/min	1.9	18.9	0.76	22	22.1
Flow, gpm	0.5	5.0	0.2	5.7	5.6
pH	4.9	3.65	2.0	3.3	3.4
Fe, mg/L	1,290	60	11,000	552	96
Cu, mg/L	2.00	0.3	18	1.1	0.22
Zn, mg/L	2.4	0.5	37	1.9	1.8
As, mg/L	0.0	0.0	100	3.5	0.09
Ni, mg/L	2.3	0.16	16.7	0.9	No data
Co, mg/L	0.0	0.0	13.30	0.5	No data
Al, mg/L	539	17	1,700	122	24.7
Mn, mg/L	-	-	-	5.9	2.8
Sulfate mg/L	30,000	750	30,000	4,342	554
Acidity mg/L	6,830	195	35,000	1,998	387
Alkalinity mg/L	0	0	0	0	0

backfilling pits. Updated data from individual MIW sources is not available but it is suspected that the mass contribution from the Chase Hill Pad was significantly reduced when a geomembrane cap was installed over it, coincidentally completed when the passive treatment system was commissioned.

System Layout

Design of the passive SRBR system was based on the performance of a 2.5 year pilot-scale test and was further supported by two supplemental bench-scale studies. The design was developed in accordance with established engineering protocols; the construction was authorized under the Construction Permit 18,873-IW issued on June 15, 2004 by the South Carolina Department of Environmental Control.

A schematic of the system is provided on Fig. 3. Note that the vegetation drawn on the surfaces of the two SRBRs is slightly different in Fig. 3. The South SRBR plant community is

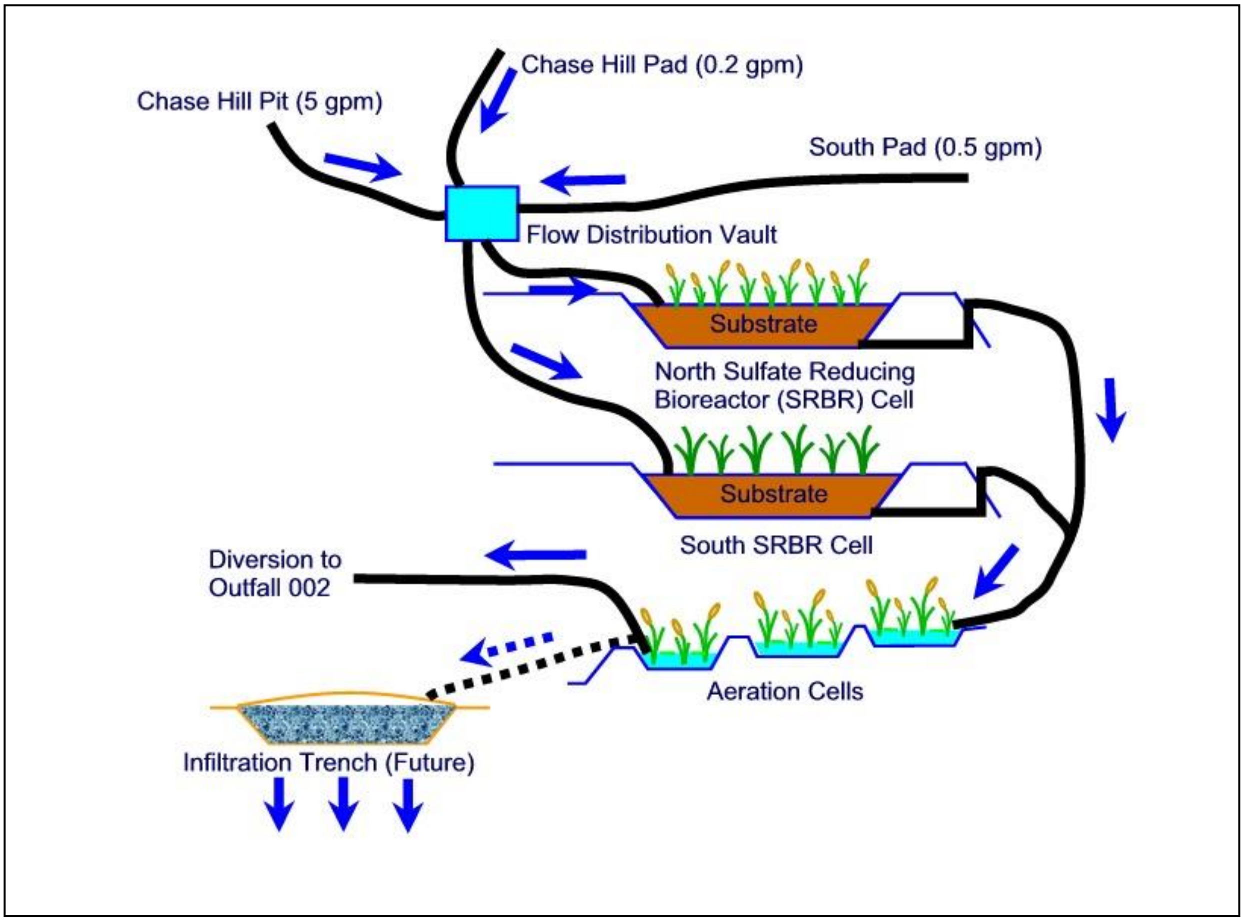

Figure 3. System Schematic Layout

dominated by willows (*salix*); the North SRBR plant community appears to be dominated by cattails (*typha*). These supposedly minor differences may account for significant variations in the relative performance of the two SRBRs. The colonization by neither of these two plant communities was intentional; their establishment occurred on a volunteer basis.

The pilot sulfate reducing bioreactor (SRBR) cell test results (Golder, 2004) demonstrated that the system has resiliency during extended periods of overloading. In the 4.5 years of actual operation, the system does not appear to have been exposed to overloading conditions. If anything, the system appears to be under-loaded with respect to its design conditions as suggested in Table 1 and subsequent performance data.

Sulfate Reducing Bioreactor Design

The design objectives of the SRBR cells included accommodating and managing about 22.7 L/min (6 gpm) of combined MIW flow, operating continually without pumps and allowing periodic (multiple decade) major maintenance operations. The SRBR cell design criteria were established in bench- and pilot-scale tests. These include satisfying a volumetric metal loading factor of 0.3 moles of metal loading per day per cubic meter of organic substrate (Wildeman et al., 1993), and a bottom area hydraulic loading factor of about 87.2 m^2 per L/min (3,550 square feet per gpm) of flow based on the findings of bench and pilot studies (Golder, 2004). Installing just 0.915 m (3 ft) of organic substrate would have satisfied the metal loading design criteria. To be conservative and to prolong the interval between major SRBR retrofitting/substrate replacement, the actual installed organic substrate thickness was 1.68 m (5.5 ft). Thus, if the design water chemistry and design flow rates were maintained, the volumetric loading "as-built" would be about 0.16 moles of metal/day/m^3. Design issues typically included in SRBR based systems are discussed in Gusek (2002).

The ratio of components in the organic substrate mixture as cited in Golder, 2004 was changed just prior to construction in response to localized procurement shortages. The final substrate mixture is provided in Table 2.

To minimize earthwork, provide for future maintenance, and conform to the existing surface contours at the proposed site, the SRBR treatment capacity required was allocated equally between two individual cells which were subsequently operated in parallel. Each cell was designed to accommodate a nominal flow of 11.4 L/min (3 gpm); however, as demonstrated in the pilot test program, each cell could handle as much as three times that MIW flow for an extended period with a small decrease in removal efficiency.

Table 2. As-Installed Organic Substrate Mixture

Material	Cubic Meters		Mixing Ratio
Aged Chipped Wood	184	or	20 buckets at $9.2m^3$/bucket
Manure	9	or	1 bucket at $9.2m^3$/bucket
Agricultural Limestone	14	or	6 buckets at $2.3m^3$/bucket
Hay / Alfalfa (bale)	21 bales	or	At 309 kg (680 lbs) per bale

Flow through the SRBR cells was arranged to be by gravity from top to bottom. The cells were lined with 60 mil thick LLDPE geomembrane. Under typical operating conditions, the organic substrate would be completely submerged beneath a standing pool of water, similar to the operation of the pilot cell.

The water exiting from both SRBR cells is commingled in a buried pipe and conveyed to the uppermost portion of an aerobic polishing cell (APC). The APC receive treated effluent from the two SRBR cells. Their primary purpose is to:

- provide re-oxygenation,
- remove any remaining dissolved ferrous iron, and
- remove a minor loading stream of dissolved manganese (about 2.8 mg/L)

The APC delivery pipe terminus was equipped with an upturned 90-degree elbow to preclude small animal incursions. The peak flow, ranging from 12.1 to 28.4 L/min. (3.2 to 7.5 gpm), is so small that beavers known to live in nearby natural drainages have not be attracted to the location.

Construction began in late October, 2004, and was substantially complete by April, 2005; monitoring of the system commenced in May, 2005. Photos of the North and South SRBR cells are provided in Fig. 4 and 5, respectively.

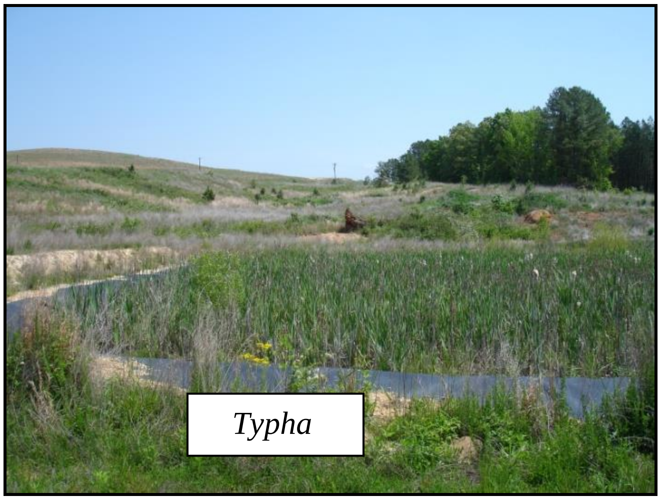

Figure 4. North SRBR (April 2008)

Figure 5. South SRBR (April 2008)

System Commissioning

The passive SRBR system was commissioned in stages. The first stage involved the sporadic pumping to fill the aeration cells in order to maintain the wetland type vegetation plantings. This was accomplished with portable pumps using water from Haile Mine Creek, only in the minimum amount required to keep the vegetation viable. The SRBR cells were commissioned in the next phase when they were filled with water from the Chase Hill Pit and were allowed to stand for a week with no flow. This allowed incubation of the sulfate reducing bacteria and the suite of cellulose-degrading bacteria to occur. After a week, flow to the cells was initiated at the full design rate of about 11.3 L/min (~3 gpm) per cell.

The final aeration cell effluent was monitored and pumped to the Haile Site lime dosing plant holding pond; eventually, the SRBR system effluent would be dispersed in an infiltration trench. Installing this structure was placed on hold while assessments to re-open the mine were underway. Samples were collected by mine personnel on a regular schedule and the data compiled for documentation and reporting to the state agency, the South Carolina Department of Health and Environmental Control. This unpublished data is the basis of the discussion of SRBR performance that follows.

System Operational Results 2004-2009

Since 2004, the Haile Mine passive SRBR system has functioned 24 hours a day, seven days a week without sustained interruptions. SRBR and APC performance data are shown for Figures 6 through 14. Discussions of individual parameters of interest follow.

Volumetric Sulfate and Metals Loading and Removal

Previously, it was noted that the SRBRs were designed for about 0.16 moles of metal removal per day per cubic meter of substrate, significantly less than the benchmark value of 0.3 moles/day/m^3. The data plotted on Fig. 6 show that both SRBRs were not excessively loaded with respect to metals during the five years of operation and that sulfate removal more or less kept pace with metals removal.

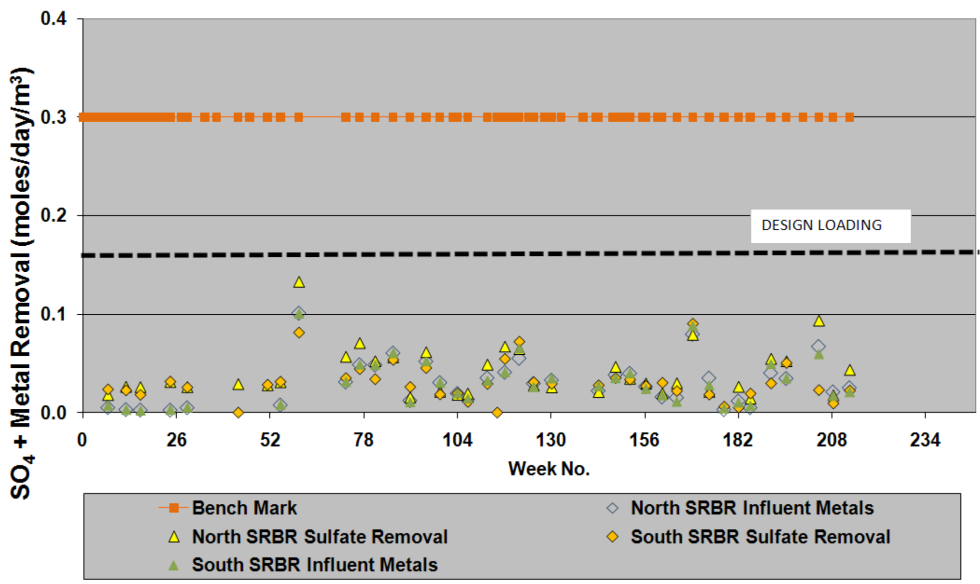

Figure 6. Volumetric Sulfate and Metal Loading/Removal

pH Improvement

The data in Fig. 7 suggest that the pH improvements were relatively insensitive to seasonal changes for the five years the SRBR system has been in operation. The rise in Aeration Cell pH compared to either of the SRBR cell effluents would suggest that excess alkalinity in the SRBR effluent (typically about 800 mg/L for the SRBR) provided a consistent buffering effect. In comparison, the average net alkalinity in the Aeration Cell was about 583 mg/L.

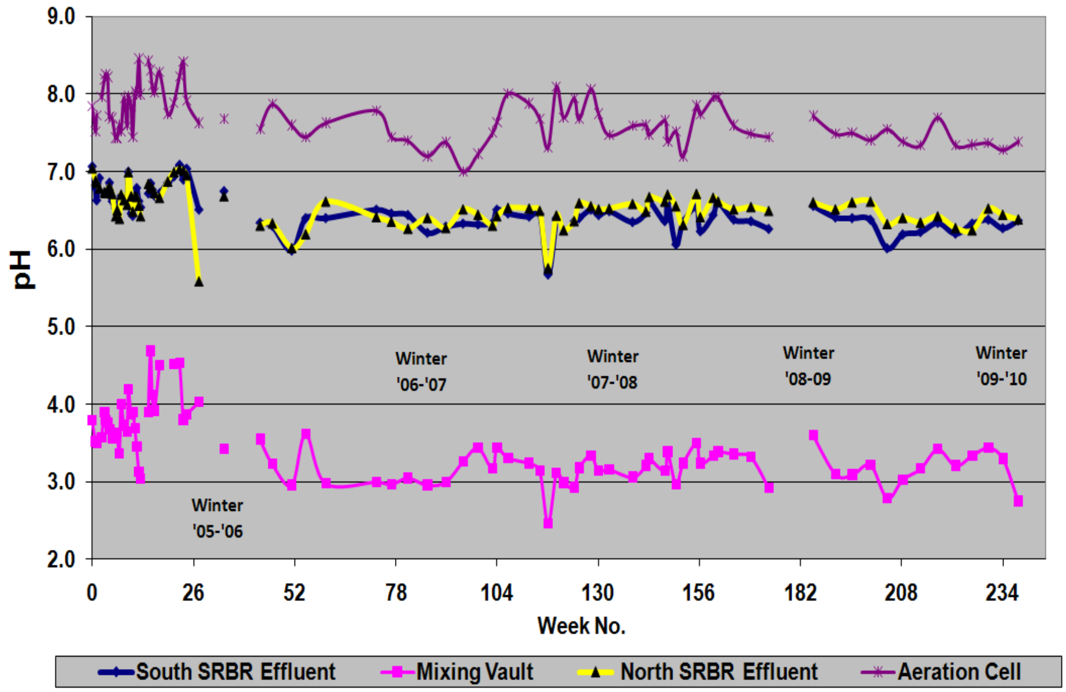

Figure 7. pH

Oxidation Reduction Potential (ORP)

Once the noisy ORP data from the first few months is filtered from Fig. 8, it is apparent that the North and South SRBR ORP data typically agree. With minor exceptions, ORP is usually negative which is indicative of robust geochemically reducing conditions. It is curious to note that the Mixing Vault ORP values decrease over time, suggesting that the mitigation measures implemented at the Haile Mine (capping, revegetation, etc.) appear to be decreasing the oxidation kinetics in the mine waste zones that the MIW contacts prior to entering the SRBR system. The typically depressed ORP in the Aeration Cell effluent suggests that the APC component of the system is being stressed. Future designs for aeration cells would probably result in larger footprints.

Dissolved Iron

As plotted in Fig. 9, dissolved iron removal in the North and South SRBRs was virtually identical for weeks 0 through 84, which coincides with the spring of 2007. At this point, the behavior of the two SRBRs diverges, and the dissolved iron removal performance of the South

SRBR appears to become worse over time. It is curious that the North SRBR appears to have had a similar excursion in about week 182, just prior to the onset of the 2008-09 winter.

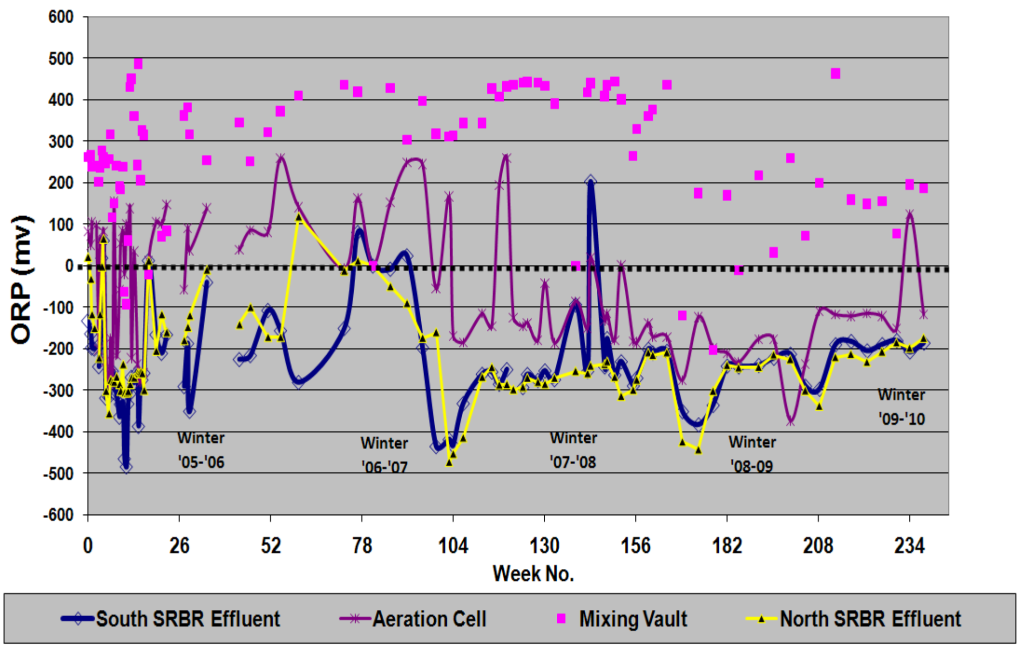

Figure 8. Oxidation Reduction Potential (ORP)

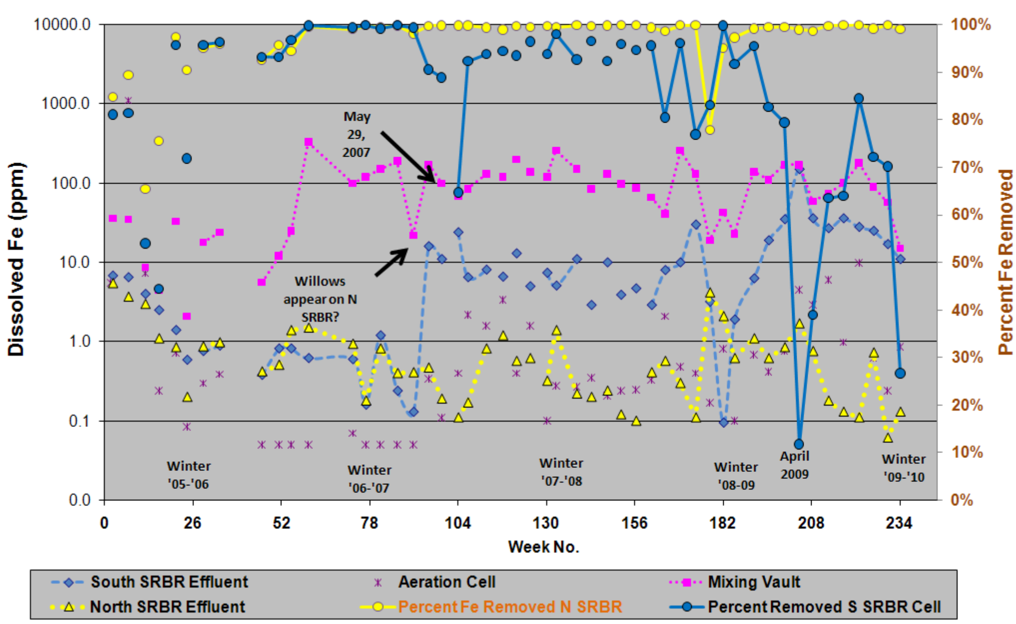

Figure 9. Dissolved Iron

Based on recollections from site personnel, it appears that willows first appeared on the surface of the South SRBR in the spring of 2007, which coincides with the drop in the South SRBR iron removal performance. Similar excursions appear to occur with a somewhat inconsistent regularity when the seasons change. The current hypothesis is that the ORP conditions on the surface of the South SRBR are changing in response to the dormancy or spring emergence of the willow community with the changing seasons. For example, in the autumn, when dormancy begins, oxidizing conditions typically surrounding the plant roots may become reducing. Any iron oxy-hydroxide that had been precipitated in this zone would likely be re-dissolved in the reducing conditions, creating a temporary spike in iron concentration in the SRBR effluent as Fe^{2+} iron. During the winter, reducing conditions would continue to prevail and ferrous iron would likely be removed in response to bacterial sulfate reduction as iron sulfide. In the spring, when the willows are no longer dormant, the iron sulfide precipitates would now be exposed to oxidizing conditions in the willow root zone and again, iron would be released when the sulfides were oxidized. This phenomenon was first observed in the iron removal data for the lime dosed aerobic cell in the Wheal Jane passive treatment system as reported by Hamilton et al. (1997). Similar spikes were observed in December of 1995 and the following spring of 1996. This aerobic cell was planted with three species of plants: *Typha, Phragmites,* and *Scirpus.*

One might expect to see a coincidental spike in arsenic in the South SRBR effluent but none was detected. Mixing Vault arsenic levels ranged from 0.007 to 0.39 mg/L and both South and North SRBR effluents consistently exhibited arsenic concentrations less than the detection limit of 0.005 mg/L.

Dissolved Copper

As plotted in Fig. 10, dissolved copper removal in the North and South SRBRs (plotted cumulatively) appears to coincide with the iron removal anomalies identified in Fig. 9. However, these "false" anomalies are attributable to depressed copper levels in the Mixing Vault and the nearly constant analytical detection limit for Cu of 0.01 mg/L. For example, the Mixing Vault copper concentration on Oct 28, 2008 was only 0.029 mg/L. With a detection limit of 0.01 mg/L, this results in an apparent removal of only 52.6% [(0.029-0.01)/0.029 = 0.526].

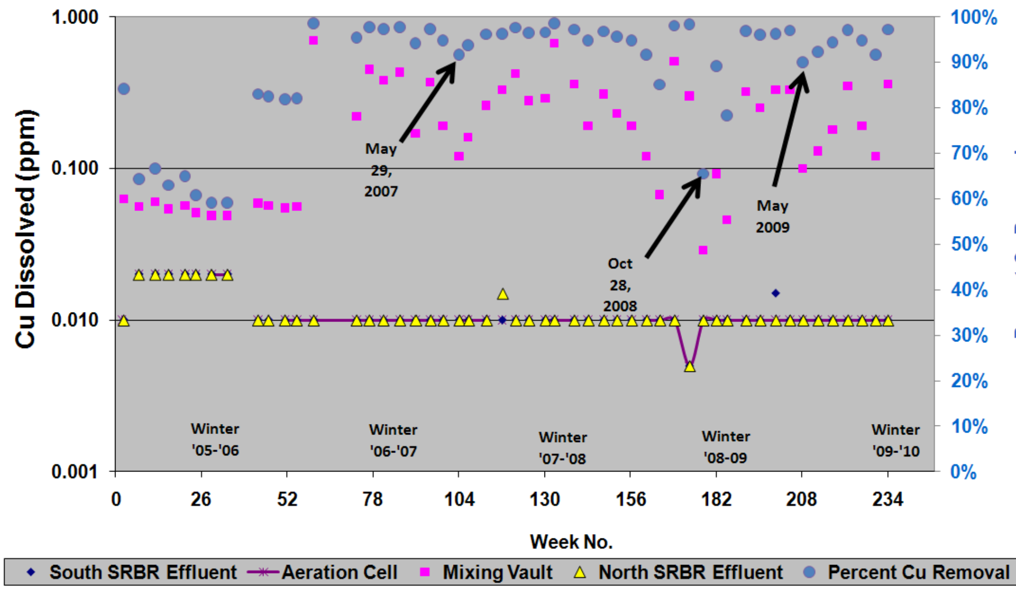

Figure 10. Dissolved Copper Removal

Dissolved Zinc

A similar masking mathematical influence was observed in a plot of Zn removal, as shown in Fig. 11. Consequently, it is concluded that the willows or some other unidentified mechanism is affecting iron removal efficiency; it is not significantly affecting Cu or Zn removal. Neither dissolved Cd removal efficiency (typically about 94%) nor dissolved Al removal efficiency (typically about 97.5%) appeared to vary seasonally in the South SRBR.

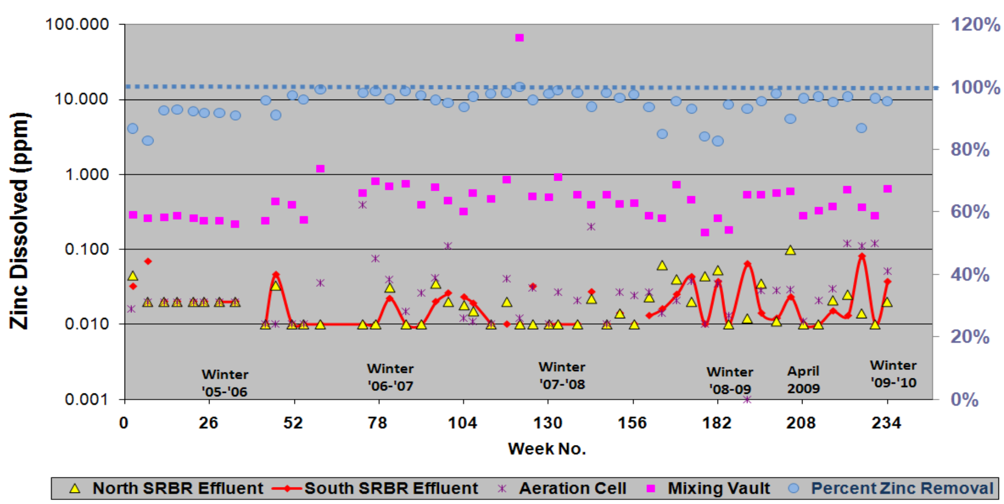

Figure 11. Dissolved Zinc Removal

Sulfate Reduction

Sulfate removal is naturally a key indicator of the relative "health" of a sulfate reducing bioreactor. Data in Fig. 12 reflect a wide scattering of influent sulfate concentrations in the Mixing Vault and relatively consistent effluent concentrations of typically less than 600 mg/L. It is curious to note that the relative difference in sulfate concentration between the influent and the SRBR effluent is about 300 mg/L in the first year of operation. Subsequent yearly peak data suggest differences up to about 900 mg/L. However, when this data is synthesized with volumetric loading, as plotted in Figure 6, the data trends are far less noisy.

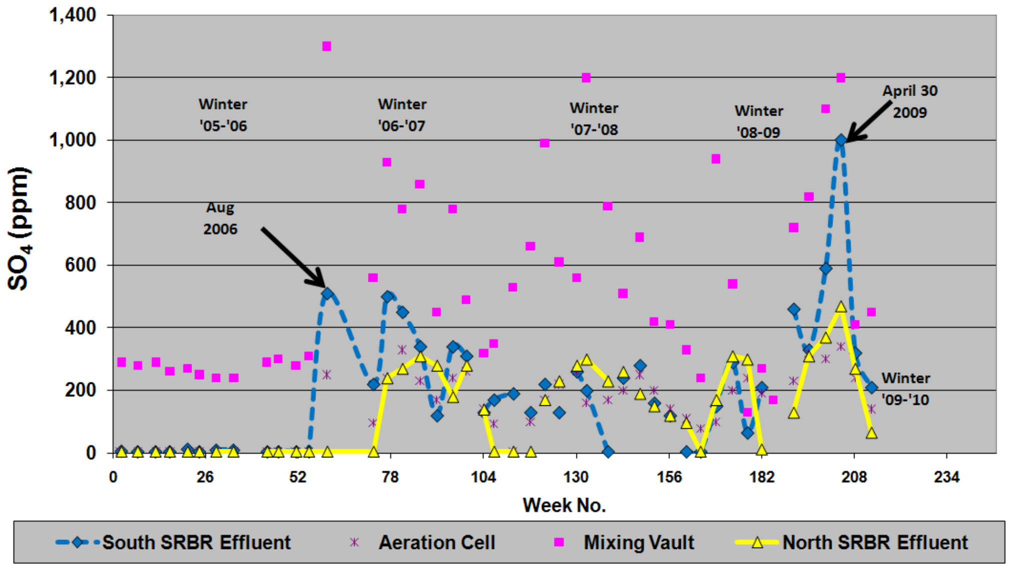

Figure 12. Sulfate Removal

Combined Metals Removal Efficiency

A final measure of success of a passive treatment system is the percentage removal of the metals of interest. Figure 13 reflects the relative removal efficiencies of the two SRBRs and the final aeration cell in removing iron, aluminum, copper, zinc, and cadmium. The alkalinity buffering in the SRBR effluent is likely countering the adverse iron performance in the South SRBR to provide its intended polishing effect.

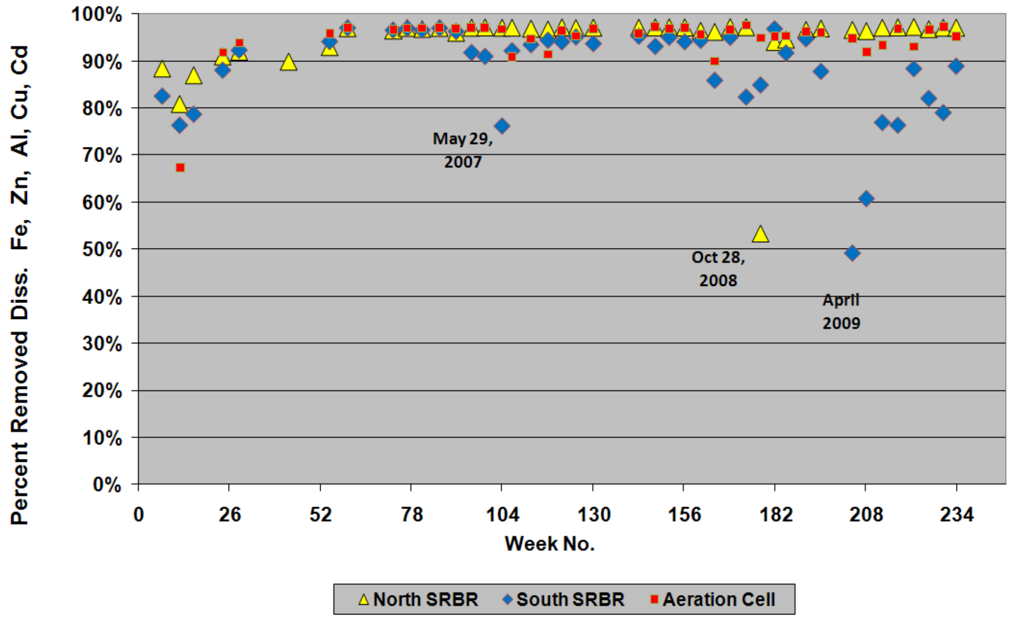

Figure 13. Combined Dissolved Metals Removal Efficiency, SRBRs and Aeration Cell

Construction and Projected Life Cycle Costs

Since its construction, records show that the Haile Mine passive SRBR system has treated about 45,800 cubic meters (12.1 million gallons) of MIW. Available records show a construction cost of about $170,000. Not including engineering and permitting costs, the unit cost of treatment is about $3.71 per m^3 or $0.14 per thousand gallons. This number will continue to decrease as the system ages and the maintenance requirements continue to be insignificant, i.e., periodic sampling and analysis. If the SRBRs were operated to the projected retrofitting date in about 2055 and the flow and chemistry continue as shown in Table 2, the undiscounted unit price of treatment would be about $0.31 per m^3.

Concluding Remarks

Since mid-2005, the Haile Mine passive SRBR system has functioned 24 hours a day, seven days a week without interruption and has met the goals of its designers and owners. As the mine approaches a potential re-birth, this technologic remedy may be decommissioned. However, the system's performance has demonstrated that the technology is capable of cost-effectively treating residual MIW.

Acknowledgements

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