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Galkeno 900 Sulfate-Reducing Bioreactor Interim Report

2009 Closure Studies

Prepared by:

Alexco Resource US Corp
For ERDC

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1. Project Summary

A bioreactor has been constructed in the Keno Hill mining district at the Galkeno 900 adit to demonstrate the viability of sulfate reduction technology for the removal of metals, especially zinc and other metals that react with aqueous sulfide. The bioreactor solid phase substrate is coarse rock from a nearby placer mining operation. The organic substrate includes dissolved organic carbon forms, with sugars, alcohols and complex carbohydrates and proteins from milk being used during the growth phase of the bioreactor operation, and sugars and alcohols being used during the maintenance phase. The purpose of the organic substrate was initially to support microbial growth until sulfate reduction became the predominant microbial activity in the reactor, and during the treatment phase its purpose is to support microbial sulfate reduction, which is a microbial reaction that transfers electrons from organic carbon, causing sulfate to be reduced to sulfide. Sulfide reacts with many dissolved metals, forming very insoluble metal precipitates. The reactor also has the potential for other reactions to occur as a result of alkalinity being generated from the oxidation of organic carbon, and such as carbonate mineral formation within the bioreactor.

The bioreactor demonstration is a multipurpose program to assess the potential to add an organic substrate to mine adit water to support metals removal, whether in a constructed bioreactor, within a mine pool, or in a naturally permeable zone outside a mine such as in a naturally occurring bog or gravel bed. Conceptually, the sulfide- and carbonate-based mineral precipitation that occurs in a bioreactor is similar to what would occur in a mine pool or natural reduction zone outside of a mine pool. Alexco owns six patents and has additional patents allowed and pending for the in-situ use of organic substrates and nutrients in earthen materials to stabilize metals. Alexco's technologies and patents provide in-situ encapsulation technologies whereby soluble toxic metals including arsenic, cadmium, nickel, selenium, and zinc are geochemically encapsulated by more benign minerals within the groundwater aquifer or within and downgradient of sources of contamination such as within a pit lake, tailings impoundment, heap leach pad or waste storage area. One patent that is applicable to this treatment approach is US patent #5,710,361, which describes amendment of metals-containing water with a carbon source to cause precipitation of metals during flow through rock or earthen materials via sulfate reduction.

Galkeno 900 has water chemistry and flow characteristics that are typical of several other adits in the district. The test is of sufficient scale and will be operated long enough to provide design information that will allow the design of either a large scale bioreactor or an in situ reduction field at several other adit drainage locations in the UKHM district. The test is operated in a lined bioreactor so that the performance of the technology will be assessed while still in containment, but the results of the tests (reaction rates and stoichiometry) can be extended in the design of either a lined or an unlined system. The operation of the reactor will be continued into the next year to continue to refine wintertime operation approaches and demonstrate durability of metals removal mechanisms. During the course of the bioreactor demonstration, the conventional lime treatment system continues to be maintained to ensure water license discharge compliance criteria are met.

This report discusses data since the last report (June 2009), with data inclusive from May 2009 through February 2010. During this time period, three distint performance periods can be identified:

- Recirculation phase: A recirculation period with where minor adit inputs (averaging ~ 1 liter per minute) continued from June 2009 through July 2009. During this time the bioreactor appears to have continued to be in a growth phase with incomplete formation of reducing conditions. During this period of time, the reactor likely had zones of aerobic conditions as well as zones with anaerobic conditions. The removal mechanisms during this time period may include oxidative mechanisms (iron and manganese oxide formation), carbonate mineral formation, and perhaps sulfide precipitation.
- Reduction Onset Phase: A recirculation period, where higher concentrations of carbon sources were used to hasten the onset of more strongly sulfate-reducing conditions, which occurred from the end of July 2009 through September 2009. During this time an onset and development of stronger reducing conditions was observed, characterized by greater sulfate reduction, the dissolution of manganese and iron from the reactor solid phase (likely manganese and iron oxides formed during initial bioreactor operations), and greater metals removal as sulfides.
- Operational Treatment Phase: A through-flow period was initiated in October 2009, and has continued to the present. An initial adit flow into the reactor was at a rate of 0.5 liters per second, and after stable conditions had been maintained for several consecutive bimonthly samples, the flow rate was increased to 1 liter per second in December 2009. This is the current flow rate into the bioreactor, and is approximately one-fourth of the Galkeno 900 adit flow.

This report primarily focuses on the operational treatment phase. The other phases, while important, are reflective of treatment performance during the development of the reactor into a competent treatment bioreactor, and were not at a rate of adit water inputs that would be required for the bioreactor technology to be effective as a treatment technology for adit discharges in the district.

During the operational treatment phase at 0.5 l/s, results showed metals removal close to 99.8% zinc has been achieved since early May 2009 (5-6 mg/L reduced to 0.011 mg/L). During the operational treatment phase at 1.0 l/s 97.8% removal has been achieved. Table 1 shows that other metals have also been substantially removed in the bioreactor at 0.5 l/s and 1.0 l/s respectively: antimony (78% and 80%), arsenic (58.8 and 82%), cadmium (93.2% and 93.2%), cobalt (79.2% and 64%), and nickel (97.5% and 83.7%). While zinc is the primary constituent of concern, the reduction of these other constituents will have beneficial effects in the reduction of toxicity where elevated metals have a combined toxicity more than any one metal alone. Iron and manganese, which showed good removal during the recirculation phase (99% for both metals) showed a dissolution and production from the bioreactor during the reduction onset and throughflow phases. Manganese now passes through the reactor unchanged, while iron is still slowly releasing from the reactor. Conservative elements show less than 10% change during passage through the bioreactor, including calcium, magnesium, silica, sodium and strontium, showing that dilution is not a significant factor causing metal removal in the reactor.

Table 1. **REMOVAL PERCENTAGES FOR THE THREE OPERATIONAL TIMEFRAMES FOR KEY PARAMETERS.**

	As-D	Sb-D	Cd-D	Co-D	Fe-D	Mg-D	Mn-D	Ni-D	Sr-D	SO4-D	Zn-D
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Recirculation (% reduction)	97%	79%	69%	99%	99%	-2%	99%	88%	4%	10%	91%
Reduction Onset (% reduction)	-5%	69%	57%	8%	-233%	-6%	-107%	82%	-5%	21%	96%
Throughflow 0.5 l/s (% reduction)	58.8%	78.0%	93.2%	79.2%	-503.1%	-0.8%	-13.4%	97.5%	3.9%	19.0%	99.8%
Throughflow 1.0 l/s (% reduction)	82.0%	80.0%	93.2%	64.0%	-376.2%	6.5%	-1.7%	83.7%	1.1%	5.4%	97.8%

2. Bioreactor Operations

Operational notes from the previous report are included below for context. The bioreactor construction occurred in the fall 2008. The following timeline outlines the major events associated with construction and startup:

- July-August 2008: pond construction and lining (see Figures 13 and 14)
- September 2008: pond filling with placement of sand lining layer and placement of rock from placer operation (see Figures 15-17)
- October 2008: pond filling with water began October 4.
- October 2008: 200 lbs sucrose added October 10-11.
- October 2008: 110 gallons methanol and 4 lbs dried milk solids added October 16
- October 2008: covering bioreactor with geotextile and several feet soil cover.
- October 2008-present: occasional "top up" of mine water from Galkeno 900 adit discharge to maintain full conditions in bioreactor in range of 1 m3/day
- January 2009: 110 gallons methanol added January 23
- January 2009: determination of leakage rate from bioreactor: 1.09 m3/day
- February 2009: tank overflow and loss of ~135 m3 water from bioreactor through tank overflow
- May 2009: began adding methanol at a rate of 1 liter per day.

Since this initial operation period, the following major events occurred:

- July 2009: added 10 kg sucrose on both July 11 and 12 to jumpstart reduction, continued methanol addition at 1 liter per day.
- August 2009: installed totalizer and flowmeter
- October 9, 2009: initiated flowthrough at a rate of 0.5 liters per second
- December 12, 2009: initiated flowthrough at a rate of 1.0 liters per second.
- January 7-20: valve box flooded and frozen, thawed and repaired on January 20
- February 15: power loss to pump
- February 16-18: backsiphon loss of approximately one half of the volume of the bioreactor through pump side, power restoration and line thawing, refill bioreactor

2.1. RECIRCULATION DYE TEST

The exact volume of the reactor needs to be determined independently to assess residence time and other performance characteristics of the bioreactor. The dimensions of the reactor are approximately 100 feet x 90 feet and the depth of the water in the reactor is approximately 10 feet. With an estimated porosity of 0.35, the volume is estimated to be 31,500 ft^3, or approximately 235,000 gallons. A dye test was used to independently assess the volume in the reactor.

0.5 pounds of rhodamineWT dye were added to the bioreactor on August 25, and water was recirculated in the bioreactor at a rate of 2 liter per second. After equilibrium conditions were reached in 6 days, a final dye concentration of 0.25 ppm dye was measured. The volume of the bioreactor was determined by the following formula:

Volume of reactor (in gallons) = lbs dye added ÷ concentration measured × 1,000,000 ÷ 8 lbs per gallon

Using this formula, the volume of the bioreactor was calculated to be approximately 240,000 gallons, which is consistent with the estimated volume based on the dimensions of the bioreactor and the estimated porosity of the rock. This is equivalent to 909 m3 of water contained in the bioreactor.

It is also instructive to determine the amount of hydraulic residence time for water entering the reactor. At 0.5 l/s, assuming the total porosity of the bioreactor is utilized, approximately 21 days of residence time is available, and at 1.0 liters per second, approximately 10.5 days of residence time are available.

The dye test was run at a faster rate and under recirculation conditions. By definition, when the peak concentration of dye is measured in the effluent, 50% of the dye has passed through the reactor. The time for the peak dye to exit the bioreactor at 2 liter per second recirculation was determined to be approximately 1.03 days into the bioreactor operation. This much faster flow rate indicates breakthrough of the dye along flow paths that "short circuit" i.e., do not interact with the entire porosity of the bioreactor. Figure 1 shows conceptualization of flow in the bioreactor.

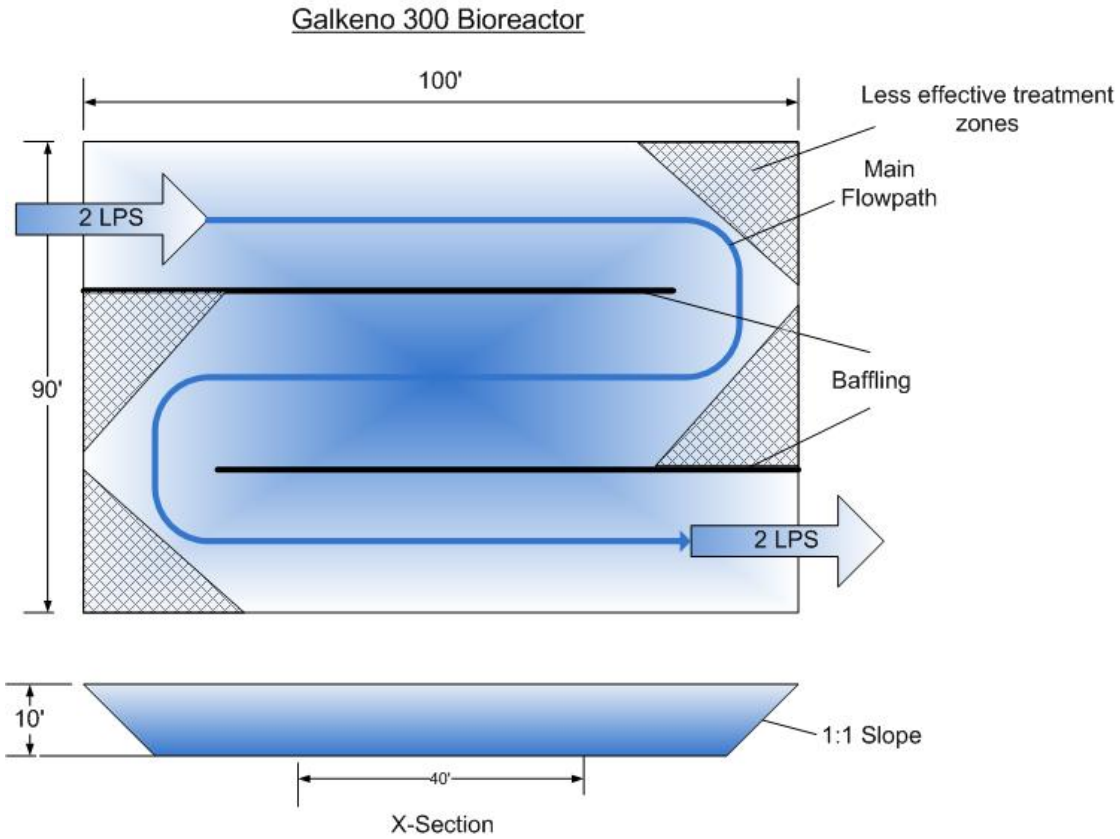


FIGURE 1. CONCEPTUALIZATION OF FLOW PATHS IN THE BIOREACTOR.

The "less effective treatment zones" are zones where water entering the bioreactor does not interact with the media in the bioreactor, and hence these zones only minimally contribute to the treatment performance of the bioreactor. The practical residence time in the bioreactor can be

estimated as 2 times the breakthrough time of the dye peak. This residence time corresponds to the volume of the reactor that participates in rapid exchange of influent water to the bioreactor discharge (this will be termed the "effective residence time"). (Note, in most porous media, there is a tailing phenomenon, where dye concentrations do not behave "normally" in a bell shape curve, but the second half of the curve "tails", i.e., there is a slow bleed out of dye from slower flowing zones in the reactor which increases the time required for the washout of the dye. However, for design of bioreactors, these zones cannot be relied upon for treatment, and hence the 2X dye peak is used for design purposes.)

TABLE 2. CALCULATED RESIDENCE TIMES FOR TOTAL AND ACTIVE POROSITY IN THE GALKENO 900 BIOREACTOR.

Flow rate	Residence time (total porosity)	Residence time (active porosity)
0.5 l/s	21.0 days	9.0
1.0 l/s	10.5 days	4.5
2.0 l/s	5.25 days	2.25

Table 2 summarizes that residence times for the bioreactor under relevant flow conditions.

2.2. FLOWTHROUGH DYE TEST

This section to be completed in final draft as test is being re-run now.

3. Bioreactor Performance

The operation of the bioreactor with respect to water chemistry changes is summarized in Table 3 and 4, and Appendix 1 which contains all of the field data.

3.1. General parameters

The pH of the reactor did not substantially change through the operational period, with the inflow and outflow from the reactor in the same range as the pH of the adit drainage. Figure 2 illustrates the pH of the influent and effluent from the reactor.

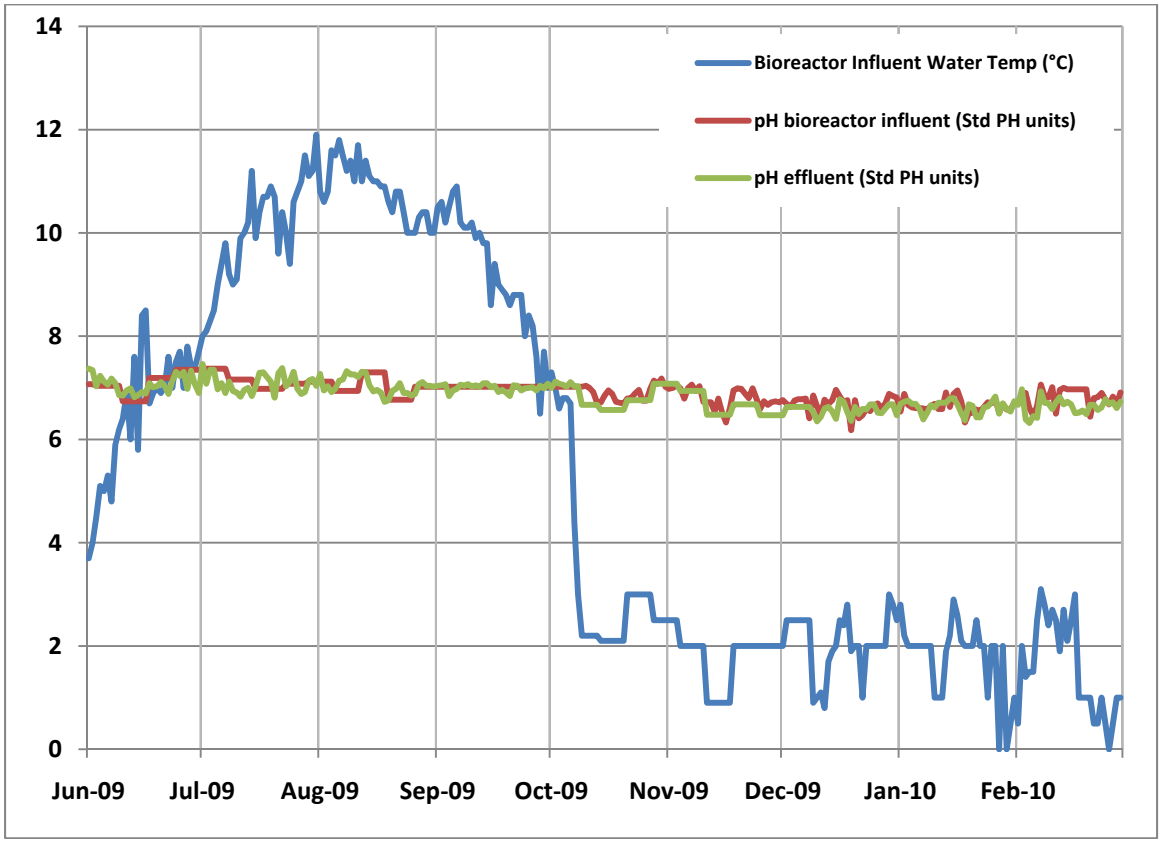


Figure 2. Comparison of Galkeno 900 adit pH and Bioreactor pH.

Figure 2 also shows water temperature of the influent water. It is important to note that the throughflow tests were performed in the cold period of the bioreactor, while the recirculation and reduction onset phases occurred while the bioreactor water temperature was over 4°C.

3.2. Dissolved Metals

The primary metal being tracked at the Galkeno 900 bioreactor is zinc. However, other metals will contribute to the toxicity of the water, and hence the water chemistry of all dissolved metals have been evaluated. Tables 3 and 4 summarize the key parameters in the influent and effluent of the bioreactor, respectively. Key metals are discussed in the following sections.

TABLE 3. CONCENTRATIONS OF KEY CONSTITUENTS IN THE GALKENO 900 ADIT DISCHARGE/BIOREACTOR INFLUENT.

		As-D	Sb-D	Cd-D	Co-D	Fe-D	Mg-D	Mn-D	Ni-D	Sr-D	SO4-D	Zn-D
Location	Sample Date	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Bioreactor Influent												
Galkeno 900 Adit Discharge	5/7/09	0.0680	0.0026	0.0014	0.0250	1.85	39.00	17.90	0.1880	0.4530	1095.0	6.07
Galkeno 900 Adit Discharge	6/6/09	0.0687	0.0024	0.0016	0.0273	1.66	39.00	18.00	0.2030	0.4490	1113.0	6.29
Galkeno 900 Adit Discharge	7/8/09	0.0628	0.0026	0.0015	0.0254	1.72	38.00	16.50	0.1830	0.4810	966.0	5.93
Galkeno 900 Adit Discharge	8/18/09	0.0641	0.0026	0.0014	0.0265	1.39	39.00	17.60	0.1970	0.4470	930.0	6.05
Galkeno 900 Adit Discharge	9/11/09	0.0640	0.0025	0.0014	0.0252	1.84	41.00	17.90	0.1940	0.4540	910.0	6.05
Galkeno 900 Adit Discharge	10/9/09	0.0679	0.0027	0.0014	0.0252	1.96	39.00	17.50	0.1830	0.4850	930.0	4.97
Galkeno 900 Adit Discharge	11/12/09	0.0508	0.0022	0.0014	0.0264	0.62	38.00	17.60	0.1950	0.4530	960.0	5.90
Galkeno 900 Adit Discharge	12/2/09	0.0702	0.0026	0.0016	0.0285	2.00	43.00	19.00	0.2110	0.4700	950.0	6.22
Galkeno 900 Adit Discharge	1/12/10	0.0589	0.0025	0.0015	0.0234	1.57	38.00	17.70	0.1830	0.4590	940.0	5.90
Galkeno 900 Adit Discharge	2/11/10	0.0586	0.0023	0.0013	0.0246	1.74	38.00	16.50	0.1880	0.4170	960.0	5.77
Recirculation (Avg)		0.0665	0.0025	0.0015	0.0259	1.74	38.6667	17.4667	0.1913	0.4610	1058.0	6.09
Recirculation (Std-Dev)		0.0032	0.0001	0.0001	0.0012	0.10	0.5774	0.8386	0.0104	0.0174	80.0	0.18
Reduction Onset (Avg)		0.0641	0.0026	0.0014	0.0259	1.61	40.0000	17.7500	0.1955	0.4505	920.0	6.05
Reduction Onset (Std-Dev)		0.0001	0.0001	0.0000	0.0009	0.32	1.4142	0.2121	0.0021	0.0049	14.1	0.0
Throughflow 0.5 l/s (Avg)		0.0630	0.0025	0.0015	0.0267	1.53	40.0000	18.0333	0.1963	0.4693	946.7	5.69
Throughflow 0.5 l/s (Std-Dev)		0.0078	0.0002	0.0001	0.0019	0.56	2.1679	0.8905	0.0117	0.0254	13.0	0.46
Throughflow 1.0 l/s (Avg)		0.0588	0.0024	0.0014	0.0240	1.65	38.0000	17.1000	0.1855	0.4380	950.0	5.83
Throughflow 1.0 l/s (Std-Dev)		0.0002	0.0001	0.0001	0.0008	0.12	0.0000	0.8485	0.0035	0.0297	14.1	0.09

TABLE 4. CONCENTRATIONS OF KEY CONSTITUENTS IN BIOREACTOR EFFLUENT.

		As-D	Sb-D	Cd-D	C-TOC	Co-D	Fe-D	Mg-D	Mn-D	Ni-D	Sr-D	SO4-D	Zn-D	Sulfide
Location	Sample Date	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Bioreactor Effluent	5/21/09	0.0024	0.0004	0.0005	3.1	0.0001	0.02	38.00	0.15	0.0357	0.4340	1100.0	0.6390	0.0060
Bioreactor Effluent	6/4/09	0.0016	0.0004	0.0004	3.4	0.0002	0.02	41.00	0.21	0.0238	0.4260	940.0	0.5500	0.0080
Bioreactor Effluent	6/18/09	0.0018	0.0006	0.0004	2.9	0.0005	0.02	42.00	0.23	0.0190	0.4310	880.0	0.5420	0.0050
Bioreactor Effluent	7/2/09	0.0022	0.0007	0.0004	3.5	0.0005	0.02	41.00	0.24	0.0190	0.4430	920.0	0.5320	0.0050
Bioreactor Effluent	7/16/09	0.0018	0.0006	0.0006	22.5	0.0005	0.02	36.00	0.43	0.0170	0.4680	900.0	0.6040	0.0080
Bioreactor Effluent	7/30/09	0.0058	0.0020	0.0026	19.8	0.0273	0.04	41.00	26.50	0.0680	0.4550	850.0	1.1100	0.0180
Bioreactor Effluent	8/13/09	0.0339	0.0005	<0.0001	17.1	0.0731	0.18	42.00	56.10	0.0660	0.4660	840.0	0.2200	0.0110
Bioreactor Effluent	8/27/09	0.0670	0.0005	<0.0001	34.4	0.0136	18.90	43.00	40.10	0.0040	0.4680	850.0	0.0100	0.0770
Bioreactor Effluent	9/10/09	0.0880	0.0005	<0.0001	21.7	0.0033	6.01	44.00	33.60	<0.001	0.4830	640.0	0.0100	0.0150
Bioreactor Effluent	9/24/09	0.1400	0.0005	<0.0001	14.3	0.0014	1.74	42.00	27.20	0.0010	0.4910	440.0	0.0100	0.1220
Bioreactor Effluent	10/9/09	0.0143	0.0008	<0.0001	12.3	0.0051	0.17	43.00	21.40	0.0180	0.4340	410.0	0.0100	
Bioreactor Effluent	10/20/09	0.0447	0.0005	<0.0001	3.8	0.0070	13.10	40.00	20.80	0.0060	0.4620	800.0	0.0180	0.2160
Bioreactor Effluent	11/5/09	0.0327	0.0005	<0.0001	10.7	0.0060	16.30	41.00	20.80	0.0010	0.4460	860.0	0.0100	0.0910
Bioreactor Effluent	11/16/09	0.0383	0.0005	<0.0001	2.1	0.0059	15.00	40.00	20.30	0.0010	0.4580	780.0	0.0100	0.1080
Bioreactor Effluent	11/30/09	0.0053	0.0005	<0.0001	10.5	0.0055	0.02	40.00	19.90	0.0020	0.4520	870.0	0.0100	0.0990
Bioreactor Effluent	12/14/09	0.0202	0.0005	<0.0001	9.3	0.0038	10.70	38.00	19.50	0.0020	0.4550	880.0	0.0130	0.1040
Bioreactor Effluent	12/28/09	0.0105	0.0005	<0.0001	2.0	0.0058	7.39	40.00	18.60	0.0090	0.4740	920.0	0.0700	0.3400
Bioreactor Effluent	1/11/10	0.0104	0.0005	<0.0001	1.1	0.0070	7.16	39.00	18.80	0.0070	0.4510	990.0	0.0320	0.7600
Bioreactor Effluent	1/25/10	0.0075	0.0005	<0.0001	1.3	0.0063	6.18	37.00	18.10	0.0110	0.4680	820.0	0.0480	0.2180
Bioreactor Effluent	2/9/10	0.0081	0.0005	<0.0001	1.2	0.0251	4.95	33.00	16.70	0.1310	0.4720	870.0	0.4760	0.0810
Recirculation (Avg)		0.0020	0.0005	0.0005	7.1	0.0004	0.02	39.6000	0.2498	0.0229	0.4404	948.0000	0.5734	0.0064
Recirculation (Std-Dev)		0.0003	0.0001	0.0001	8.6	0.0002	0.00	2.5100	0.1048	0.0076	0.0166	87.8635	0.0461	0.0015
Reduction Onset (Avg)		0.0669	0.0008	0.0006	21.5	0.0237	5.37	42.4000	36.7000	0.0348	0.4726	724.0000	0.2720	0.0486
Reduction Onset (Std-Dev)		0.0515	0.0007	0.0011	7.8	0.0294	7.94	1.1402	12.1637	0.0373	0.0143	182.2910	0.4772	0.0492
Throughflow 0.5 l/s (Avg)		0.0259	0.0006	0.0001	8.1	0.0056	9.21	40.3333	20.4500	0.0050	0.4512	766.6667	0.0118	0.1236
Throughflow 0.5 l/s (Std-Dev)		0.0151	0.0001	0.0000	4.1	0.0011	7.31	1.6330	0.6892	0.0066	0.0100	179.2949	0.0033	0.0520
Throughflow 1.0 l/s (Avg)		0.0113	0.0005	0.0001	3.0	0.0096	7.28	37.4000	18.3400	0.0320	0.4640	896.0000	0.1278	0.3006
Throughflow 1.0 l/s (Std-Dev)		0.0051	0.0000	0.0000	3.6	0.0087	2.14	2.7019	1.0455	0.0554	0.0104	63.4823	0.1958	0.276722

3.2.1. Zinc

The concentrations of zinc in the bioreactor were approximately 90% reduced comparing influent and effluent from the reactor during the recirculation phase where only minor additions of water (approximately 1 liter per second) was being added to the reactor. During the onset of more strongly reducing conditions in the summer of 2009, dissolved zinc concentrations were decreased to below detection limits (0.01 mg/L). After this removal was confirmed for several consecutive sampling periods, the bioreactor treatment phase was initiated at 0.5 l/s in October 2009. Figure 4 illustrates the removal efficiency of the bioreactor during both treatment periods, incluing the 0.5 l/s flow rate, and the 1.0 l/s flow rate. During the 0.5 l/s time period approximately 3 pore volumes were exchanged (calculated on a total porosity basis) and when calculated on a reactive volume estimated by 2X the dye peak, nearly 8 pore volumes would have been exchanged during this period. This shows that the treatment cannot be attributed to dilution by previously treated water.

During the 1.0 l/s treatment phase, approximately 6 pore volues (calculated on a total porosity basis) passed through the bioreactor prior to the loss of power and pump failure that led to the bioreactor being back-siphoned out. The loss of complete treatment that occurred after the refilling of the bioreactor is attributed to the refilling of the bioreactor with approximately half of the volume of the reactor in February 2010. However, even with this refilling the bioreactor still removed over 95% of the zinc in the sample taken immediately after refilling. (Note: preliminary March 2010 data indicates that the removal efficiency has dropped to closer to 80%, indicating that the freezeup and refilling of the reactor has had some lasting negative effects.)

The conclusions that can be reached from the first 4 months of bioreactor operation, before the pump failure, are that dissolved zinc can be effectively removed at 0.5 l/s flow rate with an effective residence time of 9 days, or a total residence of 21 days, and the first two months of operation at 1.0 l/s also effectively removed dissolved zinc. However, there was a difference between dissolved zinc removal and total zinc removal within the bioreactor at the faster flow rate. Table 5 outlines the difference between dissolved and total zinc removal during the different operational phases.

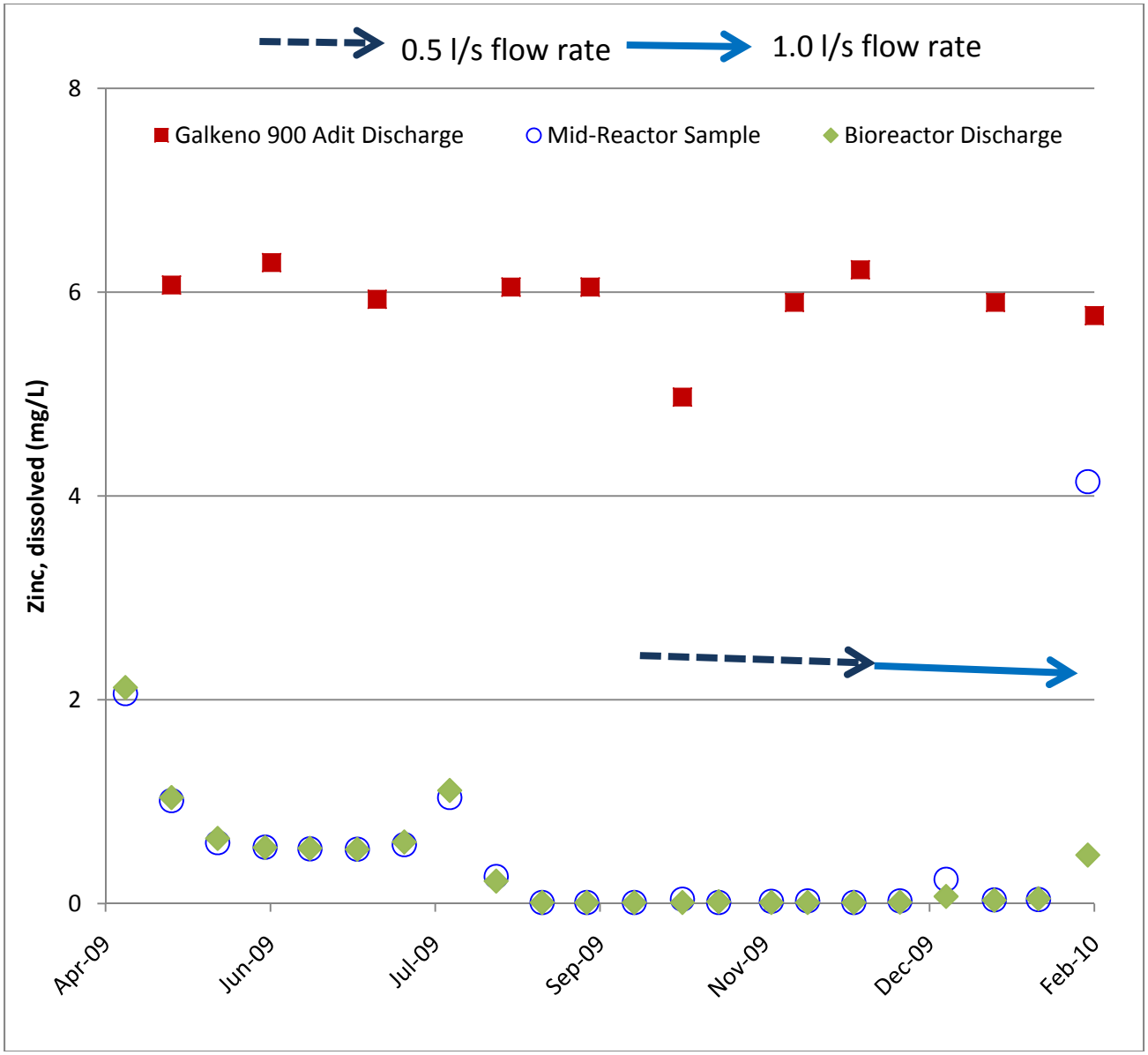


FIGURE 3. ZINC REMOVAL BY GALKENO 900 BIOREACTOR.

TABLE 5. COMPARISON OF TOTAL VS. DISSOLVED ZINC IN DIFFERENT OPERATIONAL PHASES.

	Average total zinc concentration (mg/L)	Average dissolved zinc concentration (mg/L)	% total zinc that is dissolved
Recirculation phase	0.64	0.65	100%
Reduction onset phase	0.32	0.27	86%
0.5 l/s treatment phase	0.28	0.012	4%
1.0 l/s treatment phase	0.74	0.13	17%

The difference between total and dissolved zinc is that total zinc can be filtered out, i.e., it is particulate zinc that has been removed from the soluble phase and has become a particulate zinc phase that can be filtered. Because of the coarseness of the bioreactor rock (see figures 14-18, Alexco US Resource Corp, 2009) it does not act as a very good filter. In addition, freshly formed sulfides are very fine particulates. In rapidly flowing systems, small or colloidal particles can

remain suspended and exit the bioreactor without being agglomerated into larger particles that would drop out via gravity or by being caught in bioreactor media pore throats. Dissolved zinc averaged below the discharge treatment objective of 0.5 mg/L during both the 0.5 and 1.0 l/s treatment regimes. However, the treatment objective was not achieved for total zinc for the higher flow rate (1.0 l/s) regime (0.74 mg/L). This indicates that additional residence time is required in the bioreactor to filter the particulate materials, or a subsequent filtration step could be taken in the discharge if the higher flow rate were to be used. An example of natural filtration is a wetlands or bog system, or infiltration into an underground porous aquifer. This is discussed further in this report in the "Recommendations" section.

3.2.2. Antimony

Antimony concentrations declined approximately 80% during the test (0.0025 mg/L reduced to below the detection limit (0.0005 mg/L) during all phases of the test (Figure 6). Antimony removal in an organic carbon-rich reducing system is typically attributed to an antimony sulfide phase, or by sorption to iron or manganese oxides, carbonates, or sulfides that are stable in reducing conditions.

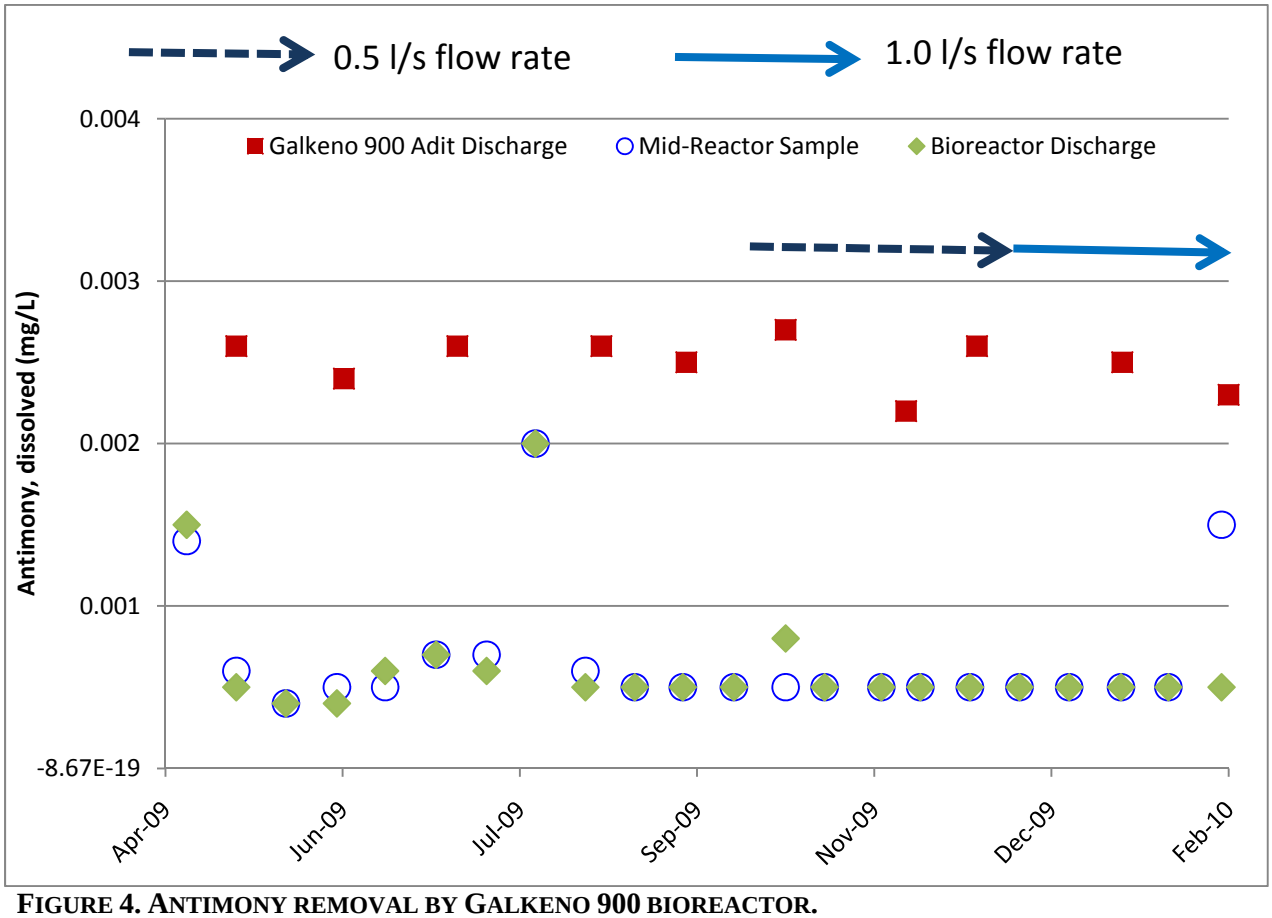


FIGURE 4. ANTIMONY REMOVAL BY GALKENO 900 BIOREACTOR.

3.2.3. Arsenic

Arsenic concentrations declined approximately 97% (0.068 mg/L reduced to 0.0015 mg/L average of last 2 months) during the recirculation phase. Arsenic concentrations increased during the reduction onset phase, indicating a temporary dissolution of arsenic-bearing mineral phases during this transition period. During both treatment phases, however, arsenic removal increased again as sulfate reducing conditions were established. During the treatment phases, arsenic removal averaged 58% for the 0.5 l/s period, and 80% during the 1.0 l/s. The performace during the 0.5 l/s period was likely affected by the residual washout of dissolved arsenic released during the reduction onset period, so a long term average removal would more likely be similar to the 1.0 l/s performance.

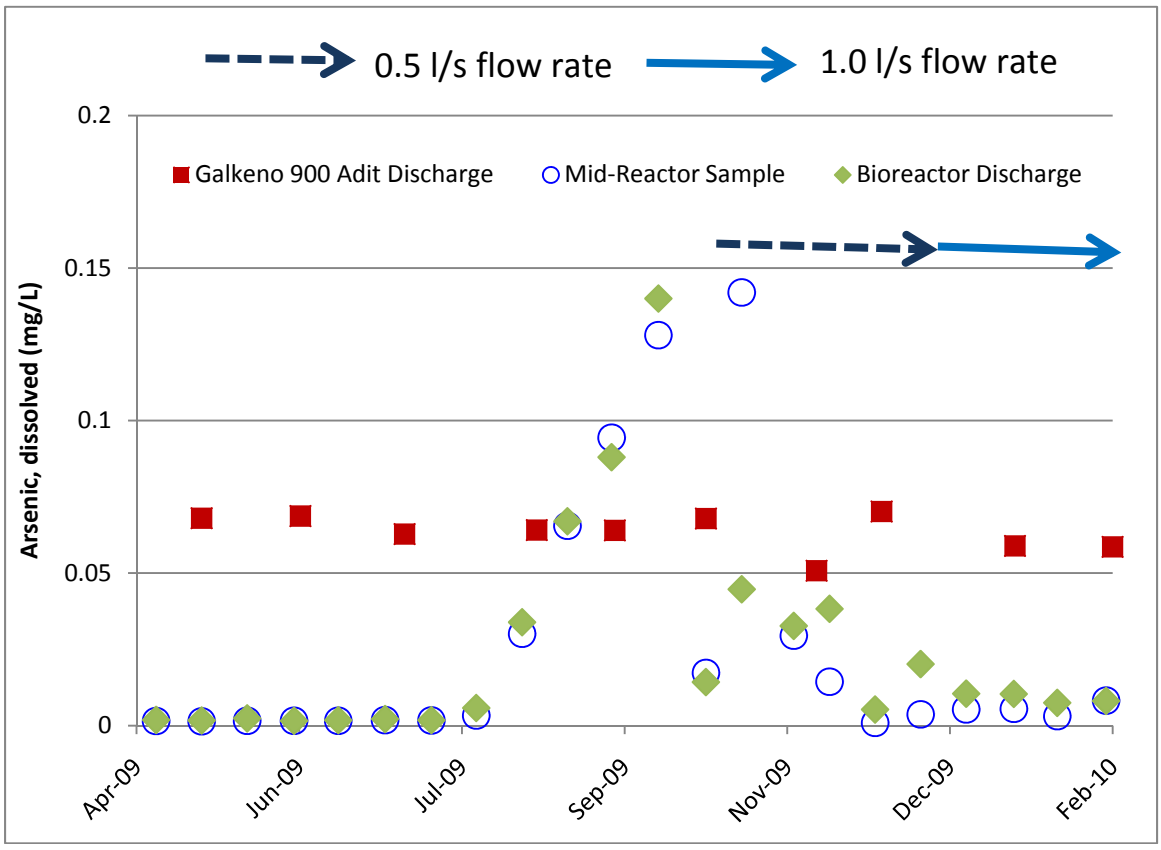


FIGURE 5. ARSENIC REMOVAL BY GALKENO 900 BIOREACTOR.

3.2.4. Cadmium

Cadmium concentrations declined approximately 60% (0.0015 mg/L reduced to 0.0005 mg/L average of last 2 months) during the recirculation phase (Figure 6). After the beginning of the reduction onset phase, cadmium has been removed to below the detection limit and has remained at those levels during both 0.5 l/s and 1.0 l/s treatment phases.

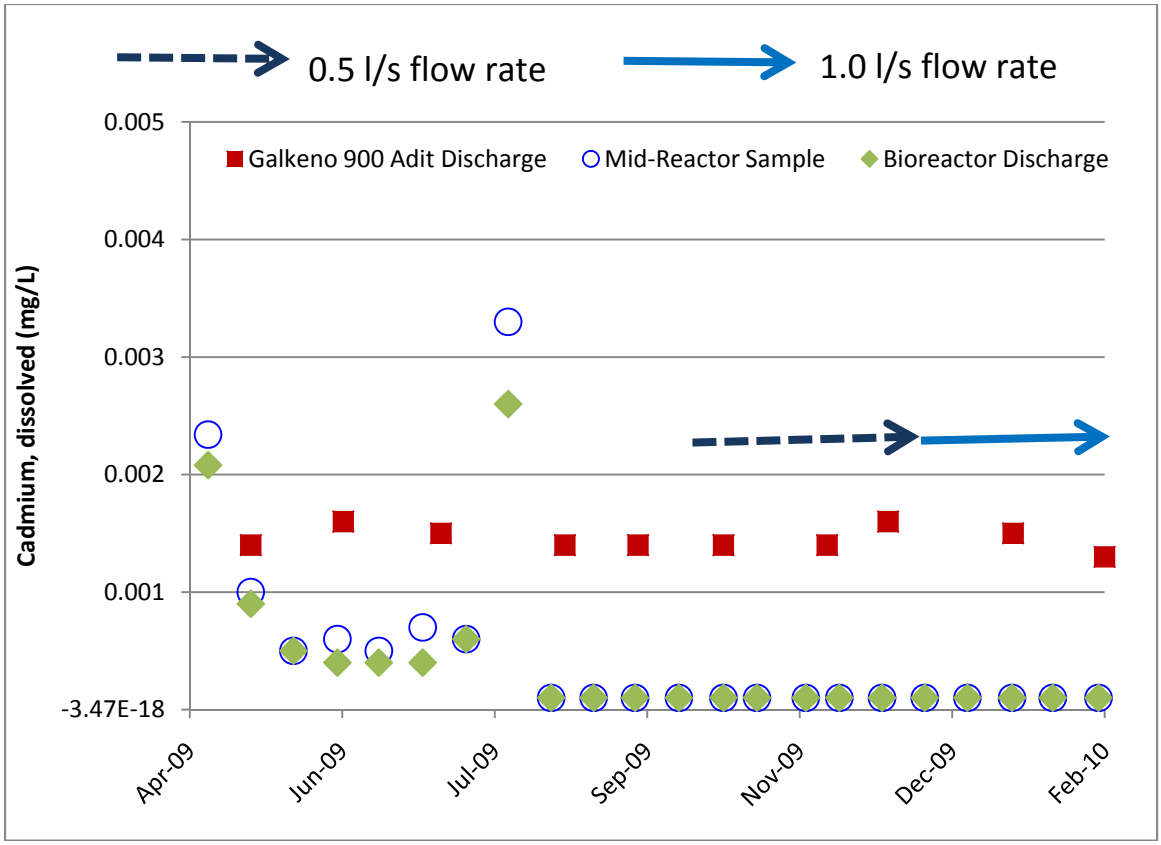


FIGURE 6. CADMIUM REMOVAL BY GALKENO 900 BIOREACTOR.

3.2.5. Iron

Iron concentrations declined approximately 97% reduction (1.75 mg/L reduced to 0.032 mg/L average of last 2 months) during the reciculation phase (Figure 7). During this phase iron appears to have been removed primarily by precipitation as an oxide. During the reduction onset phase, iron dissolved from the reactor and has been released at a rate higher than the amount entering the reactor through the recent operations.

Iron removal in the bioreactor provided sorption and coprecipitation phases for other trace metals removal during the recirculation phase. Some of the iron was likely also removed as sulfides in their initial amorphous precipitate form (operationally called "acid volatile sulfides" or AVS). The rate of formation of this phase may be limited by the residence time provided in the bioreactor. An operational objective could include operating the reactor to create AVS. The iron removal in the bioreactor will be a key parameter tracked during the next operational phase.

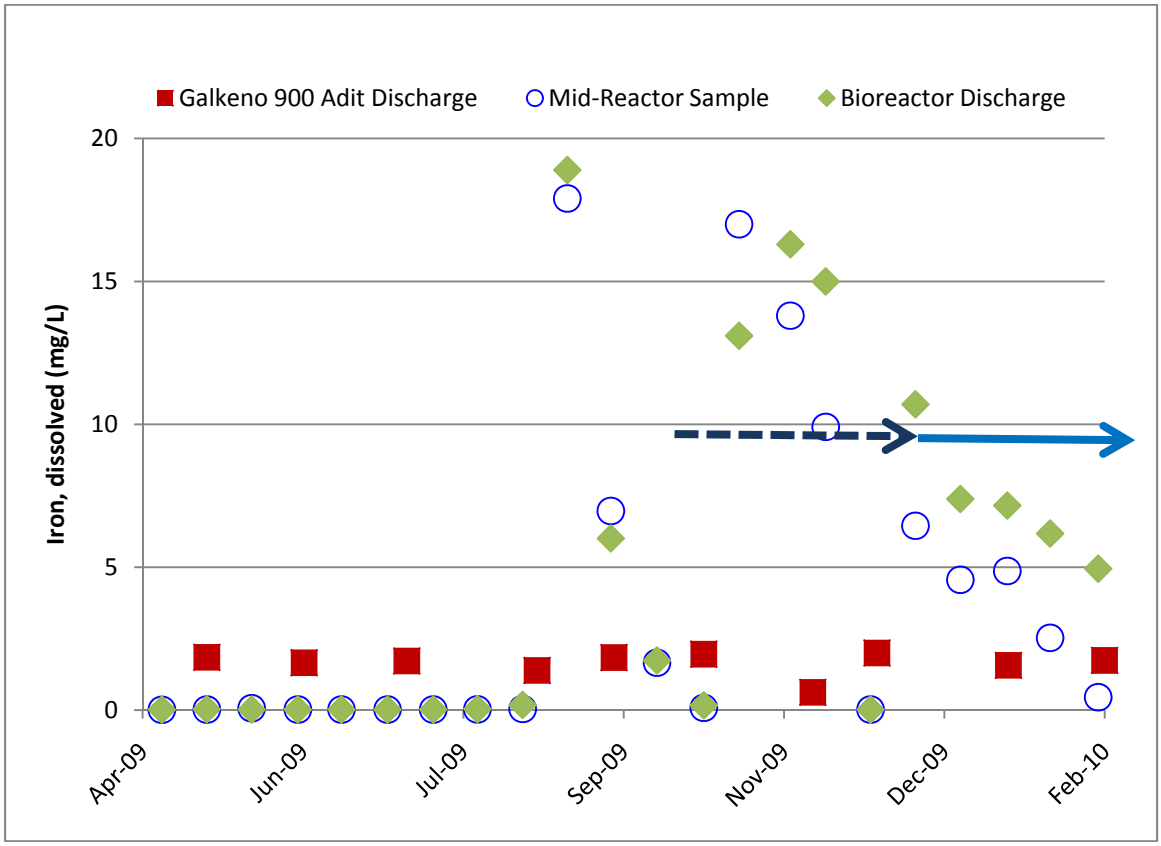


FIGURE 7. IRON IN THE GALKENO 900 BIOREACTOR.

3.2.6. Manganese

Manganese concentrations declined approximately 98% (18 mg/L reduced to 0.25 mg/L) during the recirculation phase (Figure 8). During the reduction onset phase, some manganese was released from the bioreactor, indicating that some of the manganese removal in the recirculation phase was as a manganese oxide. In both the 0.5 l/s and 1.0 l/s treatment phases the manganese concentrations entering the bioreactor and exiting the bioreactor were nearly the same, indicating manganese is not being removed from the reaction in the bioreactor under the more strongly reducing conditions and at the hydraulic residence times provided under the current flow regime.

Similar to iron, manganese removal in the bioreactor has important effects for other metals. Manganese carbonates and oxides that may have formed during the initial bioreactor operation phase have good sorption capacity for trace metals. Manganese precipitates may play a significant role in the removal of metals in the bioreactor. This will be studied further after the reactor operations are complete.

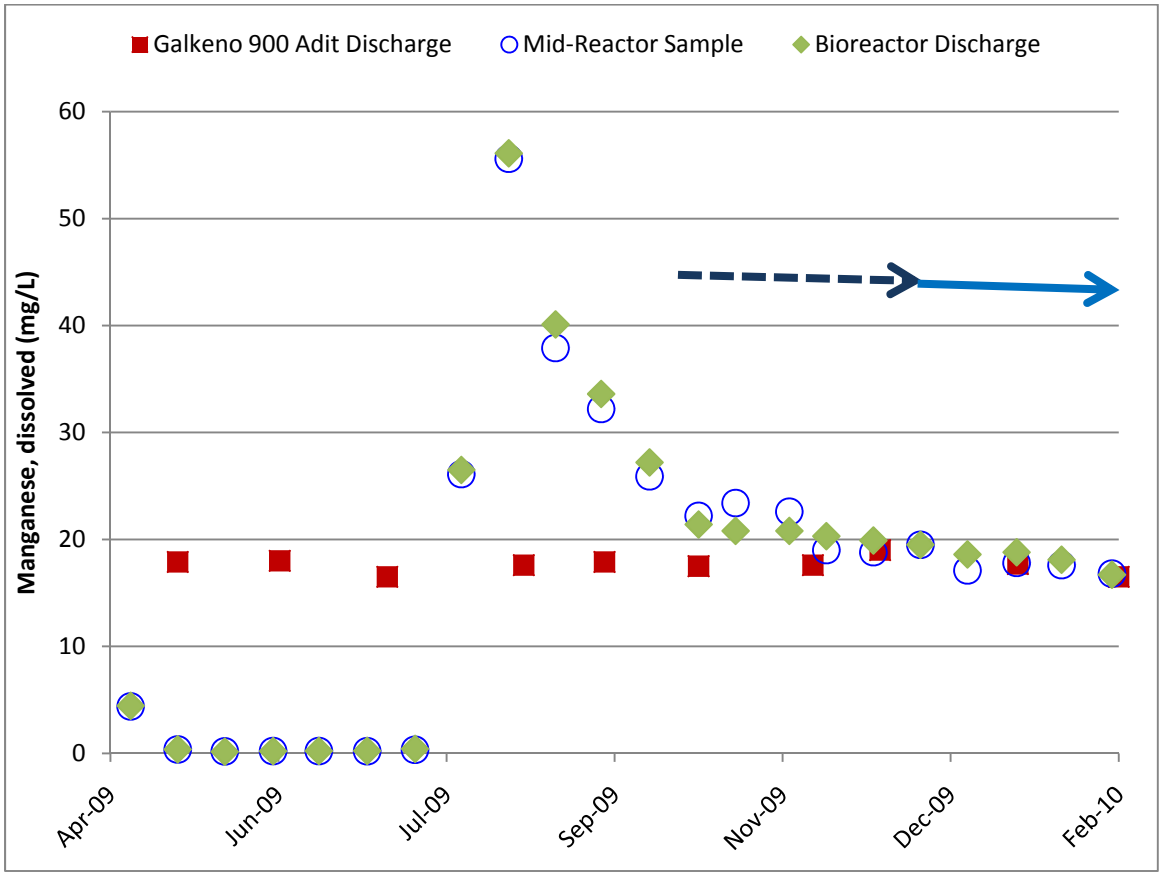
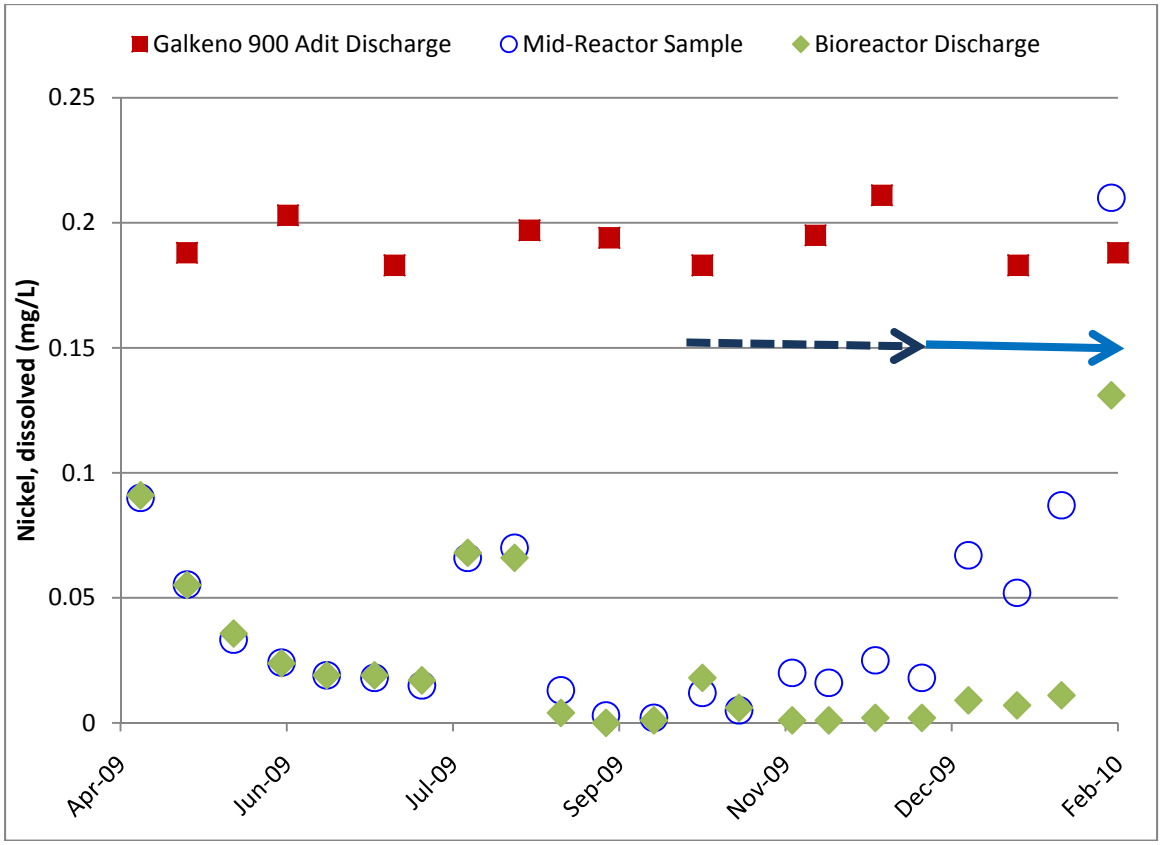


FIGURE 8. MANGANESE IN THE GALKENO 900 BIOREACTOR.

3.2.7. Nickel

Nickel concentrations declined approximately 80% (0.2 mg/L reduced to 0.04 average of last 2 months) during the recirculation phase (Figure 9). During the reduction onset, a portion of the nickel was returned to solution, but as sulfide production increased, the nickel concentrations decreased to detection limits. Nickel removal during the 0.5 l/s was 97.5%, and declined during the 1.0 l/s flow rate to 83.7%. The treatment capacity of the reactor appears to be more sensitive for nickel than some other metals, as the mid-reactor sample increased during the switch to the higher flow rate. If nickel removal were an objective, operation of the bioreactor at a slower flow rate appears to be beneficial.



3.2.8. Major Cations

Conservative elements show less than 10% change during passage through the bioreactor, including calcium, magnesium, silica, sodium and strontium (Table 3 and 4), indicating that dilution is not a significant factor causing metal removal in the reactor.

4. METALS REMOVAL MECHANISMS DURING BIOREACTOR TREATMENT OPERATIONS

The formation of metal precipitates in bioreactors has been extensively studied. One "reversible" mechanism often attributed to removal of metals is sorption to organic matter. Because only coarse rock was used as a solid substrate, this mechanism can be dismissed as relevant for the bioreactor performance.

After the operation of the bioreactor shifted from recirculation to throughflow, metals removal mechanism appear to have shifted from mixed reaction that were discussed in the prior report (Alexco Resource US Corp, 2009) to primarily a sulfide-based precipitation process. The effectiveness of this process is sensitive to important variables including the hydraulic residence time in the bioreactor, the sulfate reduction rate, and the filtration capacity of the media.

Because the products of the sulfate reduction reaction include both sulfide and bicarbonate alkalinity, it is possible that carbonate precipitation is also an important mode of precipitation for some of the metals removed in the reactor. However, for most of the metals being removed in the bioreactor, including antimony, arsenic, cadmium, cobalt, iron, nickel, and zinc, a sulfide precipitation mechanism appears more likely because sulfide precipitates are less soluble than the carbonate precipitates of these elements. Thus the sulfate reduction reaction is the primary reaction that we will focus on optimizing in the bioreactor operations.

4.1. DETERMINATION OF THE SULFATE REDUCTION RATE

Microbial production of sulfide from sulfate is dependent on the presence of sufficient numbers of sulfate-reducing bacterial (SRB) cells, and the availability of organic carbon, according to the following reaction:

4 moles methanol + 3 moles sulfate ➔ 3 moles sulfide + 4 moles bicarbonate

The rate of the reaction is nearly the same at temperatures in natural environments where the longterm temperature is around freezing (-2^{O}C to 2^{O}C) as it is in natural environments where the long term temperature is around 20 ^{O}C when the abundance of SRB is the same (Knoblauch, Jorgensen, and Harder, 1999). This is due to the development of psychrophilic (i.e., 'cold loving") SRB. The growth rate of psychrophilic SRB is typically far slower than temperate SRB, which is reflected in the long growth period (October 2008 to August 2009) required to get the bioreactor grown up so that it was competent to begin treating mine water. However, once the bioreactor was competent as evidenced by net sulfide concentrations leaving the reactor in the 1 to 10 µM range, indicating that there is excess sulfide created above what was required to react with the soluble and solid phase metals.

The sulfate reduction rate (SRR) is measured in terms of mM sulfate reduced per m^3 per day. The influent sulfate compared to the effluent sulfate is compared to determine the amount of sulfate removal. The average sulfate removal amount during the recirculation phase was 128 mg/L, or 1.33 mM. With a known bioreactor volume of approximately 2,550 m^3, and a flow rate of 1 l/s, the total sulfate removal per day was 115,200 mM, which yields a SRR of 45 mM/m^3/day. For comparison, artic ocean sediments have SRRs in the range of 5-40 mM/m^3/day (Knoblauch, Jorgensen, and Harder, 1999), showing that we have a similar rate as natural systems that have long term adaptation to cold environments.

The SRR calculated for the Galkeno 900 bioreactor is conservatively calculated based on the entire bioreactor participating in the sulfate reduction process. However, dead zones can limit the exchange of organic carbon and therefore it is likely that minimization or elimination of dead zones will improve the performance of the bioreactor.

5. Factors that Affect Scale-up of the Galkeno 900 Bioreactor

Demonstration of the metals removal obtained in the bioreactor and determination of the SRR that can be achieved in the wintertime at the 1.0 l/s flow rate enables us to project that the bioreactor could be scaled by a factor of 4 and likely treat the entire flow from the Galkeno 900 adit. The flow from the Galkeno 900 adit is approximately 4 l/s and does not vary much annually.

Factors that affect the scaleup include the following factors:

1. Required safety factor. The purpose of the reactor will affect the required safety factor. If compliance at a discharge location is necessary, a greater safety factor will be required. If load reduction is the primary purpose, a lesser safety factor may be appropriate.
2. Bioreactor dead zones. As discussed above, approximately 40% of the bioreactor is actively participating in the water as it passes through the reactor. These dead zones can be minimized by creating longer and narrower flow paths. Assuming a design can be performed that provides for longer bioreactor cells, this improvement can be used to minimize the amount of scaleup required, or provide additional safety factors. The sulfate reduction rate that has been achieved combined with a greater fraction of the bioreactor providing sulfate reduction would allow for a smaller scaleup.
3. Filtration requirements. If a greater total zinc removal is necessary in the bioreactor, larger size reactors or finer materials in the reactor would be necessary.

6. Achievement of 2009 Workplan Objectives

6.1. CONSISTENTLY ACHIEVE WATER QUALITY IMPROVEMENTS

The minimum goal of 0.5 mg/L zinc was consistently achieved with one exception when the pump failed. Other metals were also consistently improved with the exception of a short period when reduction onset occurred, when some metals were released with the reductive dissolution of iron and manganese.

6.2. DEMONSTRATE OPERATIONAL STABILITY

With the exception of the pump failure, the continuous flow and water quality improvements were achieved.

6.3. DEMONSTRATE IRREVERSIBILITY OF PRECIPITATION/REMOVAL REACTIONS

This will be performed at the end of the next year of operation.

6.4. QUANTIFY OPERATIONAL PARAMETERS AND COST

Hydraulic residence times associated with the 0.5 l/s flow rate (9 to 21 days hydraulic residence time) were sufficient to consistently achieve treatment goals. Hydraulic residence times associated with the 1.0 l/s flow rate (4.5 to 10.5 days hydraulic residence time) may have been sufficient to achieve treatment goals, with the pump failure being the source of uncertainty in this assessment.

The sulfate reduction rate was assessed and will be updated in the next year after consistent treatment approach is maintained to determine if there is an annual range that may be affected by temperature.

The organic carbon loading rate requirement has been assessed and will be further refined in the next year.

Monitoring requirements for the bioreactor system have been assessed and will be adjusted in the following year to reflect an updated operational approach. Several biological toxicity tests will be performed to demonstrate that the system is stably achieving the water quality improvements sufficient to allow direct stream discharge.

7. References

Alexco Resource US Corp. 2009. Galkeno 900 Sulfate-ReducingBioreactor Interim Report 2009 Closure Studies.

Knoblauch, C., B. Jorgensen, and J. Harder. 1999. Community Size and Metabolic Rates of Psychrophilic Sulfate-Reducing Bacteria in Arctic Marine Sediments. Applied and Environmental Microbiology, Volume 65, pg 4230–4233.