CASE STUDIES – BENCH SCALE BIOCHEMICAL REACTOR RESULTS FROM TWO SITES AT THE ELIZABETH MINE, VERMONT[1]

Patrick Smart[2], David Reisman, James Gusek, and Edward Hathaway

Abstract: A passive treatment study involving eight bench-scale biochemical reactors (BCRs) was conducted at the Elizabeth Mine Superfund Site near South Strafford, Vermont from April 2005 through October 2006. The bench BCR cells are vertical flow reactors that were fabricated from 200 liter plastic drums; the cells contained different mixtures of organic media developed with local sources of wood chips, sawdust, crushed limestone, and cow manure. The abandoned Elizabeth Mine consists of underground workings, open cuts, pit lakes, and multiple mine waste piles (tailings, waste rock, and process residues), all of which discharge mining-influenced water (MIW) with elevated concentrations of heavy metals, including Fe, Al, Cu, and Zn, into a tributary of the Connecticut River. A portion of the site is listed on the National Register of Historic Places; the mine supplied the Union with Cu during the Civil War. It closed in the 1950's.

In 2005, four of the bench BCR cells accepted mildly acidic MIW from the South Open Cut, whose pit lake chemistry has not discouraged local college students from swimming in it despite a pH of 3. Another four bench BCR cells accepted leachate MIW from an abandoned tailings storage facility, TP-1, whose chemistry is much more aggressive than the South Open Cut water. The eight cells remained on-site throughout the winter, where they were routinely exposed to sub-freezing temperatures. In April 2006, the four South Cut cells were transported to the TP-1 area. The eight bench cells treated comparable MIW chemistries for 26 weeks during 2006.

This paper asses the performance of a passive treatment system when the reactors are subjected to sustained sub-freezing temperatures followed by dramatic changes in MIW chemistry. The discussion highlights operational challenges such as vandalism and construction challenges in a remote setting, as well as performance data from 2005 through 2006. The appropriateness of the technology for the passive treatment of MIW at the two sites will be discussed.

Additional Key Words: passive treatment, acid rock drainage, sulfate reducing bioreactors

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Introduction

The Elizabeth Mine Superfund Site (the Site) is an abandoned copper mine located in South Strafford and Thetford, Vermont. The mine was active from 1821 to 1958. Several smelters and processing facilities were operated at the site, and produced over 12 million tons of Cu. The mine is considered to be historically significant, and is considered eligible for listing on the National Register of Historic Places (URS, 2005).

When active mining ceased, the mine property encompassed approximately 567 ha (1,400 acres). Today, the Site contains features including exposed rock cuts, acidic pit lakes, a 12 ha (30 acre) mine waste pile (TP-1), and several kilometers of underground workings. Mining influenced water (MIW) generated at the Site impacts the Lord Brook and Copperas Brook Watersheds (Fig. 1).

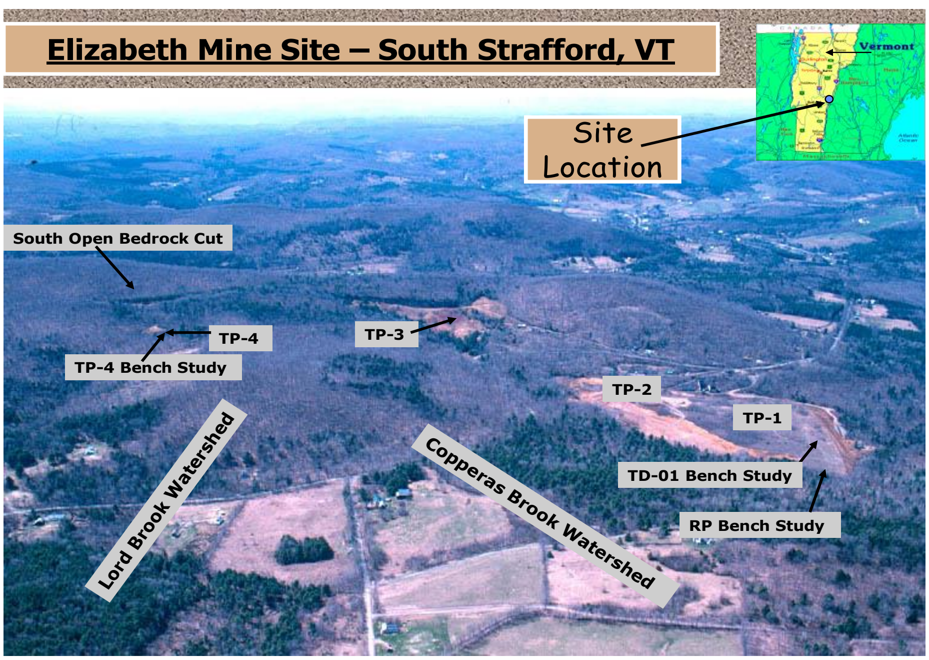

Figure 1: Elizabeth Mine Site location and Features.

Two significant sources of MIW generated at the Elizabeth Mine include the South Open Cut and the TP-1 mine waste dam. The South Open Cut contains an acidic MIW pit lake which seasonally discharges MIW into the Lord Brook watershed. TP-1 contains several drains which perennially discharge acidic MIW directly into Copperas Brook.

The use of biochemical reactors (BCRs) was identified as potentially applicable technology to mitigate site-generated MIW impacts on the local watersheds. A BCR is a passive treatment technology which typically functions using gravity flow, and requires minimal operation and maintenance. Typical full-scale BCRs resemble bermed ponds and operate as vertical-flow reactors. BCRs employ geochemical and biological processes to reduce metals concentrations and perform pH adjustment of MIW. Key processes occurring in BCRs include:

- biological reduction from sulfate to sulfide,
- precipitation of metal sulfide compounds,
- dissolution of limestone (in the treatment medium),
- precipitation of metal hydroxides, and
- complexation / precipitation of metals with organic material present in the BCR.

BCRs typically use locally available, ecologically friendly materials such as limestone, cow manure, wood chips, and hay; are simple to construct, and are designed to operate virtually unattended for decades (Gusek, 2002).

Three bench-scale treatability studies were conducted at the Site to evaluate BCRs for treating site-generated MIW. In April 2005, four 200-liter bench-scale BCR cells were constructed to treat South Cut MIW; an additional four 200-liter reactors were constructed in July to treat MIW generated at the TP-1 facility. In 2006, the TP-1 BCR study was continued for an additional 26 weeks while the South Cut cells were relocated to a retention pond at the toe of TP-1, where they received TP-1 MIW for approximately 26 weeks. These studies were performed to evaluate the BCR technology's ability to treat site-generated MIW. Focus was placed on BCR performance in response to adverse operational conditions, including seasonal freeze-thaw cycles, and dynamic MIW metals chemistries.

Methods

Experimental design

The South Cut and TD-01 drain pipe in the TP-1 site were selected as MIW sources for the 2005 treatability studies. The South Cut was identified as a significant source of MIW impacting the Lord Brook Watershed; TD-01 was selected because historic water quality data indicated TD-01 MIW contained the highest metals acidity and concentrations compared to other MIW sources in the vicinity of TP-1. In 2006, the South Cut BCR cells were relocated to TP-1 where they received MIW discharged from the TP-1 retention pond (RP). The RP MIW included a mixture of MIW generated from numerous toe and head drains installed at TP-1, including the TD-01 drain. RP MIW water quality was representative of the MIW discharged into Copperas Brook, and the MIW that would likely be treated by a larger-scale passive treatment system. Average water quality data from the South Cut and TD-01 (TP-1 MIW source water) are presented in Table 1. Seepage water from the South Open Cut did not contain the high concentrations of Fe and SO_4^{2-} typical of acidic MIW. TD-01 seepage water exhibited characteristics typical of acidic MIW, which includes elevated acidity and elevated concentrations of Fe, SO_4^{2-}, and other metals. RP MIW was similar to TD-01 water quality, with elevated SO_4^{2-} and metals concentrations, especially Fe.

Table 1: Average Water Quality Data from the South open Cut Pit Lake, TD-01, and RP MIW sources

Parameter	Units	South Cut	TD-01	RP
pH	s.u.	3.75	6.22	4.55
ORP	mV	-168	-27.2	-33.7
Al	mg/L	5.4	0.2	1.3
Cd	mg/L			
Co	mg/L	0.07	0.13	0.08
Fe	mg/L	11	702	589
Ni	mg/L	0.07	0.07	0.01
Zn	mg/L	0.90	0.94	0.27
SO_4^{2-}	mg/L	328	2,178	4,070

The BCR cells used in the treatability studies were designed as 200 liter downward-flow reactors configured to mimic full-scale systems. The BCRs included a drainage layer to collect effluent, a substrate mixture of organic media and limestone, and a layer of freeboard intended to prevent oxidation of the substrate (Fig. 2).

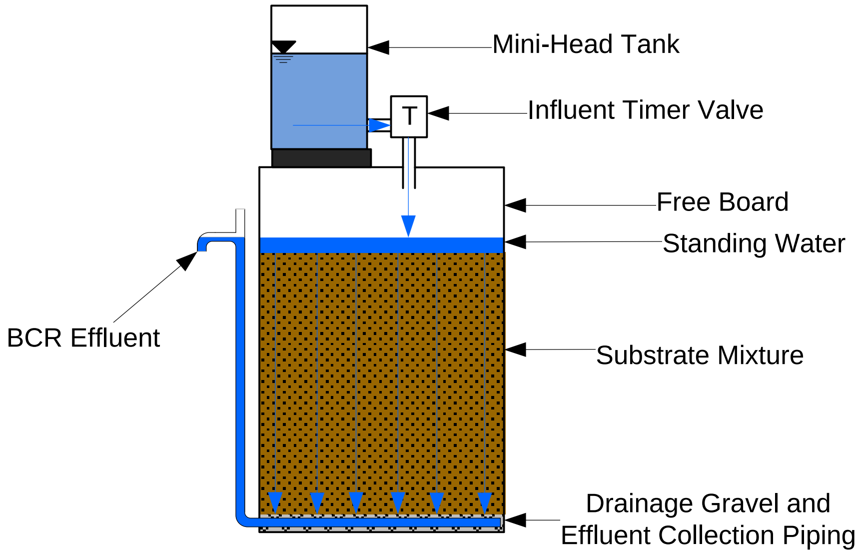

Figure 2: Cross-section of BCR Cells used in Elizabeth Mine Treatability Studies

During the three bench studies, the cells operated utilizing gravity flow. BCR Flow rates were controlled using calibrated mini-head buckets and battery-powered timed valves. Consequently, the BCRs operated under slug-flow conditions, where several slugs of MIW would be delivered to the BCRs each day (Fig. 3).

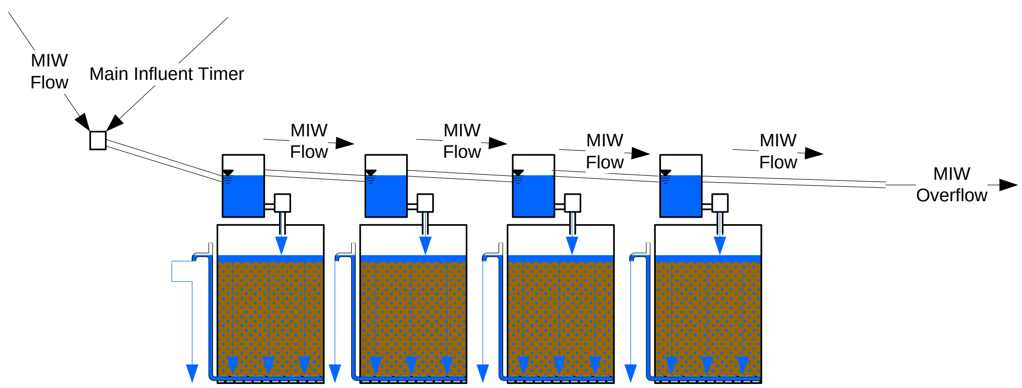

Figure 3: BCR test cell configuration used for the South Cut, RP, and TD-01 studies.

MIW flow through the cells was determined based on metals loading rates, MIW acidity, and minimum retention time requirements. Successful BCR systems have maintained metals loading rates equal to or less than 0.3 moles/day/m^3 (Gusek, 2002). Rose (2006) observed that BCRs require influent acidity loading be kept less than 35 grams/day/m^2.

Based on these criteria, MIW flow rates were selected to maintain design conditions in each cell. Occasionally, flow rates were adjusted during the studies in response to changing influent water chemistries and changing site conditions.

Bench Cell Construction

In April 2005, four BCRs (Cells 1 -4) were constructed to treat MIW generated by the South Open Cut. The BCRs were constructed using a layer of drainage gravel and heterogeneous mixtures of various organic media and limestone components, as shown in Table 2. Despite an average pH of 3.0 (Table 1), the South Cut pit lake was a local nuisance attraction for swimmers and revelers. To minimize the risk of vandalism, the bench-scale system was assembled in densely-vegetated forest at the base of tailings pile 4 (TP-4). Substrate was assembled in 20 liter batches and transported to the test site via an aerial tramway (Fig. 4). Once constructed, the BCRs were filled with South Cut MIW and incubated for two weeks.

Table 2: Substrate mixtures used to construct bench-scale biochemical reactors at the Elizabeth Mine

	South Cut and RP BCR Cells				Toe Drain 01 (TD-01) BCR Cells			
Component*	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8
Woodchips	50%	60%	30%	40%	50%	45%	30%	40%
Hay	10%	10%	10%	10%	10%	10%	10%	10%
Cow Manure	10%	10%	10%	10%	10%	10%	10%	10%
Saw Dust	0%	0%	20%	10%	0%	0%	20%	10%
Decayed Wood	0%	0%	0%	0%	0%	5%	0%	0%
Limestone	30%	20%	30%	30%	30%	30%	30%	30%

*Percent component by as-received weight.

Figure 4: South Cut BCR system construction. A tramway cable arrangement was used to transport materials from a staging area to the treatment site.

The TD-01 BCR cells (Cells 5 – 8) were constructed in June 2005 at the toe of TP-1 (Fig. 1). The cells were constructed using the substrate mixtures listed in Table 2. MIW was delivered to the Bench cells via gravity flow from TD-01 (Fig. 3). Once constructed, the TD-01 cells were filled with TD-01 MIW and incubated for two weeks.

Treatability Activities and Events

Flow through the South Cut BCRs was initiated on May 5, 2005. The South Cut cells received MIW flows ranging from 57 to 93 liters per day (L/day) from May 5 to November 1, 2005, with minor flow interruptions. On July 5, 2005, seasonal South Cut surface discharge had dried up. Consequently, the influent collection point was moved to the South Cut pit lake, which remained the source of MIW for the remainder of 2005. Flow through the TD-01 BCRs was initiated on July 12, 2005, at an initial MIW flow rate of 3.9 L/day, based on metal loading rates. Flow remained consistent until the cells were winterized on November 1, 2005.

The BCR cells were monitored weekly from May 5, 2005 through September 13, 2005, and on a 14-day schedule from September 13 through November 1, 2005. Typical monitoring activities included collecting influent and effluent samples for laboratory analyses and measuring field parameters. Samples collected for laboratory analysis were sent to the Colorado School of Mines analytical laboratory and the EPA Office of Research and Development analytical laboratory for analysis of target metals via inductively coupled plasma – atomic emission spectroscopy (ICP-AES). Monitoring results are discussed below. Temperature, pH, and oxidation-reduction potential (ORP) were measured in the field using a calibrated Oakton Acorn 310 water quality meter; specific conductivity was measured using a Horriba B-173 conductivity meter, and mini-head discharge volumes were measured using a graduated cylinder or calibrated bucket.

From November 2005 to April 2006, the TD-01 and South Cut bench cells were exposed to harsh New England winter conditions, including snow storms and extended periods of sub-freezing temperatures. Undoubtedly, the cells froze solid and subsequently thawed. In April 2006, the South Cut Cells were relocated to the vicinity of the TP-1 retention pond (RP). The cells were drained and then dragged up a densely wooden slope via a pulley system. Once at the RP Site, the cells were filled with MIW from the retention pond and allowed to incubate. The TD-01 BCR cells, which had been left in place over the winter, were topped off with MIW from TD-01, and incubated.

On May 8, 2006, MIW flow through the TD-01 and RP bench BCRs was initiated. The cells received a consistent flow of MIW until they were winterized on November 8, 2006. During the 2006 study interval, the RP and TD-01 cells were monitored on a 14-day schedule. During each monitoring event, samples were collected for laboratory analyses, and field parameters including temperature, ORP, pH, and flow were measured in the field. On November 8, 2006, flow was interrupted to the cells in preparation for winter. This marked the conclusion of the bench testing campaign at the Elizabeth Mine.

Results and Discussion

South Cut and RP Results

A summary of the data from the South Cut and RP Studies is presented in Tables 3 and 4, respectively. During both the South Cut and RP bench studies, BCR effluent metals concentrations were significantly lower than influent MIW concentrations and effluent pH values averaged about 6, indicating that the cells were treating the MIW. Detailed performance analysis follows.

Trend plots of MIW flow rate and metals loading rates observed for the South Cut and RP Bench cells are shown in Figs. 5 and 6. The South Cut cells received an average flow rate of 73 L/day. Due to low influent metals concentrations, the South Cut flow was determined based on hydraulic retention time. During the South Cut study, the cells received an average metals loading rate of

0.06 moles/day/m^3. Design flow through the RP cells was controlled by metals loading rates. Initially, the flow rate was set at 8.0 L/day. On June 5, 2006, BCR flow rates were reduced to 4.0 L/day in response to elevated metals concentrations, which had resulted in the unintended overloading of the cells. The BCR flow rate was set at 4.0 L/day for the remainder of the RP study. Unexpected major changes in the MIW water quality resulted in overloading conditions towards the end of the 2006 monitoring season. Overall, the metals loading rate averaged 0.5 mole/day/m^3 for the RP study. The cells' performance did not appear to be adversely affected by the overloading conditions during the initial weeks of the study.

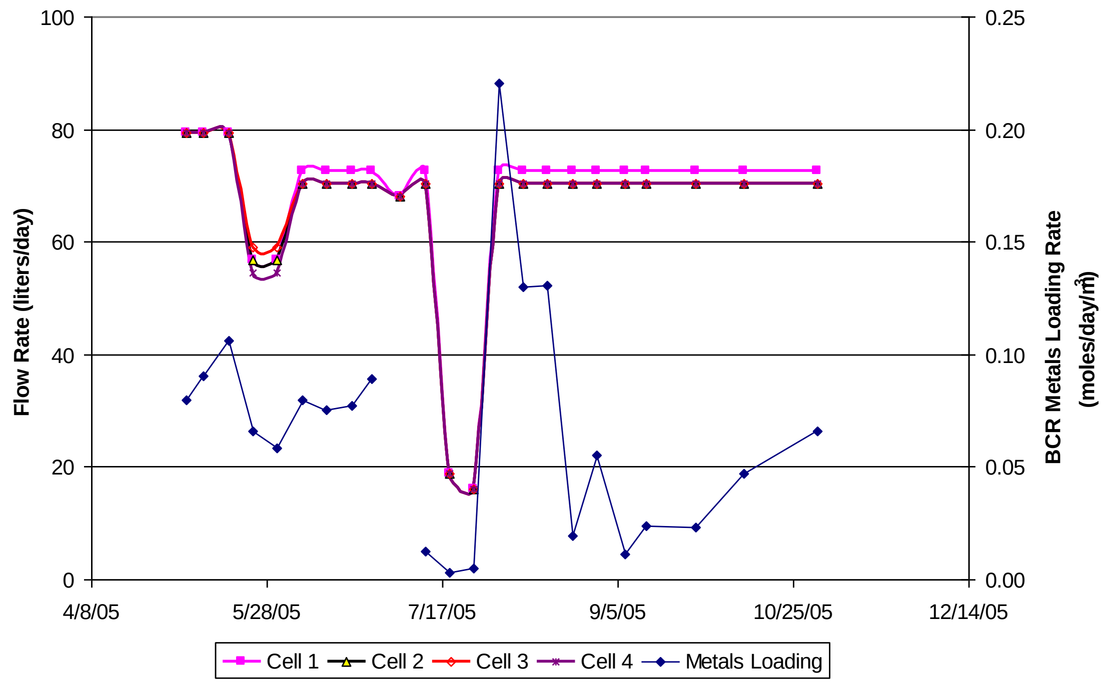

Figure 5: 2005 Flow rate and metals loading rate for South Cut BCR cells

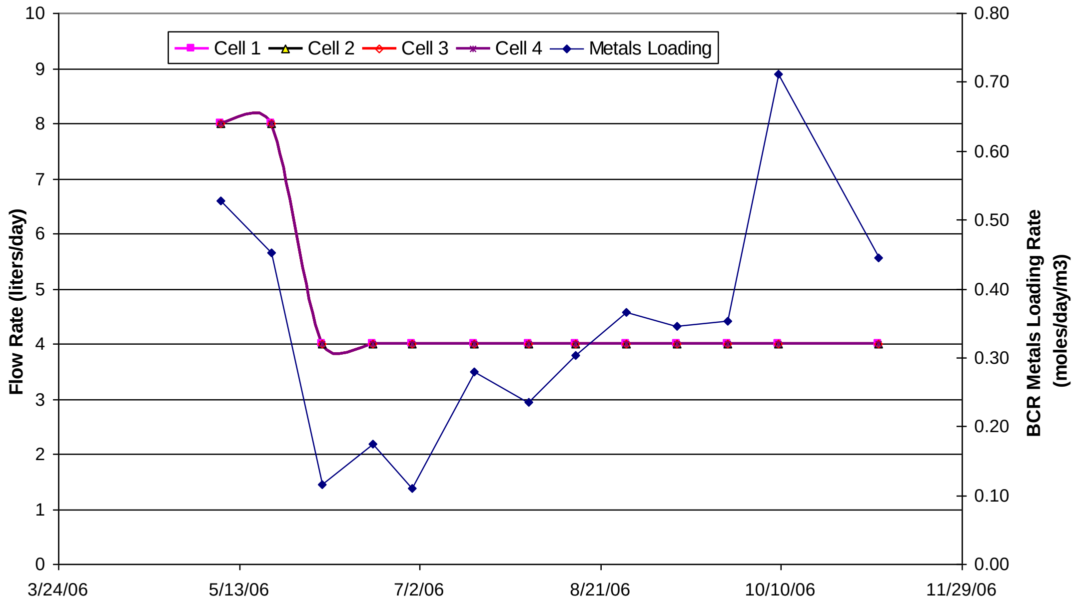

Figure 6: 2006 Flow rate and metals loading rate for RP BCR cells

Figs. 7 and 8 present trend plots of pH for the South Open Cut and RP Bench Cells, respectively. BCR cells 1, 2, 3 and 4 improved acidic South Cut MIW from an average pH of 3.5 to an average effluent pH of 6.2 (average of 4 BCR cells) during the 2005 study interval. In 2006, the cells received RP MIW at an average pH of 3.9; average effluent pH was 6.5. Trend plots for ORP and average effluent BCR temperatures observed during the South Cut and RP bench studies (Figs. 9 and 10) indicate the BCRs maintained reducing conditions throughout the 2005 and 2006 bench studies. Negative ORP values are indicative of reducing conditions conducive to robust sulfate-reducing bacteria health, and typically correspond with favorable BCR metals removal rates.

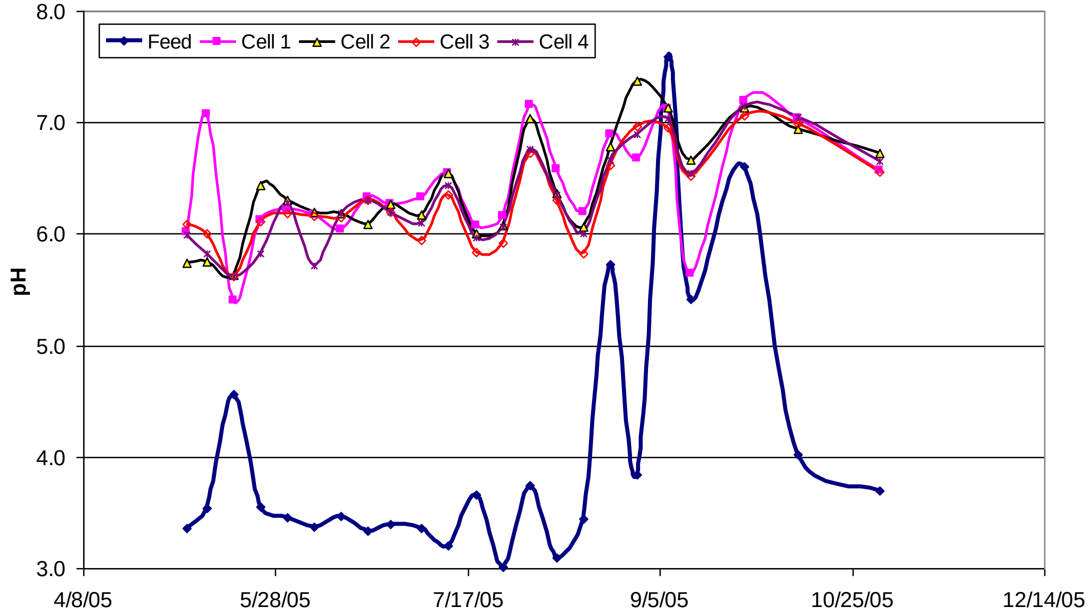

Figure 7: 2005 pH data for South Cut BCR Cells

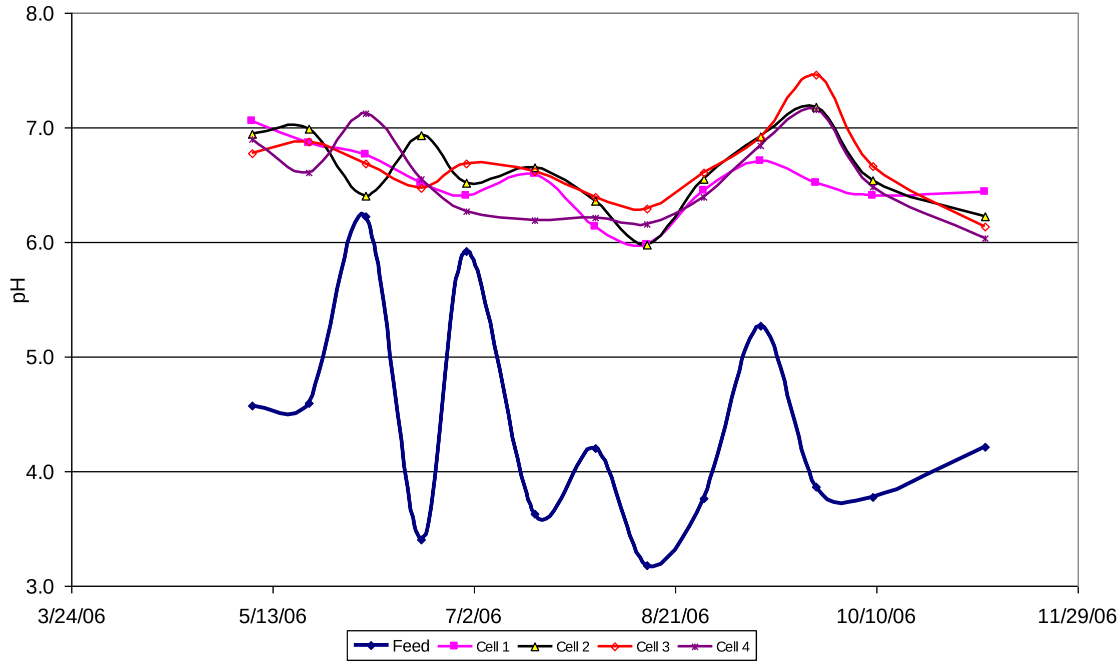

Figure 8: 2006 pH Data from RP Bench Cells

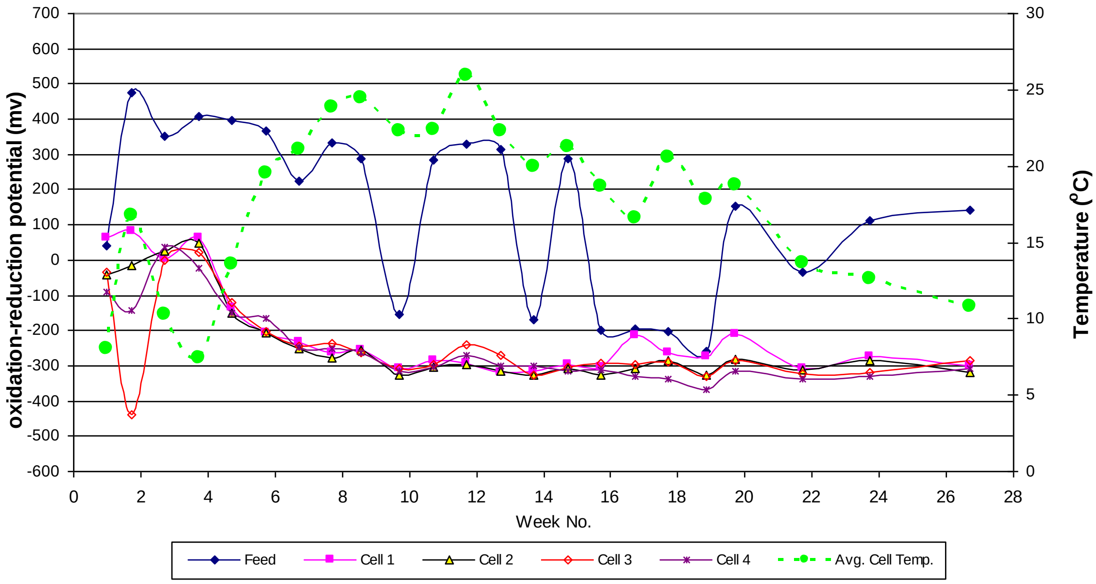

Figure 9: 2005 oxidation-reduction potential and average cell temperature for South cut BCR cells.

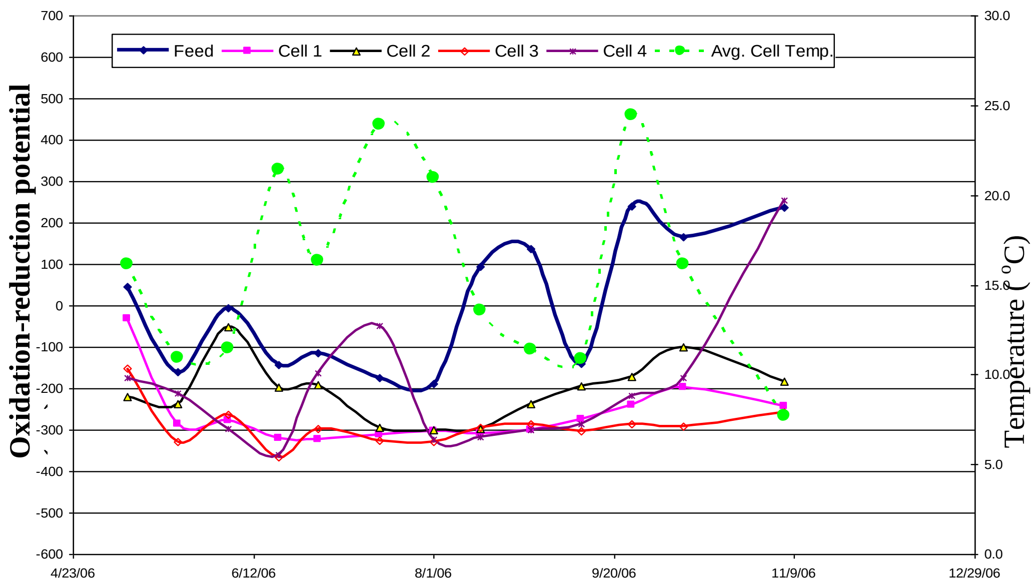

Figure 10: 2006 oxidation-reduction potential and average cell temperature for RP BCR cells.

Cell effluent average, minimum, and maximum temperatures were generally comparable to or higher than influent temperatures for the South Cut and RP studies (Tables 3 and 4). The temperature increase from source MIW to cell effluent sampling points indicates robust microbial populations were present in the cells. The observed decreasing trends in 2005 and 2006 average cell effluent temperatures (Figs. 9 and 10) are likely due to decreasing ambient temperatures corresponding to the changing seasons.

Table 3: 2005 Average South Cut Bench Study Results

Parameter	Influent	Cell 1 Effluent	Cell 1 % Removal	Cell 2 Effluent	Cell 2 % Removal	Cell 3 Effluent	Cell 3 % Removal	Cell 4 Effluent	Cell 4 % Removal
pH (s.u.)	3.5	6.2	--	6.2	--	6.2	--	6.2	--
Temp (^oC)	19	18	--	18	--	17	--	18	--
ORP (mv)	143	-223	--	-246	--	-257	--	-257	--
Al (mg/L)	2.2	0.020	99%	0.066	98%	0.041	98%	0.034	98%
Cd (mg/L)	0.0026	0.0020	23%	0.0020	22%	0.0024	7%	0.0023	12%
Co (mg/L)	0.042	0.0050	88%	0.0058	86%	0.0073	82%	0.0070	83%
Fe (mg/L)	1.7	0.17	90%	0.40	77%	0.807	53%	0.590	66%
Ni (mg/L)	0.042	0.006	86%	0.008	80%	0.013	69%	0.010	76%
Zn (mg/L)	0.35	0.12	65%	0.091	74%	0.082	77%	0.079	78%

Table 4: Average RP BCR study results.

Parameter	Influent	Cell 1 Effluent	Cell 1 % Removed	Cell 2 Effluent	Cell 2 % Removed	Cell 3 Effluent	Cell 3 % Removed	Cell 4 Effluent	Cell 4 % Removed
pH (s.u.)	3.9	6.5	--	6.5	--	6.6	--	6.5	--
Temp (^oC)	20	14	--	14	--	18	--	14	--
ORP (mv)	0.1	-245	--	-193	--	-272	--	-190	--
Al (mg/L)	1.5	0.055	96%	0.049	97%	0.067	96%	0.043	97%
Cd (mg/L)	0.017	0.00021	82%	0.0031	82%	0.0031	82%	0.0031	82%
Co (mg/L)	0.084	0.0033	96%	0.0076	91%	0.004	95%	0.0059	93%
Fe (mg/L)	724	1.1	>9%	22	97%	4.6	99%	37.5	95%
Ni (mg/L)	0.014	0.0032	78%	0.0028	80%	0.0031	78%	0.0023	84%
Zn (mg/L)	0.36	0.011	97%	0.0092	98%	0.011	97%	0.011	97%

Figure 11 reflects the observed combined metals (Al, Cd, Cu, Co, Fe, Ni, and Zn) concentration differences between the South Cut MIW and the BCR effluents observed for the South Cut study. The combined heavy metals removal rate sums the removal of Fe, Al, Cu, Zn, Cd, and Co into a single percent removal rate. Excluding Cell 3, removal percentages were consistently above 80% beginning in Week 5 (5/31/05) of the South Cut study. Cell 1 was the only cell whose average metals removal rate was greater than 90% for the duration of the 2005 study. Cell 2 had the second highest average removal percentage, 87%. During the last two months of the South Cut study, Cells 1, 2, and 4 had average removal percentages of greater than 90%.

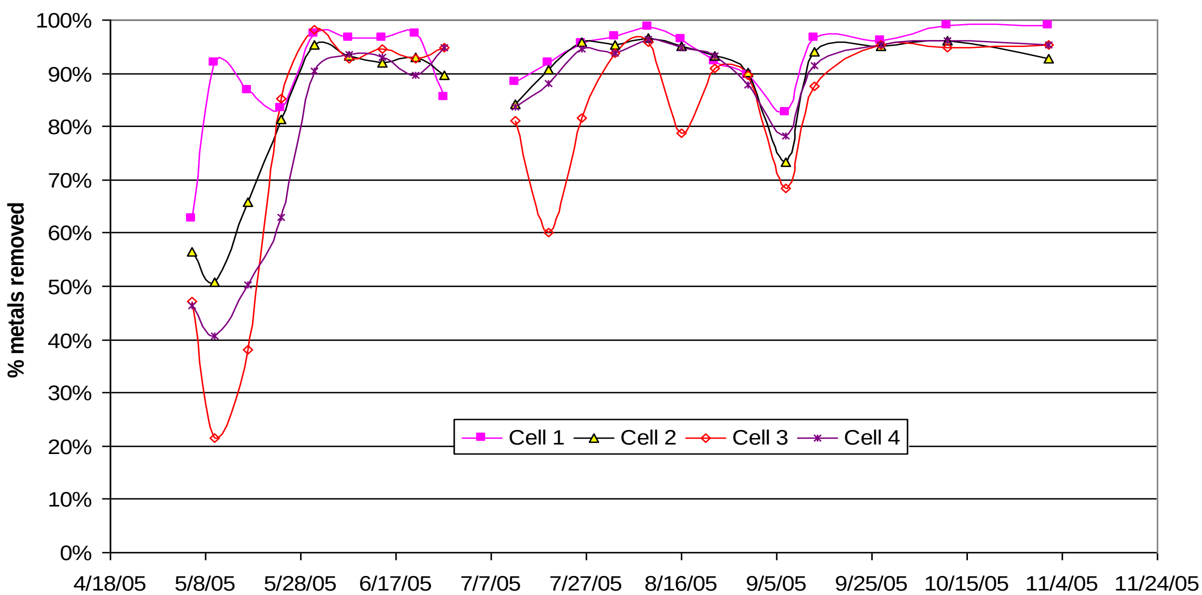

Figure 11: % removal graph for 2005 South Cut BCR data. Combined metals concentrations include Al, Cd, Cu, Co, Fe, and Zn.

During the RP study, average percent removal rates ranged from 89.3% (Cell 4) to 99.9% (Cell 3). Combined metals removal rates were typically greater than 90% with the exception of two sampling events for the Cell 2 effluent (86.0% on 6/30 and 84.1 % on 7/17/2006) and one sampling event for Cell 4 (18.9 % on 7/17/2006). The observed reduced removal rates in Cell 2 and Cell 4 may have been in response to the metals overloading conditions the cells experienced during the start of the study. However, the observed reduction in the metals removal was inconsistent with other cell 2 data, and is considered anomalous. Figure 12: presents combined metals (Al, Cd, Cu, Co, Fe, Ni, and Zn) percent removal graph for 2006 RP BCR data.

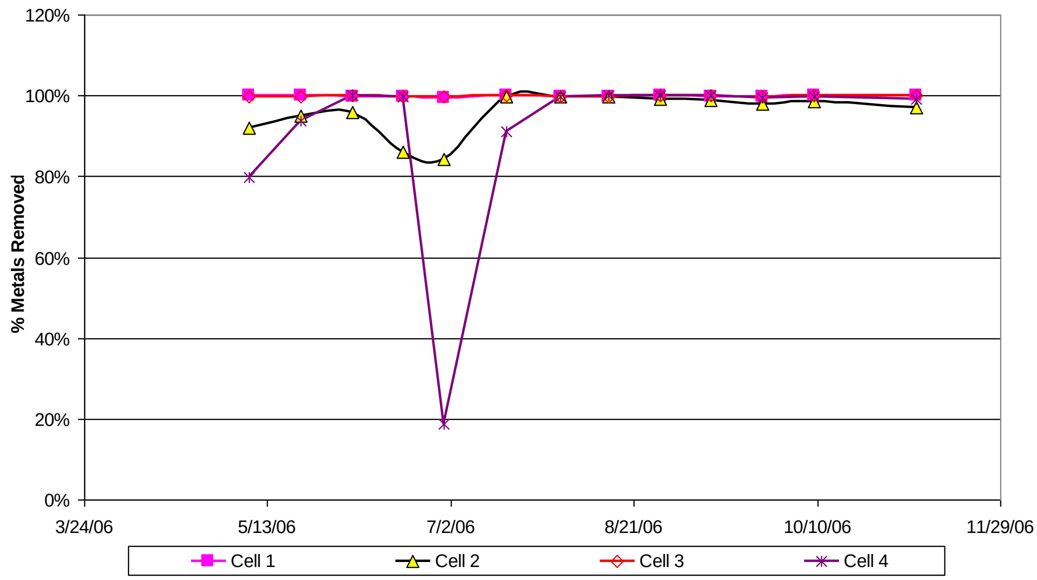

Figure 12: Combined metals % removals for the 2006 RP study.

TD-01 Study

Data from the 2005 and 2006 TD-01 studies are summarized in Table 5 and Table 6. In 2005, the TD-01 MIW influent iron concentrations ranged from 321 to 886 mg/L, while 2006 influent iron concentrations ranged from 926 to 1,650 mg/L. Cobalt, Cd, Ni, Zn, and Mn concentrations were also higher in 2006 than those observed during the 2005 study. Ongoing construction activities on the TP-1 site were a suspected cause of the MIW chemistry changes. The elevated metals concentrations observed in 2006 resulted in overloading the bench cells for the first 10 weeks of the 2006 study interval. Persistent overloading per se is not recommended in full scale system designs and has been cited as a primary cause for system failure (Gusek, 2001). However, this unanticipated situation has provided data to validate the deleterious effects of long term BCR overloading conditions.

Table 5: 2005 TD-01 study BCR average data

Parameter	Parameter	Influent	Cell 5 Effluent	Cell 5 % Removed	Cell 6 Effluent	Cell 6 % Removed	Cell 7 Effluent	Cell 7 % Removed	Cell 8 Effluent	Cell 8 % Removed
pH (s.u.)	pH	5.2	5.9	--	6.0	--	5.8	--	5.8	--
Temp (^oC)	Temp	21	25	--	25	--	25	--	24	--
ORP (mv)	ORP	-42	-152	--	-144	--	-192	--	-99	--
Al (mg/L)	Al	0.52	0.13	76%	0.087	83%	0.17	68%	0.079	85%
Cd (mg/L)	Cd	0.021	0.0069	66%	0.0068	67%	0.0069	66%	0.0079	61%
Co (mg/L)	Co	0.16	0.010	94%	0.012	92%	0.023	85%	0.020	87%
Fe (mg/L)	Fe	657	46	93%	47	93%	26	96%	112	83%
Ni (mg/L)	Ni	0.047	0.011	76%	0.014	70%	0.038	19%	0.014	71%
Zn (mg/L)	Zn	1.0	0.071	93%	0.067	93%	0.11	89%	0.097	90%

Table 6: 2006 TD-01 BCR study average data

Parameter		Influent	Cell 5 Effluent	Cell 5 % Removed	Cell 6 Effluent	Cell 6 % Removed	Cell 7 Effluent	Cell 7 % Removed	Cell 8 Effluent	Cell 8 % Removed
pH (s.u.)	pH	5.7	6.2	--	6.3	--	6.2	--	6.2	--
Temp (^oC)	Temp	16.9	14.7	--	15.1	--	15.2	--	14.8	--
ORP (mv)	ORP	97	-18	--	-20	--	-33	--	-31	--
Al (mg/L)	Al	0.50	0.050	90%	0.064	87%	0.057	89%	0.065	87%
Cd (mg/L)	Cd	0.035	0.022	38%	0.0071	80%	0.018	48%	0.017	52%
Co (mg/L)	Co	0.24	0.057	76%	0.023	90%	0.044	81%	0.034	85%
Fe (mg/L)	Fe	1200	770	36%	495	59%	643	46%	535	55%
Ni (mg/L)	Ni	0.057	0.0078	86%	0.0042	93%	0.0059	90%	0.0059	90%
Zn (mg/L)	Zn	1.35	0.056	96%	0.020	99%	0.035	97%	0.034	98%

Influent metals loading and cell flow rates for the 2005 and 2006 TD-01 studies are presented in Fig. 13. During the 2005 study, the cells' molar metal removal averaged 0.25 moles/day/ m^3 over the course of the 2005 study, which was consistent with the benchmark design value. 2006 influent metals loading was unintentionally above the benchmark rate for the first ten weeks of the 2006 bench test, i.e., from April 24 through June 30. During this period, the cells were overloaded with up to twice the designed metals loading rate due to delays in receiving analytical results. In an attempt to recreate reducing ORP conditions and allow cell recovery, influent loading was set below the benchmark from June 30 through November 6, 2006. Cell metals removal was consistently below the influent loading rate throughout the 2006 study. The sustained elevated metals loading early in the 2006 study interval may have influenced cell metals removal for the entire 2006 field season.

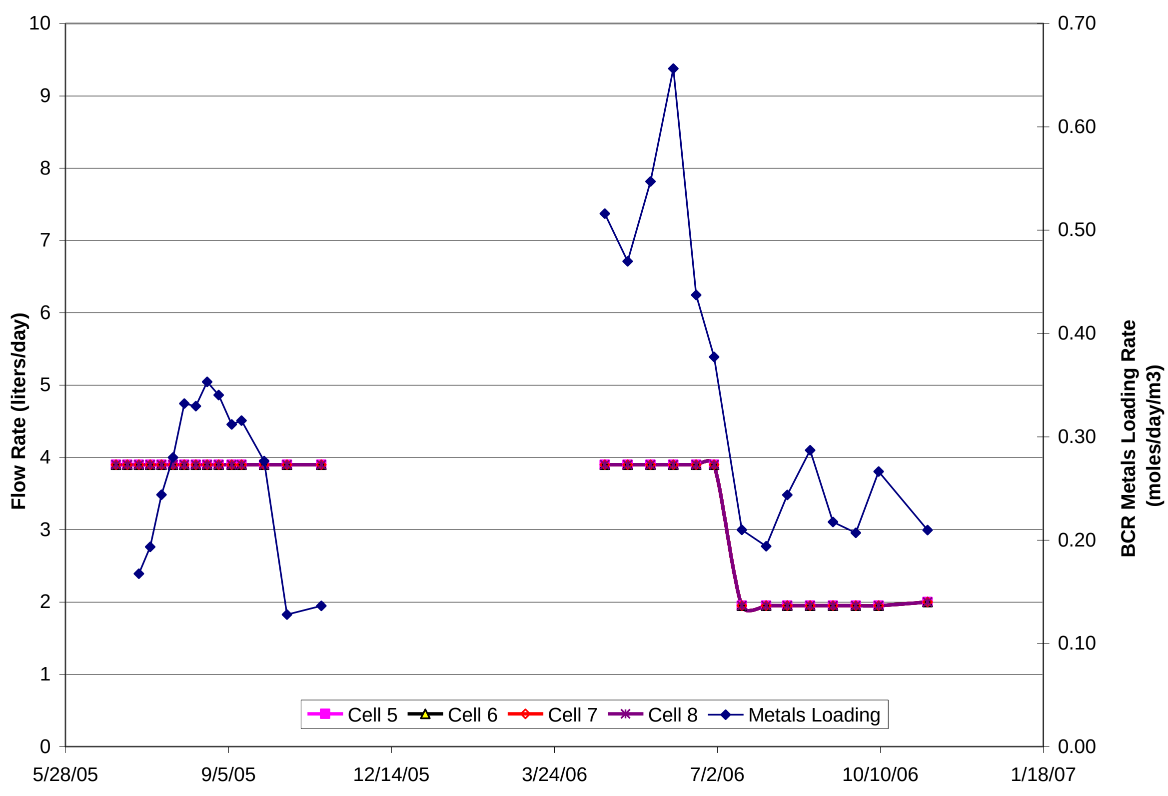

Figure 13: TD-01 Flow rate and metals loading rate for 2005 and 2006 studies.

TD-01 pH results are plotted in Fig. 14. The influent pH to the bench cells averaged 5.7 and the effluent pH from all four cells averaged 5.9. The influent pH was relatively constant except for 9/13/05, when it dropped to 4.2. This may have been in response to a storm event at the site on August 31, 2005 when nearby Lebanon, NH recorded 3.66 cm (1.44 inches) of rain in a 24 hour period. Cell 7 had the lowest average pH (5.8) and Cell 6 had the highest average pH (6.0).

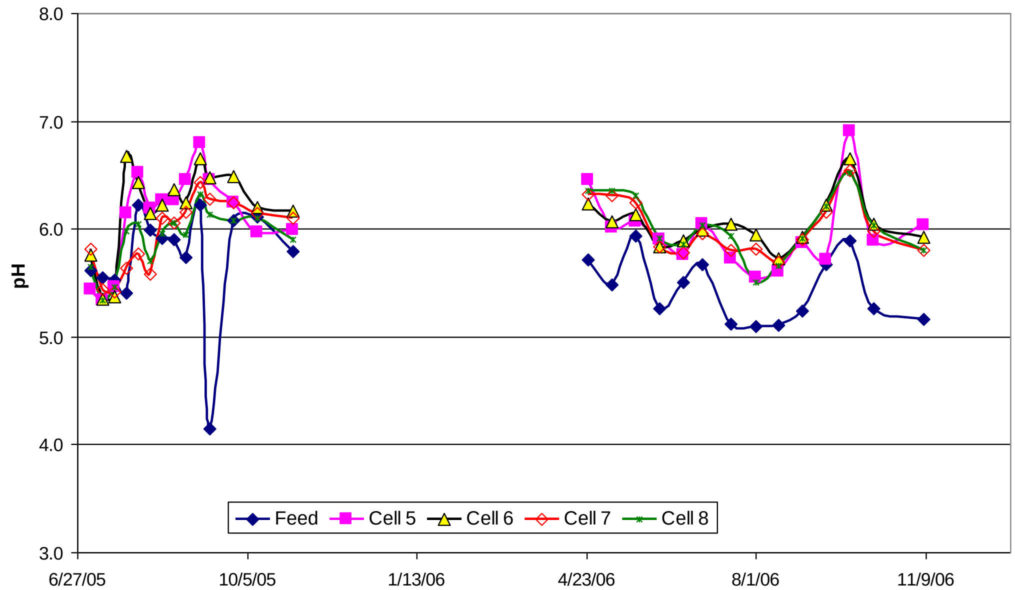

Figure 14: pH Results from the TD-01 BCR study.

As stated previously, negative ORP values are indicative of anaerobic-reducing conditions conducive to robust sulfate reducing bacteria health. All four cells had consistently negative ORP readings during the 2005 study (Fig. 15). In 2006, cells 5, 7, and 8 fluctuated between positive and negative ORPs, suggesting that the microbial populations were stressed. During 2005, the average influent and effluent water temperature was 21 °C and 25 °C, respectively. These elevated temperatures were likely beneficial to bacterial growth and activity. During 2006, the average cell effluent temperature was 15 °C. Again, this may have been in response to conditions created by ongoing construction activities at the TP-1 site.

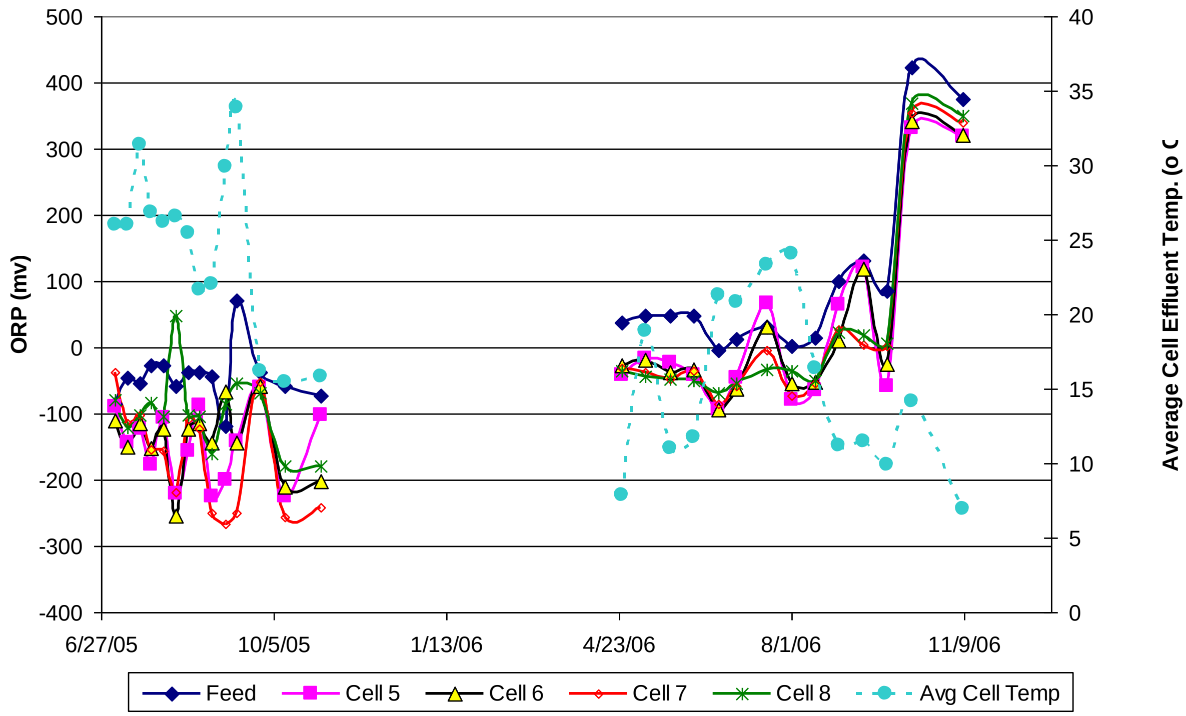

Figure 15 Oxidation-Reduction Potential (ORP) and Temperature.

Combined metals removal percentages are presented in Fig. 16. Excluding Cell 8, average 2005 removal percentages were greater than 90%. Cell 7 had the highest average removal rate, 96%. Cell 8 had the lowest average removal rate (84%) and had two weeks (weeks 4, 5) during which removal was significantly less than that observed in the other cells. Reasons for this remarkable difference in performance were undetermined; Cell 8 appeared to recover by the end of the 2005 study interval.

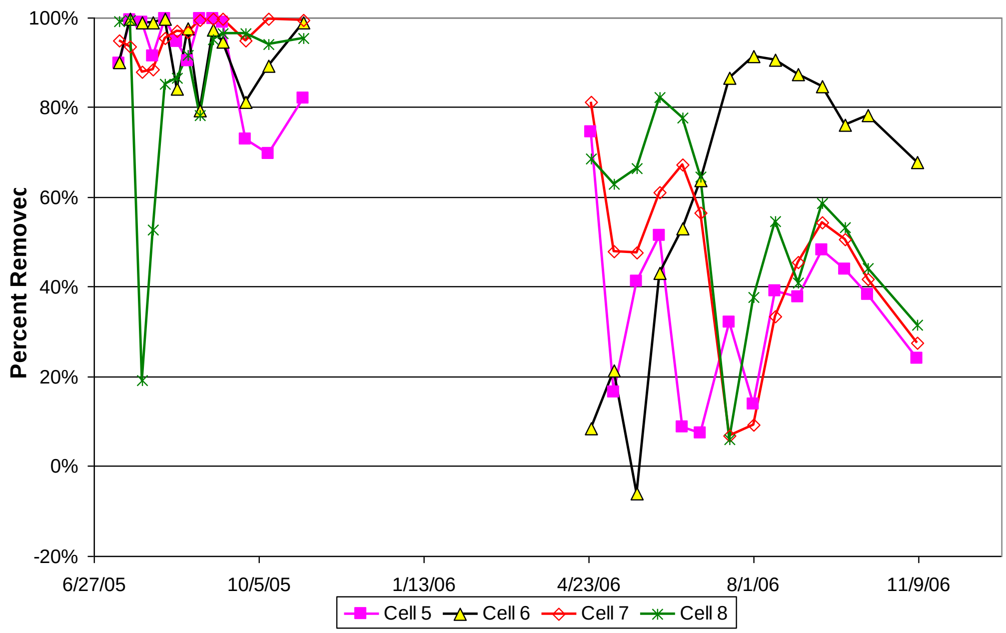

Figure 16: combined Fe, Al, Cu, Zn, Cd, and Co percent removal from TD-01 BCR cells.

In 2006, average combined metal removal rates in increasing order were: Cell 5 (34%), Cell 7 (48%), Cell 8 (58%), and Cell 6 (64%). 2006 metal removal was significantly less than the removal observed in 2005 (Fig. 16). During the 2006 study, Cell 6 out-performed the other cells from early July though November 2006. However, the lingering effects of earlier overloading still appeared to be present.

<u>BCR Performance Summary</u>

The BCR cells accomplished significant reductions in influent metals concentrations during the South Cut, RP, and TD-01 bench studies. BCR cells 1, 2, 3, and 4 were exposed to a dramatic change in MIW chemistry when the cells were relocated from the South Cut to the RP MIW in April 2006. Despite exposure to temperature extremes over the previous winter, being drained of MIW during cell relocation, and a major change in MIW chemistry, BCR cells 1, 2, 3, and 4 exhibited higher metals removal rates during the RP study than during the South Cut study. BCR performance during the RP study suggests the microbial populations in BCRs may be more resilient to changing environmental conditions than previously thought. By maintaining BCR operating conditions including molar loading rates of 0.3 moles/day/m^3, the RP bench cells were able to consistently accomplish greater than 90% reduction of influent metals concentrations.

Conversely, The TD-01 BCRs (Cells 5, 6, 7, and 8) achieved better metals removal in 2005 than 2006. The TD-01 ORP data (Fig. 15) suggests the cells were stressed and transformed between reducing and oxidizing conditions during 2006. Multiple compounding factors contributed to the decreased cell performance in 2006. The BCR cells were inadvertently overloaded with respect to metals (Fig. 13) and acidity for the first 10 weeks of the 2006 study interval. These overloading conditions occurred due to unanticipated increased metals concentrations in the MIW. The sustained overloading likely limited the BCR microbial populations' recovery from the winter freeze. During this time, the RP BCRs were exposed to typical design conditions with respect to metals and acidity loading. Additionally, BCR Cells 5, 6, 7, and 8 were left in place between the 2005 and 2006 bench studies. During freezing conditions, BCRs have been observed to freeze from the outside in, resulting in formation of a layer of ice between the cell substrate and the wall of the reactor. Upon melting, this ice layer may have created a preferential pathway for water to short-circuit the BCR, resulting in decreased metals removal. During transportation of Cells 1, 2, 3, and 4 to the RP site, the substrate was mixed sufficiently to eliminate any preferential pathways that may have occurred from freeze-thaw action. If BCR test cells are allowed to freeze and subsequently thaw, the authors recommend taking measures to eliminate preferential pathways that may have formed along the BCR cell walls.

Conclusion

The BCR treatability studies demonstrated the technology was capable of reducing acidity and metals concentrations from MIW generated at the Elizabeth Mine. The 2006 RP study results suggested seasonal freeze-thaw cycles did not negatively impact cell performances. The 2006 TD-01 data indicates Cells 5, 6, 7, and 8 did not achieve the anticipated metals removal rates, likely due to the cells being chronically overloaded with metals and acidity concentrations during the first 10 weeks of the 2006 study. These studies provided useful performance data about BCRs, which will be used when designing larger systems for the Site.

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