TWO-YEAR SULFATE REDUCING BIOREACTOR PILOT TEST RESULTS AT THE GOLINSKY MINE, CALIFORNIA[1]

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Abstract. The Golinsky site is a small underground copper mine complex consisting of abandoned mine workings and remnants of smelter operations located on a steep hillside above Little Backbone Creek, a tributary to Lake Shasta. The mine pool is typical acidic mining influenced water (MIW) with a pH of 2.5 to 4 containing heavy metals including Fe, Al, Cu, Zn, Cd, and Mn. The US Forest Service committed to a bench and pilot scale testing program to demonstrate that the SRBR technology would work at the remote site and reduce metal loading on Lake Shasta.

A pilot scale SRBR test system was constructed in 2004 and decommissioned in September, 2006 after 26 months of year-round operation. Despite overloading and other operational challenges (e.g., the site is only accessible by boat), the pilot system performed as expected. At the conclusion of the pilot test run, the pilot scale effluent was field-titrated with raw MIW. The results of this effort suggest that SRBR-treated MIW has geochemical benefits beyond the expected straight dilution effects. That is, the elevated alkalinity and sulfide concentrations of the SRBR effluent appear to be capable of providing additional treatment of raw MIW in a simple mixing and settling operation. The titrated mixtures were also tested for toxicity using MetPLATE™ testing kits. A first-phase treatment module is being designed based on the pilot test results.

Additional Key Words: passive treatment, mining influenced water, heavy metals, sulfate reducing bioreactor; aquatic toxicity

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Introduction

The Golinsky Mine is an abandoned underground base metal mine near Lake Shasta, located in Shasta County, California in the Shasta-Trinity National Forest (Fig. 1). The mine was last active in the early part of the 20th century (SHN, 2004) when Cu and Zn and minor amounts of the precious metals were recovered. The mine and an associated milling/smelting complex are in rugged, mountainous terrain. While active, the mine was accessible by a narrow gauge railway that hugged the steep hillside above Little Backbone Creek. The mine was reportedly closed in 1937 when the site's accessibility was severely restricted as a result of the construction of a nearby dam on the Sacramento River (Kinkel et al., 1956). Today, the site can only be reached by boat, about a three-mile (4.8 km) trip from either of two boat launch sites. The mine complex is about a two-mile (3.2 km) hike from the landing site in Little Backbone Bay. The mine complex is at an elevation of 1800 ft. (549 m); the shoreline of Lake Shasta is at an elevation of about 980 ft. (300 m). The challenging access issues at this site were discussed in a previous ASMR paper (Gusek et al, 2005).

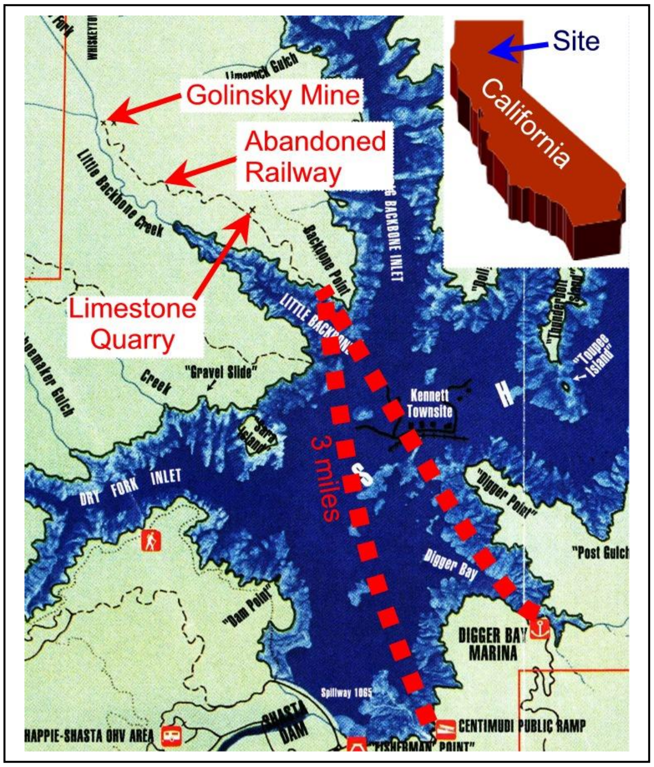


Figure 1. Site vicinity

The geochemistry of the Golinsky Mine ore was dominated by sulfide mineralization, including pyrite. This lead to the inevitable production of acidic mining influenced water (MIW) from three adits, two of which have concrete bulkheads. After the installation of a buried pipeline that terminates in the vicinity of the limestone quarry (Fig. 1), the bulkhead valves were opened so that a mine pool no longer develops behind them. It is noteworthy that the chemistry of the MIW from the third, un-bulkheaded adit has improved since this site management measure was implemented in late 2006. This observation supports an earlier hypothesis (SHN 2004) that MIW from the bulkheaded adits was mixing with the otherwise clean water that may have discharged historically from the third adit prior to the bulkheads' construction. The bulkheaded adit's MIW chemistry had a pH of 2.5 to 4 and contains heavy metals including iron, aluminum, copper, zinc, cadmium, and manganese.

In late 2003, Region 5 of the U.S.D.A. Forest Service elected to investigate methods of treating and discharging the main Golinsky MIW and potentially treating the MIW discharging from the third adit if necessary. These measures would help to protect Little Backbone Creek, which is a tributary to Lake Shasta. Due to the site's inaccessibility and total lack of infrastructure; i.e., no power, passive treatment methods were viewed as especially attractive.

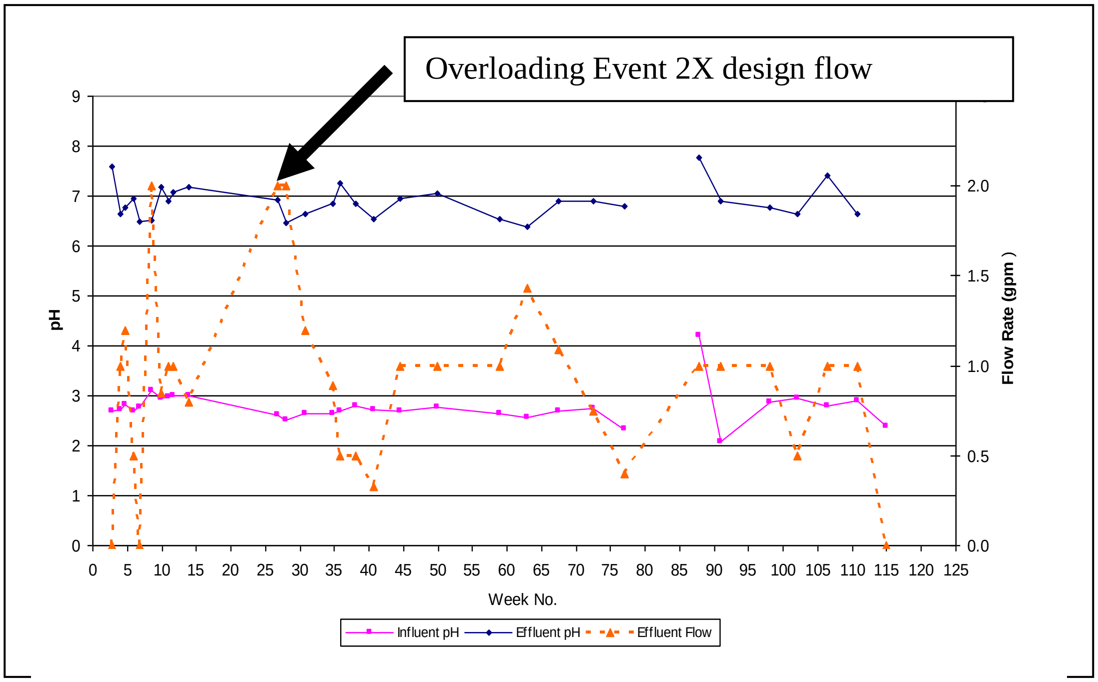
Operational and Analytical Results

The primary purpose of this paper is to share performance data from a 27-month long pilot treatability test of a sulfate reducing bioreactor (SRBR) (see Fig. 2) that was constructed at the

Figure 2. SRBR pilot test cell

limestone quarry in June and July, 2004. The cell dimensions were 9.76 m by 9.76 m (32 ft by 32 ft) with a substrate depth at construction of about 0.76 m (2.5 ft). The geomembrane-lined cell contained 72.5 m^3 (95 cy) of organic-containing substrate comprised of "co-gen fuel" (mostly wood chips) [40% by weight], rice hulls [10%], limestone sand [29%], cow manure [10%], hay [10%] and ash [1%] as described in more detail in Gusek, et al. (2005). MIW flow to the cell commenced in early August, 2004 at a rate of 3.8 L/min (1 gpm). This was the target flow rate for the next 26 months; the cell was decommissioned and dismantled in October, 2006. The pilot test system was typically sampled on a monthly schedule, weather permitting; 33 sampling events were completed during the course of the study. Due to operational difficulties associated with a temporary one-inch (25.4mm) diameter MIW delivery pipeline and the commissioning and operation of a permanent six-inch (152 mm) diameter buried pipeline, the target flow rate was sometimes difficult to maintain precisely.

The average flow for the entire study period was 3.4 L/min (0.9 gpm). Flows were measured using a bucket and stopwatch. The flow rate was only measured during field visits and flow was assumed to be constant between field measurements. Flows and pH data are provided in Fig. 3.



Overloading Event 2X design flow

Figure 3 – Flow and pH Data

While the plotted data throughout the paper is displayed connected by lines may suggest trends, the continuity of data is not inferred due to the infrequency of sampling events necessitated by the restricted access to the site.

The pH of the pilot cell influent ranged from 2.1 to 4.2 and effluent ranged from 6.4 to 7.8. The consistently circum-neutral effluent pH is a good indication that the buffering capacity of the SRBRs substrate was never exceeded. Lab analysis performed for the organic media characterization after decommissioning also demonstrated that the majority of the buffering capacity contained in the limestone fraction of the organic media was undiminished after 26 months of operation.

Water samples were analyzed at the Colorado School of Mines (CSM) Chemistry Department for heavy metals and selected anions using Induction Coupled Plasma/Atomic Emission Spectroscopy (ICP/AES) methods. CSM is not a certified analytical laboratory; to confirm the CSM data quality, split samples were sent to ACZ Laboratories in Steamboat Springs, Colorado for analysis on three occasions. The split sample analysis by ACZ indicates that the CSM analysis results were in close agreement.

Combined Heavy Metals Removal

The combined heavy metals removal percentage (Fig. 4) includes Al, Cd, Co, Cu, Fe, Pb, and Zn removal. The average removal percentage, calculated on a moles per day basis, for the 27-month operational period was 96.1%. This removal rate includes all sampling events including events conducted during the initial three-month startup period. The pilot cell performed remarkably well during the first three months of operation when the removal percentage was always greater than 97%. There were two periods during which the removal rate decreased significantly: the overloading period during Weeks 26 to 30 (flow doubled [Fig. 3] and the MIW average acidity levels increased by 50%), and for Week 87.

The decrease in removal for Weeks 26 to 30 was due to the cell being overloaded with respect to flow and metals loading; the system required another two months to recover (Golder 2005). The low removal rate in Week 87 was due to poor iron removal (53%) while the removal rates of toxic metals such Zn, Cu, and CD did not decrease. Likely causes of the poor Fe removal are subsequently discussed.

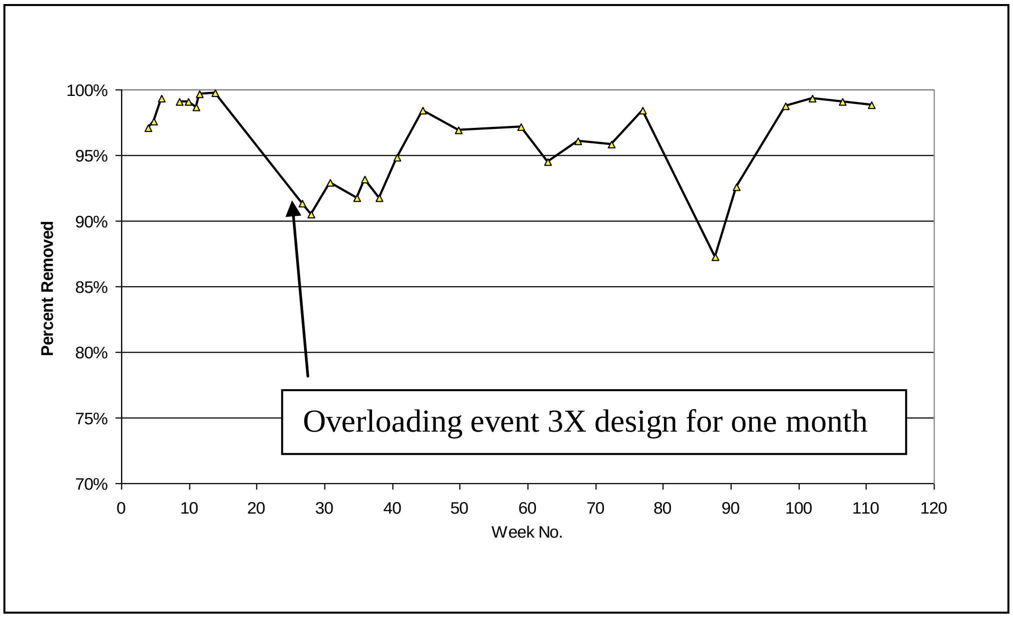


Figure 4 – Combined Metals Removal (Al, Cd, Co, Cu, Fe, Pb and Zn)

Iron and Aluminum Removal

Influent Fe concentrations (Fig. 5) averaged 73 mg/L and ranged significantly from 3.2 to 165 mg/L. Effluent concentrations averaged 6.1 mg/L and ranged from 0.22 to 29 mg/L. Influent Fe concentrations decreased significantly over the 27-month operational period. From startup to June 2005, influent iron concentrations averaged 103.6 mg/L. The decrease in Fe removal in Week 87 may have been due to decreased microbial activity as a result of colder winter temperatures (Fig. 5). Because of residual alkalinity typically present in SRBR effluent, residual iron that may have evaded sequestration in the SRBR can be readily removed aerobically in an aeration channel.

The average influent Al concentration (Fig. 6) was 23 mg/L and average effluent concentration was 0.16 mg/L. Percent removal of Al averaged 99%. Similar to Fe, Al influent concentrations decreased slightly since startup, with the lowest concentrations occurring in the summer of 2006. From startup through decommissioning, the maximum influent concentration was 52 mg/L and minimum influent concentration was 7.6 mg/L.

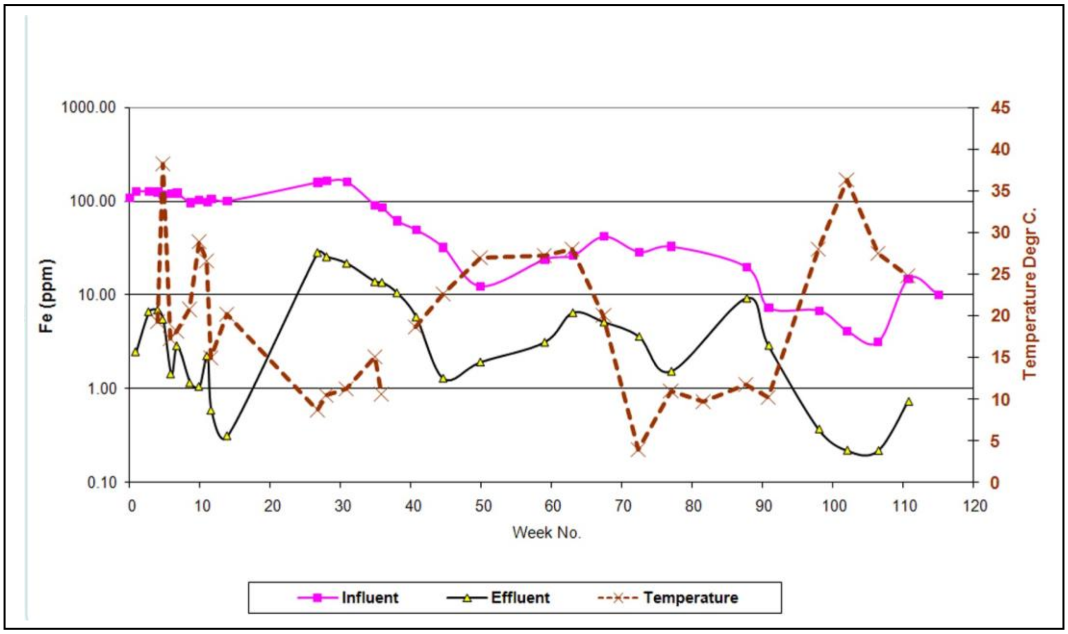


Figure 5 – Iron Removal and Temperature

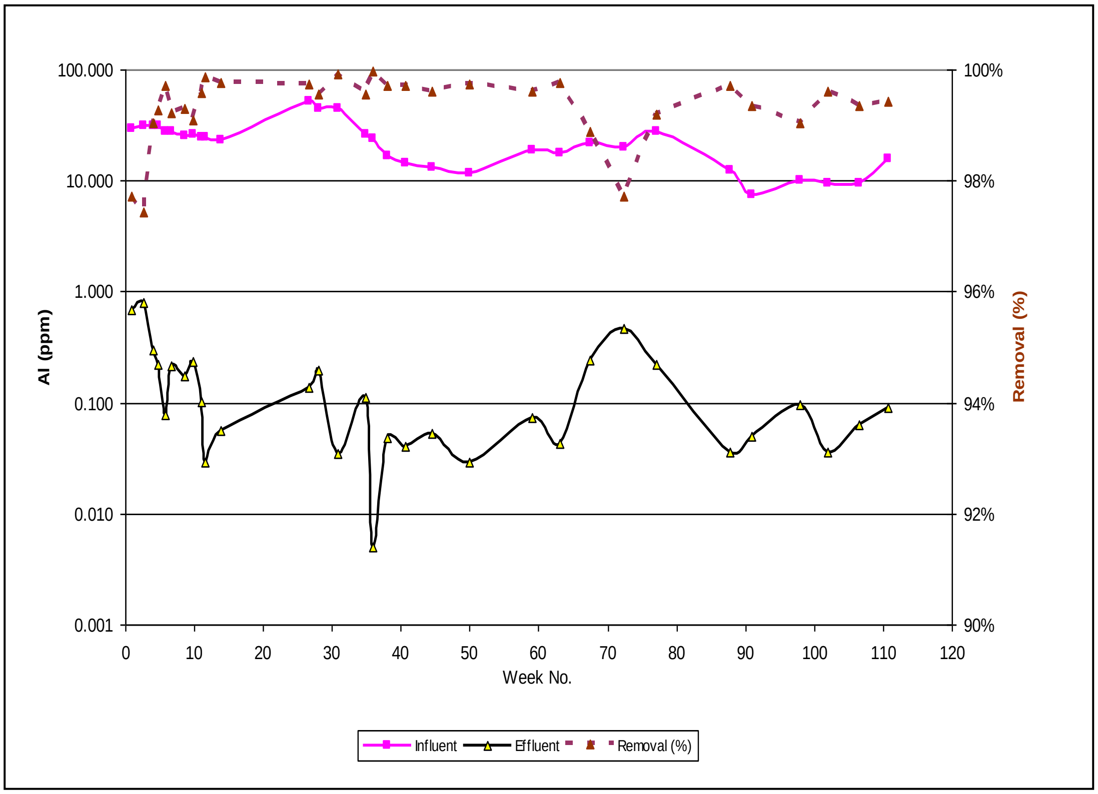


Figure 6 – Aluminum Removal

Copper, Zinc, and Cadmium Removal

The pilot cell typically reduced copper concentrations in the influent by at least two orders of magnitude. Influent and effluent Cu concentration values averaged 12 and 0.027 mg/L, respectively. Copper removal efficiencies above 99% were typical since cell startup.

Influent and effluent Zn concentrations averaged 37 and 1.2 mg/L, respectively. Percent Zn removal improved from an average of 96% prior to July 2005 to 99.6% from July 2005 to August 2006 (final sampling event). The maximum effluent Zn concentrations (11 mg/L peak) occurred briefly (one sampling event) during the overloading event and its after-effects between Weeks 26 to 38.

Cadmium removal performance remained relatively constant from July 2005 to August 2006. The average influent concentration was 0.47 mg/L and the average effluent concentration was 0.0071 mg/L. Removal percent averaged 99% during the 27-month operational period.

Manganese Changes

Influent and effluent manganese concentrations averaged 0.85 mg/L and 1.8 mg/L, respectively. Effluent Mn concentrations were consistently greater than influent concentrations since startup. This is to be expected as Mn removal is typically poor in SRBRs. In fact, the reducing conditions in SRBRs typically release Mn bound in the substrate, at least on a temporary basis, until the mobile Mn compounds have been depleted. For the final year of the test, influent and effluent concentrations were similar, which indicated that the pilot cell had released the easily-soluble Mn that had been present in the substrate and a steady-state condition may have been achieved.

Oxidation-Reduction Potential (ORP) and Temperature (Fig. 7)

Negative ORP values are indicative of anaerobic-reducing conditions conducive to robust sulfate-reducing bacteria health. ORP measurements of the pilot cell effluent were consistently negative throughout the test period, even during the overloading event in 2005 (Weeks 26 to 38).

Figure 7 also shows the history of effluent water temperature. These values reflect ambient temperature of the surrounding air rather than mine pool or buried pipeline soil temperatures, which may be different. Temperatures less than 10ºC are usually inhibiting to bacterial growth; as a rule of thumb, bacterial population reproduction rates typically double for every 10ºC of temperature increase. The lowest effluent temperature (3.7ºC) was measured during Week 72 (December 5, 2005) and three sampling events had measurements of less than 10ºC. However, between October

25, 2005 and January 6, 2006, low air temperatures measured at Shasta Dam were less than or equal to 10º C for 72 days out of the 84-day interval. This suggests that the SRBR cell operated at or perhaps slightly below 10ºC for a significant block of time. With the exception of iron as previously discussed, this condition does not appear to have significantly permanently affected cell performance, which rebounded when the ambient temperatures rose. Certainly, the exposed un-insulated sides of the pilot cell contributed to the temperature effect; full scale SRBR cells would have earthen berms that would mitigate the effects of depressed temperatures. In extreme cases, SRBR cells have been completely buried to protect the substrate from cold climates.

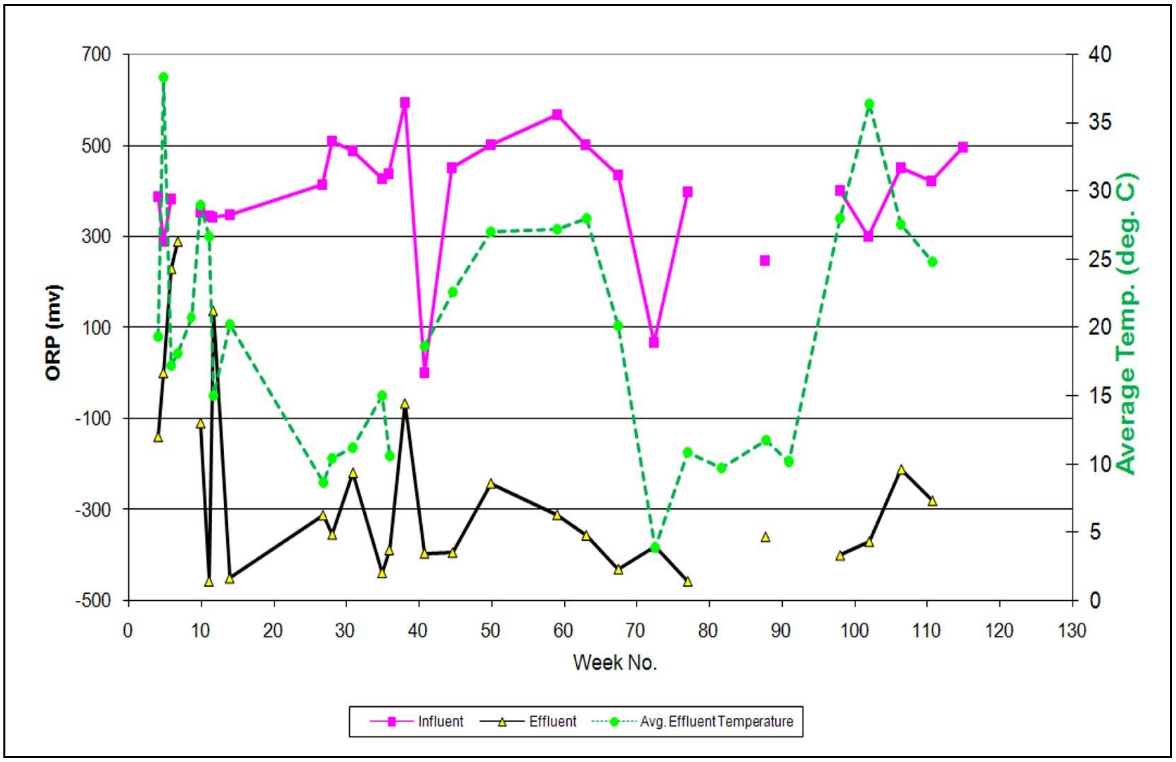


Figure 7 – Oxidation Reduction Potential (ORP) and Temperature

SRBR Effluent – Raw MIW Mixing Study

SRBR effluent typically contains acquired alkalinity and residual dissolved sulfide. These characteristics can be beneficially exploited to neutralize and precipitate metals in MIW that might be by-passed around the primary SRBR treatment unit. This supplemental study consisted of mixing different ratios of MIW and SRBR effluent water to determine a suitable mixing ratio for future treatment efforts at the site. The primary metals of concern for the site are copper and zinc which constitute the majority of the non- Fe or Al metal loading (Table 1). For the purposes of this study, the water treatment goals for the site were the California hardness-based criterion continuous concentration (CCC) (California Federal Register, 40 CFR Part 131).

The study was conducted in four phases:

- Field One-Liter Batch Tests,
- Field 76-Liter Batch Tests,
- Laboratory Sludge Volume Determination, and
- Laboratory MetPLATE™ Analysis.

Details and results of these four phases follow.

Table 1 - California Water Quality Criteria[4] and MIW Characteristics

Parameter		CMC[1] mg/L	CCC[2] mg/L	SRBR Influent mg/L	SRBR Effluent mg/L
Cadmium[6]	Cd	0.0043	0.0022	**0.33**	**0.0052**
Copper[6]	Cu	0.013	0.0090	**5.0**	0.0002
Zinc[6]	Zn	0.12	0.12	**24.9**	0.068
Arsenic	As	0.34	0.15	<0.043	<0.043
Chromium (VI)[3,6]	Cr^{+6}	0.016	0.011	0.0035	0.0011
Lead[6]	Pb	0.065	0.0025	***0.063***	<0.018
Nickel[6]	Ni	0.47	0.052	0.023	0.0036
Silver[6]	Ag	0.0034	-	<0.0033[5]	<0.0033

Notes:

[1] Criterion Maximum Concentration

[2] Criterion Continuous Concentration

[3] Chromium speciation was not undertaken to determine Cr (III) versus Cr (VI) fractions.
Cr present in site water was conservatively assumed to be Cr (VI) which has a more stringent standard.

[4] California Federal Register, 40 CFR Part 131

[5] < Values shown with "<" are below the detection limit shown.

[6] Hardness of 100 mg/L assumed for hardness-based criteria.

Values in **BOLD** exceed the CMC and the CCC.

Values in ***Bold Italics*** exceed the CCC only.

Phase 1 – Field One-Liter Batch Tests

The initial mixing tests were conducted at the Golinsky bioreactor in 1-liter containers and allowed to mix for a two hour period. Temperature, pH, oxidation-reduction potential (ORP), and conductivity were measured at 0, 15, 30, 60, and 120 minutes after mixing. Copper concentration and alkalinity were measured with Hach kits after 120 minutes. After 120 minutes, a dissolved, nitric-preserved, 50 mL decant sample was collected for ICP-AES analysis at the Colorado School of Mines Geochemistry Laboratory in Golden, CO. Summary laboratory results are provided in Table 2 and field parameters are provided in Table 3. The following ratios were mixed:

- 4 Effluent: 1 Influent (4EF:1IN);
- 3 Effluent: 1 Influent;
- 2 Effluent: 1 Influent;
- 1 Effluent: 1 Influent;
- 1 Effluent: 1.5 Influent;
- 1 Effluent: 2 Influent; and
- 1 Effluent: 3 Influent.

Table 2 - One-Liter Batch Test Dissolved Metal Results

Analyte	CCC mg/L	Influent (mg/L)	Effluent (mg/L)	4E:1I (mg/L)	3E:1I (mg/L)	2E:1I (mg/L)	1E:1I (mg/L)	1E:1.5I (mg/L)	1E:2I (mg/L)	1E:3I (mg/L)
Aluminum	NA	16	0.090	0.15	0.12	0.11	0.064	0.071	2.7	11
Copper	0.0090	5.0	0.00025	0.012*	0.0053	0.0043	0.0040	0.0082	0.0079	0.0026
Iron	NA	15	0.73	0.068	0.044	0.082	2.0	1.1	3.8	4.6
Zinc	0.12	25	0.068	0.043	0.020	0.034	0.038	14.0*	4.4	12.4

* Suspected analytical errors.

Table 3 - One-Liter Batch Test Field Parameters after 2 Hours

Mixing Ratio	pH Standard Units	Temperature Degrees Celsius	ORP Millivolts	Conductivity Micro-Siemens per cm.	Alkalinity mg/l as $CaCO_3$
Influent	2.88	30.6	152	1453	0
Effluent	6.55	26.7	-299	1027	527
4EF:1IN	6.49	26.3	-282	944	374
3EF:1IN	6.44	26.8	-299	873	357
2EF:1IN	6.43	27.8	-354	813	289
1EF:1IN	6.08	27.9	-256	707	153
1EF:1.5IN	5.67	34.9	-78	698	119
1EF:2IN	4.83	27.7	-206	638	51
1EF:3IN	4.34	28.6	-93	663	34

Field results from the Phase 1 tests were used to determine mixing ratios for Phase 2. The 1EF:1IN and 1EF:1.5IN ratios were chosen for Phase 2 because these were the lowest ratios that contained acceptable pH values.

Phase 2 expanded on the Phase 1 results using larger test volumes and longer mixing times. A 24-hour mixing study was used to evaluate the 1EF:1IN and 1EF:1.5IN mixtures in 76 liter (L) [20-gallon] plastic containers. After blending, each batch was mixed for approximately 1.5 minutes. Once again, field parameters (temperature, pH, ORP, conductivity), Cu, and alkalinity were measured. For field expediency and to simulate conditions in a mixing/settling pond effluent, decanted samples were collected for total and dissolved analysis after 18 and 24 hours. The amount of settled sludge was also recorded. Summary laboratory results are provided in Table 4 and field parameters are provided in Table 5.

Table 4 - 76-Liter Batch Test Dissolved Metal Results

Analyte Name	CCC[2] mg/L	1 EF:1 IN (18 hrs, DIS[1]) (mg/L)	1 EF:1 IN (24 hrs, DIS) (mg/L)
Aluminum	NA	0.051	0.031
Copper	0.0090	0.0037	0.0022
Iron	NA	1.9	0.83
Zinc	0.12	0.056	0.15

Analyte Name	CCC[2] mg/L	1 EF:1.5 IN (18 hrs, DIS[1]) (mg/L)	1 EF:1.5 IN (24 hrs, DIS) (mg/L)
Aluminum	NA	4.0	3.2
Copper	0.0090	0.018	0.029
Iron	NA	8.2	7.3
Zinc	0.12	5.2	5.0

Notes:

[1] The 76-Liter test solutions were sampled after 18 and 24 hours. Results from dissolved (DIS) samples are shown.

[2] Criterion Continuous Concentration (CCC) (California Federal Register, 40 CFR Part 131), based on 100 mg/L of hardness.

Table 5 - 76-Liter Batch Test Field Parameters

Mixing Ratio	Time and Date	Elapsed Time hrs:min	pH Standard Units	Temperature Degree Celsius	ORP Millivolts	Conductivity Micro-Siemens per cm.	Alkalinity mg/l as $CaCO_3$*
Influent	NA	NA	2.88	30.6	152	1453	0
Effluent	NA	NA	6.55	26.7	-299	1027	527
1EF:1IN	8/30/2006 15:09	0	5.97	30.9	-202	714	NA
1EF:1IN	8/30/2006 15:45	0:36	5.99	32.2	-152	701	NA
1EF:1IN	8/30/2006 16:15	1:06	6.02	32.9	-185	700	NA
1EF:1IN	8/31/2006 9:10	18:01	6.48	25.9	-322	944	136
1EF:1IN	8/31/2006 10:05	18:56	6.49	26.3	-282	944	NA
1EF:1IN	8/31/2006 10:45	19:36	6.51	NA	-248	880	NA
1EF:1IN	8/31/2006 14:37	23:28	6.29	25.8	-230	877	153
1EF:1.5IN	8/30/2006 15:22	0	4.53	29.4	-76	669	NA
1EF:1.5IN	8/30/2006 16:15	0:53	4.54	31.6	-74	670	NA
1EF:1.5IN	8/31/2006 9:15	17:53	4.76	20.3	100	673	34
1EF:1.5IN	8/31/2006 10:10	18:48	4.64	21.8	197	667	NA
1EF:1.5IN	8/31/2006 10:45	19:23	4.67	23.2	255	678	NA
1EF:1.5IN	8/31/2006 14:40	23:18	4.60	31.5	153	681	34

* Alkalinity measurements were conducted at 18 and 24 hours only.

The dissolved Cu results for the 1EF:1IN mixture were similar to the 1-liter batch test results and indicate that no additional benefit was derived from the longer Phase 2 mixing time. The 1EF:1.5IN results in Table 4 provide a more credible zinc concentration than the Phase 1 (1-L) 1EF:1.5IN Zn result of 14 mg/L as shown in Table 2. The 76-L 1EF:1IN zinc concentrations, all of which are approximately 5 mg/L, fit the trend of the 1-L results (Table 2) better than the 14 mg/L value, which is suspected of being due to analytical error.

The field results from the 76-L batch test for the 1EF:1IN mixtures were similar to the 1-L results with respect to pH, conductivity and alkalinity. The 76-L batch test results for the 1EF:1.5IN differed from the 1-L results in terms of pH and alkalinity. The 76-L batch test had a significantly lower pH and less alkalinity than the 1-L batch. The 76-L batch test samples were allowed to react for 24 hours rather than the 2 hours used for the 1 - L tests.

Both of the 1EF:1IN copper concentrations (18 and 24 hr.) and the 18 hr. Zn concentration met the CCC standards. For the 1EF:1.5IN batch tests, neither the Cu nor the Zn concentrations met the CCC standards.

The amount of sludge that precipitated in the 76-L batch tests was not enough to be measured in the field. Consequently, sludge volume analysis was completed in Golder's laboratory, as described below.

Phase 3- Laboratory Sludge Volume Determination

The sludge determination was performed at Golder's Water Treatment Laboratory in Lakewood, CO. Sludge volumes were determined for the 1EF:1IN and 1EF:1.5IN mixtures using one-liter Imhoff cones. After 24 hours, a wet sludge volume was recorded and the mixtures were filtered through Whatman #40 filters. The filters were placed in a drying oven overnight and weighed the next day to determine a dry sludge mass.

The 1EF:1IN solution generated 7 milliliters of wet sludge and 0.024 grams per liter of dry sludge. The 1EF:1.5IN solution generated 2.5 milliliters of wet sludge and 0.029 grams per liter of dry sludge. Based on these results, an appropriate sludge generation rate will be incorporated into future passive treatment mixing/settling pond designs at the site.

Phase 4- Laboratory MetPLATE™ Toxicity Testing.

Toxicity testing was conducted in a US Geological Survey Laboratory in Denver, Colorado to provide another basis of comparison for the mixing solutions. The goal of the testing was to determine the toxicity of mixing ratios relative to the toxicity of raw SRBR effluent. Aside from outright metals removal, bioreactor treatment decreases metal toxicity by increasing hardness, organic matter, and alkalinity.

The trend toward using the Biotic Ligand Model (BLM) in biological assessments is gaining regulatory acceptance (USEPA 2003). However, the model has difficulty assessing the cumulative impacts of multiple metals in a given MIW. The MetPLATE™ method avoids this difficulty by directly testing the MIW, and has proven to be faster, more cost-effective, and it requires less manual labor than traditional methods using other aquatic toxicity testing organisms (e.g., Whole Effluent Toxicity [WET]), so it was used in the evaluation. The MetPLATE™ inhibition bioassay test methods have been adapted from Bitton (1994) and recently evaluated by Blumenstein (2006); for the sake of economy and project schedule, the bioassay technique was used in place of WET testing.

The MetPLATE™ bioassay measures the inhibition of the β-galactosidase hydrolase enzyme when *Escherichia coli* (*E. coli*) bacteria come into contact with heavy metal (such as Zn and Cu) contaminated waters. When the E. coli are healthy, there will be high β-galactosidase enzyme activity and high absorbance readings. Conversely, when there are metals present in the sample water, the *E. coli* will be unhealthy and there will be low β-galactosidase enzyme activity, resulting in lower absorbance readings. The MetPLATE™ bioassay was used to assess the health of aquatic organisms that had been exposed to different mixing ratios of SRBR effluent water and untreated MIW. A detailed assessment of this part of the study may be addressed in a future paper. For completeness, the mathematically-based BLM was first used to estimate impacts from Cu, Zn, and Cd in the Golinsky MIW combined in various ratios of SRBR effluent. The results suggested that 2 EF: 1IN mixing ratio would provide a net system effluent that would pass the BLM criterion for Cu and Zn but not for Cd. This is considered a relatively dilute ratio when compared to 1EF:1IN.

The data shown in Fig. 8 suggest that there are two relative conditions of *E. coli* bacterial inhibition: the relatively dilute mixtures of straight SRBR effluent and up to 2EF:1IN show a comparable level of inhibition, while the untreated Golinsky MIW and the 1EF:1IN mixtures show a high (100%) level of inhibition. In other words, any mixing ratio that consists of at least two parts SRBR effluent to one part MIW influent, or 2EF:1IN should result in water of comparable toxicity to raw SRBR effluent for the *E. coli* organisms in the MetPLATE™ bioassay. Unfortunately, Fig. 8 does not include a control data set; typical MetPLATE$^{\text{TM}}$ controls might expect 30% or higher inhibition values. The authors recommend that any full scale system designs that incorporate the benefits of by-pass mixing at other sites should use the MetPLATE™ bioassay to test appropriate mixing ratios. It should be noted that typical SRBR effluent receives a final polish in an aerobic environment before discharge. Thus, the percent inhibitions shown in Fig. 8 might be even less in a full scale treatment system with or without a mixing unit.

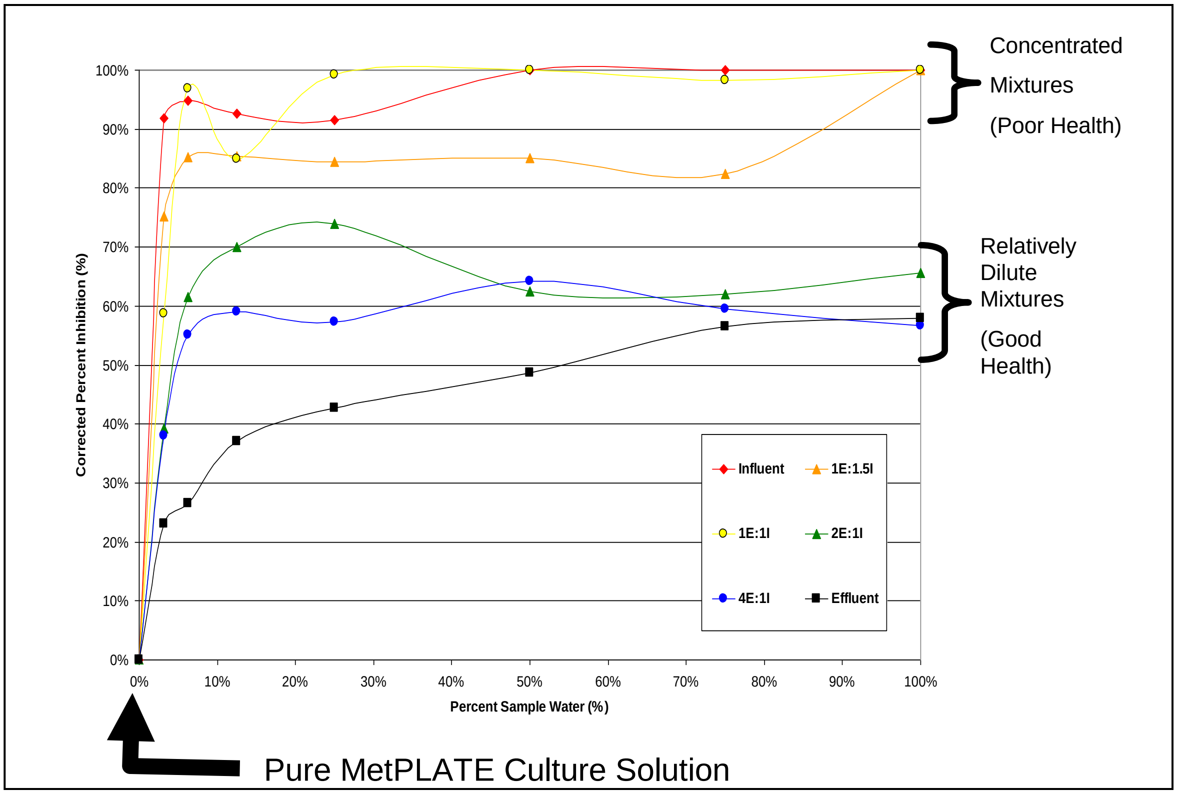


Figure 8 – Mixing Study MetPLATE^{TM} Results; Corrected Percent Inhibition vs. Sample Water Content

Pilot Test Performance Summary

The pilot cell performance was consistent with SRBR cell performance at other mining sites with similar MIW chemistry. Key system performance observations include:

- The system was operated virtually unattended at steady-state without any upset conditions.
- The flow-driven concentrations of metals observed during pilot operation were similar to what were previously documented at the site (SHN, 2004). Concentrations of iron, Al, Cu, Zn, and Cd are greatest during the rainy, high-flow winter months and decrease in the low-flow summer months.
- The concentration of metals present in the pilot cell influent decreased over the course of the test. In the example of iron, the average influent concentrations for the first 12 months of

operation compared to the final 15 months of operation exhibited about an order of magnitude decrease (see Fig. 5). Other metals exhibited similar behavior. One potential contributing factor to the decrease may have been the reduced detention time of MIW in the mine pool due to its steady withdrawal and treatment, even at the average rate of only 3.4 liters per minute (about 34,272 liters per week). A shorter contact time between the mine pool water and the pyritic mine rock should decrease the acidity and metals concentrations of the mine pool water. If this reasoning is correct, a smaller ultimate treatment system may be required if metals concentrations and acidity remain depressed.

- The average metals removal was typically greater than 95%.
- The system sustained temporary overloading of three times design in Weeks 26 to 30 but eventually recovered by Week 41, when combined removal efficiency returned to about 95%.
- By the end of the test period, effluent Mn concentrations decreased to influent levels. This suggests that the substrate was finished releasing Mn into the pilot effluent and Mn solubility had reached a steady state condition in the SRBR substrate.
- The pilot scale treatment system treated a volume of approximately 4.3 million liters (1.13 million gallons) between July 2004 and October 2006.
- Mixing study results suggest that the 1EF:1IN mixing ratio meets the applicable water quality standards for Cu and Zn at the Golinsky site.
- Toxicity testing results suggest that an effluent to influent ratio of 2EF:1IN would likely meet Biotic Ligand Model derived standards and produce and effluent of comparable toxicity to raw SRBR effluent.

Conclusions

The implementation of a sulfate reducing bioreactor system with a by-pass/mixing component at the Golinsky site was included in a conceptual design developed for a supplemental engineering evaluation/cost estimate (Golder 2007). Subsequent design efforts of a Phase 1 module for treating a portion of the Golinsky MIW are underway and they too include a by-pass mixing pond. The treatment design approach has included bench, pilot, and laboratory scale testing and the authors feel that this design protocol should result in a treatment system that is protective of the waters of Lake Shasta by meeting effluent goals, requires infrequent maintenance, and is a cost-effective use of available remediation funds.

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