Alexco Keno Hill Mining Corp
1150-200 Granville Street
Vancouver BC V6C 1S4

August 19, 2011

Yukon Water Board
Suite 106, 419 Range Road
Whitehorse, Yukon   Y1A 3V1

Attention: Ms. Carola Scheu, Manager

Dear Ms. Scheu:

Re: Water Licence QZ09-092, Clause 88

Attached to this letter please find the Bioreactor Design and Operation Plan.

Should you have any questions, please contact our office at (604)-663-4888.

Sincerely,

Jim Harrington
VP, Environment, Alexco Resource Corp

cc. external D. Buyck, FNNND, Troy Searson, Government of Yukon, Water Resources, Robert Holmes, Arlene Kyle, Government of Yukon, Energy Mines and Resources, Steve Arell, Environment Canada

cc. internal C.Nauman, B.Thrall, T.Hall, V. Benwood, E. Allen, Alexco Resource Corp.

Bellekeno Bioreactor Design and Operation Plan

Condition of Water Licence QZ09-092

Prepared by:

Alexco Resource US Corp
for AKHM

August 2011

AKHM

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LIST OF ABBREVIATIONS

AKHM...................................... Alexco Keno Hill Mining Corp.
AVS.. Acid Volatile Sulphides
BK .... Bellekeno
COC.. Constituent of Concern
gal .... Gallons
gpm... Gallons per minute
KHSD .... Keno Hill Silver District
kg .... Kilogram
l... Litres
lb... Pounds
lpm.. Litres per minute
lps .... Litres per second
PLC... Programmable Logic Device
SRB .... Sulphate-Reducing Bacteria
SRR .... Sulphate Reduction Rate

1. Executive Summary

Alexco Resource Corp. (Alexco), through its wholly owned subsidiary Alexco Keno Hill Mining (AKHM) Corporation, owns the former United Keno Hill Mine assets and claims within the Keno Hill Silver District (KHSD). AKHM maintains and operates a water treatment facility at its Bellekeno Mine under Type "A" Water Use Licence (WUL) QZ09-092. Pursuant to Condition 88 of WUL QZ09-092, AKHM must develop a Bellekeno Bioreactor Design and Operation Plan within one year of the effective date of the licence. This document fulfills the requirements of Condition 88.

To better understand how to design and operate a bioreactor in the KHSD, Alexco installed and has operated a test bioreactor at the Galkeno 900 mine site since October 2008 as part of the district wide closure planning process. During this time, it was found that once sulphate reduction onset occurred after a commissioning period, effective treatment was accomplished, with the efficiency of the treatment dependent on flow rates through the bioreactor. The lessons learned and results of the Galkeno 900 bioreactor study were used within this report for the proposed design and operation plan of the Bellekeno bioreactor after the decommissioning of the Bellekeno mine.

The proposed Bellekeno bioreactor design will include one bioreactor installed within the Bellekeno 625 Adit, maintaining the current lime active treatment system as a contingency backup measure, and a second bioreactor constructed in Pond 2 of the current Bellekeno water treatment system. In addition, in-situ mine pool pretreatment will occur as needed to improve the overall efficiency and effectiveness of the bioreactor systems.

2. Purpose

The purpose of this report is driven by the requirements listed under Condition 88 of the Bellekeno Mine Type "A" Water Use Licence (WUL) QZ09-092. The Condition states:

Cond. 88. Within one year of the effective date of this licence, the Licensee shall submit to the Board a plan titled, "Bellekeno Bioreactor Design and Operations Plan." The plan shall include, but not be limited to:

- **a) The results of the tracer study on the Galkeno 900 pilot bioreactor and implications to the design and operation of the proposed Bellekeno bioreactor;**
- **b) The results and analysis of the Galkeno 900 pilot bioreactor operations that will inform the design of the Bellekeno bioreactor.**
- **c) Preliminary sizing, design, and operational procedures for the proposed Bellekeno bioreactor.**
- **d) Preliminary costing of the construction and long term operation of the proposed Bellekeno bioreactor;**
- **e) Scheduling of the development of the bioreactor including scheduling of a pilot or transitional phase during which the existing Bellekeno treatment plant will be available to run in series or parallel with the bioreactor; and**
- **f) Identification of passive treatment alternative that are being considered to replace or augment the proposed bioreactor.**

This document is submitted to fulfill Licence Condition 88. This document is released as Revision A.

3. Background

Beginning in May of 2008, a bioreactor was constructed and commissioned in the KHSD at the Galkeno 900 adit. After more than three years of continuous operation, the data collected demonstrated the viability of sulphate reduction technologies for the removal of metals, especially zinc and other metals that react with aqueous sulphide, in the KHSD.

The bioreactor solid phase substrate utilized in construction was coarse rock from a nearby placer mining operation. The organic substrate supplied to the bioreactor included dissolved organic carbon forms, with sugars, alcohols and complex carbohydrates and proteins from milk used during the growth phase of the bioreactor operation, and sugars and alcohols used during the maintenance phase. The purpose of the organic substrate was initially to support microbial growth until sulphate reduction became the predominant microbial activity in the reactor, and during the treatment phase to support microbial sulphate reduction.

Sulphate reduction is a biochemical transformation performed by microbes that transfers electrons from organic carbon to sulphate, causing sulphate to be reduced to sulphide. Sulphide reacts with many dissolved metals, forming very insoluble metal precipitates. The Galkeno 900 bioreactor also had 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. However, analysis of the aqueous chemistry indicates that the metals removal was primarily due to the formation of metal sulphides.

The bioreactor demonstration was a multipurpose program to assess the potential of adding an organic substrate to mine adit water to support metals removal, whether within 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 sulphide- 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 an organic carbon source to cause precipitation of metals during flow through rock or earthen materials via sulphate reduction.

Galkeno 900 has water chemistry and flow characteristics that are typical of some adits in the KHSD, and is very similar to the historic and present water quality at Bellekeno. The three years of operation were of sufficient scale and length to provide reliable feedback that allows for the design of either a large scale bioreactor or an in-situ reduction field at several other adit drainage locations within the KHSD. The Galkeno 900 bioreactor was operated in a lined bioreactor allowing for the performance of the technology to 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 continued through the winter season to demonstrate durability of metals removal mechanisms throughout the coldest part of the year.

Within this report, the design and operational results of the Galkeno 900 bioreactor will be applied to the closure planning of the Bellekeno mine and the design/construction of a Bellekeno bioreactor system.

3.1. LITERATURE BACKGROUND

The formation of metal precipitates in a bioreactor that has carbon sources added to or present in the solid phase of the bioreactor has been extensively studied for 30+ years. There are several different styles of bioreactors, both in terms of carbon sources and flow dynamics. To reduce the "black box" many studies have attempted to identify directly by examination of mineral formation or by inference from water chemistry signatures what primary mechanisms are responsible for metals removal. When complex carbon sources are added as a solid phase in the bioreactor construction, a "kitchen sink" list of mechanisms have been documented, that include:

- Sorption of metals on organic matter.
- Precipitation of iron hydrous oxides including ferric and mixed valence minerals, which then provide mineral surfaces for sorptive removal of metals, or metals can also be co-precipitated within the iron mineral matrix.
- Precipitation of manganese oxides including manganese (IV) oxides and mixed valence (III/IV) oxides and manganese carbonates, which then provide mineral surfaces sorptive removal of metals, or metals can also be co-precipitated within the manganese mineral matrix.
- Precipitation of metal sulphides, including primary metal sulphides such as ZnS or CdS, as well as precipitation of iron sulphides such as amorphous FeS and co-precipitation of metals within the FeS matrix. Depending on the pH of the bioreactor and the availability of structural iron, a very large amount of FeS minerals can be formed by aqueous sulphide formed by microbes reductively dissolving iron from the rock matrix, creating a "bank" of amorphous sulphide which has reactivity toward dissolved metals.
- Precipitation of some metals in their reduced forms, for example selenium reduction from a Se(VI or IV) anion to elemental selenium precipitates Se.
- Precipitation of metals as carbonate minerals. Some of the relevant metals have somewhat soluble carbonate minerals (e.g., zinc carbonate minerals including smithsonite, and hydrozincite) which are relatively more soluble than sulphides. When sulphide is not present, these minerals may provide a precipitation-removal mechanism.

Within the Galkeno 900 bioreactor, sorption of metals on organic matter is not a relevant metals removal mechanism, because only coarse rock was used as a solid substrate. However, for the design and implementation of the Bellekeno bioreactors, AHKM plans to use complex carbon sources, such as peat and/or wood chips, mixed with coarse rock to improve the stability and efficiency of metals removal.

4. LESSONS LEARNED – GALKENO 900 BIOREACTOR DESIGN

4.1. OVERVIEW OF SULPHATE REDUCTION

The removal of metals from mine waters by bioreactors is done around the world, utilizing a variety of approaches. The bioreactor utilized at Galkeno 900 is one type of reactor, where the only carbon source added to the bioreactor was added in a dissolved form semi-continuously during the operation of the bioreactor. Bioreactors are often constructed utilizing a mixture of substrates which either act as a carbon source for microbial reactions, or these substrates can act as sorptive surface for metals precipitation.

The results displayed in the Galkeno 900 bioreactor report (refer to Appendix C) focus primarily within the operational treatment phase of the project. One important aspect covered in the report was the determination of the Sulphate Reduction Rate (SRR). Microbial production of sulphide from sulphate is dependent on the presence of sufficient numbers of Sulphate-Reducing Bacteria (SRB) cells, and the availability of organic carbon, according to the following reaction:

4 moles methanol + 3 moles sulphate ➔ 3 moles sulphide + 4 moles bicarbonate

The rate of the reaction is nearly the same at temperatures in natural environments where the long-term 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 required for the Galkeno 900 bioreactor to reach maturity so that it could sufficiently treat mine water. However, once the bioreactor was competent to perform sulphate reduction (as evidenced by net sulphide concentrations leaving the reactor in the 1 to 10 µM range, indicating that there is excess sulphide created above what was required to react with the soluble and solid phase metals) then the bioreactor SRR could be assessed.

The SRR calculated for the Galkeno 900 bioreactor is conservatively calculated based on the entire bioreactor participating in the sulphate reduction process. However, less effective treatment zones or "dead zones" were identified in the report and were expected based on the sub-optimal configuration that was available at Galkeno 900. These areas can limit the exchange of organic carbon and therefore it is likely that minimization or elimination of these dead zones will improve the performance of other bioreactors.

4.2. BELLEKENO ENGINEERING DESIGN

From the design, construction, and operation of the Galkeno 900 bioreactor, the following components are lessons learned and will be incorporated into the Bellekeno bioreactor design:

1.) **Torturous Path -** Creating a torturous path within a rectangular bioreactor is needed to minimize short-circuiting and increase residence time. However, the use of baffling creates zones where treatment is less effective. These dead zones have been eliminated within the design of the Bellekeno 625 Adit bioreactor since the bioreactor will exist within the adit, which creates a long narrow flow path, which tends to limit dead zones.

2.) **Flowing Water -** Water must be kept moving at all times during the winter months in the KHSD. Mine drainage water is above freezing when it exits the adit, and this water temperature must be maintained while passing through the bioreactor. At the Galkeno 900 bioreactor, as long as the pump was working and water was continuously flowing through the bioreactor, freezing was avoided. Every freezing failure of the bioreactor was caused by power failures which lead to cessation of pumping and a loss of the heat capacity of the adit influent water. The Bellekeno bioreactor design has eliminated the need for discharge water pumping, with the majority of the bioreactor volume located underground in the Bellekeno 625 Adit and both the adit bioreactor and the Pond 2 bioreactor being fed by gravity flow.

3.) **Back-up Treatment System -** Similar to the back-up treatment system used at Galkeno 900, the Bellekeno bioreactor system will include an active treatment system that will be maintained as a backup contingency measure and available during the initial phase of the bioreactors operation.

From the design, construction, and operation of the Galkeno 900 bioreactor, the following components were sources of less than optimum performance and should be eliminated from the Bellekeno bioreactor design:

1.) **Fill Material -** The fill material used within the Galkeno 900 bioreactor was too coarse. As seen in Figure 5 in the Galkeno 900 report, the material was a mixture of larger, broken rocks mixed with smaller pebbles and sand. By using a consistent fill material that is a smaller, crushed rock (between 3/8" to 2" diameters) additional surface areas will be available for bio-growth and will help avoid short circuiting. In addition, AKHM plans to mix in a low percentage of a solid phase complex carbon sources such as peat and/or wood chips to improve the rate of metal sorption.

2.) **Reagent Metering Pumps -** If the metering pump that provided a carbon source to the Galkeno 900 bioreactor stopped working, there was a limited amount of stored carbon available within the substrate. For the Bellekeno bioreactors designs, a solid phase carbon source such as peat and/or wood chips will be mixed with the media to provide a secondary source of carbon to sustain the bioreactor if the soluble/primary carbon source is interrupted. This material acts as a buffer pool for carbon source availability that is less dependent on continuous supply of a liquid phase organic. In addition, an organic carbon source will be injected in-situ to the mine pool thereby providing an initial carbon source, even in the event of metering pump failure. Typically, the addition of a carbon source is done once every year; or less frequently if the recharge rate is low.

3.) **Pipe Freezing -** AKHM plans to convert Pond 2 of the existing Bellekeno water treatment system to a bioreactor. This location is lower in elevation than the mine adit, thereby allowing water to flow via gravity without the need of additional pumping. The Bellekeno bioreactor design also includes placing valves and controls inside the adit or buried within access ways to minimize freezing.

5. PROPOSED BELLEKENO BIOREACTOR SCHEDULE

AKHM proposes the following schedule to manage the Bellekeno discharge as part of the mine closure effort (refer to Appendix A). This schedule shows a 5 year timeline but the expected operation of the Bellekeno bioreactors may be longer, depending on the effectiveness of the mine pool treatment and the need for water treatment.

AKHM plans to perform the following tasks for the construction and operation of Bellekeno bioreactors used for water treatment.

Initial Closure Effort (Active Treatment System as needed):

- Mine dewatering stopped and Bellekeno mine pool allowed to form.
- Bellekeno 625 Adit filled with bioreactor material behind a chest high coffer dam.
- Existing Bellekeno water treatment system includes a lime slurry tank, ferric chloride tank, alcohol tank, rapid mix tank, and monitoring/recording equipment. The treatment system will be run in a "stand-by" mode during operation of the bioreactors. The multimedia filter will not be utilized because this is only necessary when active mining is creating fine materials that require a multimedia filter to remove.
- Pond 1 will continue to be used as a settling pond.
- Pond 2 will be converted to a second bioreactor system.
- Alcohol and/or other organic carbon material added in-situ to the mine pool (once formed) as a pretreatment step.
- The bioreactors are commissioned from water pumped from the mine pool and passes through the Bellekeno 625 adit bioreactor, with the optional addition of alcohol prior to entering the Pond 2 bioreactor if necessary, and is then discharged to the Decant Box.
- Any sludge formed in Pond 1 will be removed via vacuum truck, amended with an organic carbon source, and then re-injection back into the mine pool to elevate mine pool pH levels.

Continued Passive Treatment Operation:

- Mine pool in-situ pretreatment occurs with the addition of alcohol and/or other carbon based materials as needed.
- Expected that the Adit bioreactor and Pond 2 bioreactor provide a sufficient level of treatment.
- Monitoring equipment continues to provide flow rate and pH information as needed.
- Active lime treatment system remains in place as a contingency measure backup.

5.1. INITIAL CLOSURE EFFORT

AKHM has developed a proposed layout for modifications to the existing Bellekeno water treatment system during the closure process (refer to Appendix B). During this time, the dewatering pumps will cease operation, and the Bellekeno mine pool will form in the underground workings. Page 4 of Appendix A shows the two adits that currently exit from the

Bellekeno workings. As part of the closure effort, AKHM plans to build a bioreactor within the Bellekeno 625 adit by placing a mixture of peat, wood chips, and placer rock for a distance of 600 metres. As learned from the Galkeno 900 bioreactor report, the effectiveness of treatment increases proportional to the length of time water is in contact with the bioreactor system. Therefore, AKHM has included sufficient media in the mine bioreactor and secondary bioreactor in Pond 2 to achieve sufficient contact time. As an option to enhance the treatment, the installation of barriers (refer to page 5 of Appendix B) may be placed within the Bellekeno 625 Adit in the form of shotcrete, fine sand, and/or clay to create a tortuous path for the mine discharge water to travel around.

The adit bioreactor will be contained behind a chest high coffer dam. This dam includes piping that collects the discharged water and transfers it to the active treatment system and/or the Pond 2 bioreactor. A flow meter will be installed to allow for monitoring and recording the discharge flow rate. AKHM plans to use maintain the existing Bellekeno water treatment facility. This facility currently includes a rapid mix tank, a lime slurry tank, a ferric chloride holding tank, a metering system, and some monitoring/recording equipment. AKHM may install an additional alcohol tank as needed as part of the bioreactor system.

The rapid mix tank currently includes an agitator used for mixing adit water with the injected reagents. For closure, a pH probe may be added that would be connected to a Programmable Logic Device (PLC). This set-up could then be used to remotely monitor the pH of the adit water and drive metering pumps for the addition of reagents based on selected set points. Once water passes through the active treatment system it can be discharged to Pond 1 for settling or to the Pond 2 secondary bioreactor. Based on the performance of the Galkeno 900 bioreactor, AKHM does not believe the active water treatment system will be required for more than a few months except during initial commissioning of the bioreactors. However, this system will remain in place and be ready in “stand-by” mode in the event that the adit water requires additional treatment prior to discharge.

The Pond 2 bioreactor (refer to Figure 1 for a X-Sectional view) will be constructed similar to the Galkeno 900 bioreactor. It will contain internal baffling that creates a tortuous path for the discharged water, thereby providing sufficient time for treatment. The substrate material, unlike the Galkeno 900 bioreactor, will include complex carbon sources in the form of peat and/or wood chips in addition to placer rock or other benign material. At the base of the Pond 2 bioreactor, solution distribution piping will be installed to provide a path for the injection of a carbon source as needed. This injection system will accelerate the initial stabilization of the system by injecting carbon throughout the bioreactor during initial operation. The entire Pond 2 bioreactor will be covered with a geo-textile barrier and 2 metres of soil cover as an insulation layer. Since the operation of the bioreactor is planned to occur throughout the year, this design, which was used for the Galkeno 900 bioreactor, was found to resist freezing even during the coldest parts of the winter.

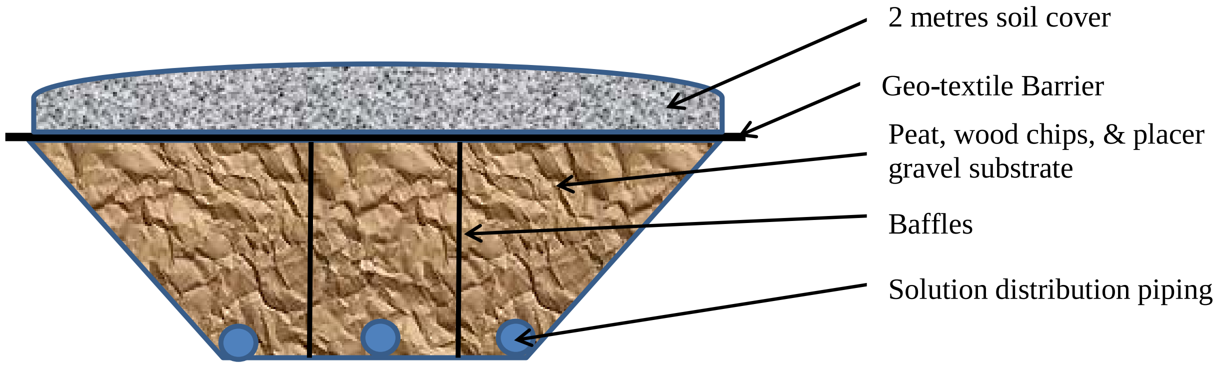

FIGURE 1 - X-SECTION OF POND 2 BIOREACTOR

The discharge from the Pond 2 bioreactor will pass to the Decant Box where it will then enter the Lighting Creek drainage via the in-ground diffuser system. This portion of the design is currently in use as part of the existing Bellekeno water treatment system.

As stated earlier, water may be discharged from the treatment system to Pond 1 for settling. Therefore, Pond 1 may slowly fill with a settled solid or sludge that has a high pH and is the result of particles dropping out of the treated water prior to entering the Pond 2 bioreactor. From other projects managed by Alexco, it has been demonstrated that this sludge could be mixed with an organic carbon source and re-injected into the mine pool as an enhancement to the in-situ pretreatment step.

5.1.1. Mine Pool Pre-Treatment

Biogeochemical processes may be used within the mine pool as a pretreatment using a combination of water treatment plant solids and an organic carbon source that will act to re-establish original chemical and geochemical conditions in the mine workings. The proposed in-situ treatment program will consist of the transfer of water treatment solids (containing excess neutralization potential) mixed with an organic carbon source such that conditions close to the original conditions can be re-established in the mine workings. The addition of concrete to the backfilled vein zones in the cemented rock fill and the paste backfill will also tend to raise the pH and limit leaching of vein material during closure.

Prior to the lowering of the ground water table and exposure of sulfide minerals to atmospheric conditions, both the ground water and the mineral phases were consistent with a low oxidation-reduction state, which is due to limited oxygen solubility in water and consumption of oxygen in the shallow soils zone during infiltration. Under such anaerobic conditions, the ground water was probably slightly acidic to neutral and dissolved metals concentrations consistent with pH conditions and low solubility of metal-bearing sulfide minerals associated with the mineralized vein at the Bellekeno mine site.

Achieving these same conditions in the Bellekeno mine workings will enhance long-term stability of solids formed by neutralization alone. The following equation presents the net stoichiometric reaction from the addition of carbohydrate-based carbon (general formula of CH_2O) sources to sulfate-saturated iron hydroxide-rich water treatment solids:

$$9CH_2O + 4CaSO_4 \cdot 2H_2O(s) + 4Fe(OH)_3(s) \rightarrow 4CaCO_3(s) + 4FeS(s) + 5CO_2(g) + 23H_2O(l)$$

Excess sulfate from gypsum and from the new formed mine pool water will be used to make iron sulfide, while excess calcium precipitates with biogenically formed carbonates as calcium carbonate.

This stoichiometric ratio is critically important to the overall mine pool stabilization process. Treatment of a mine pool under typical conditions becomes difficult as it is usually limited in available iron as sulfate continues to leave in the discharge and iron accumulates in the treatment pond solids (sludge). The biological in-situ mine pool pretreatment process that is critical to maintaining the appropriate iron/arsenic ratio for the performance of the active water treatment system requires iron as a scavenger for formed sulfide ions. Without the re-injection of iron from the treatment ponds, the ability of the pretreatment process to continue will eventually be impaired.

On a weight basis, the preceding equation can be written as:

$$270\ g\ C_6H_{12}O_6 + 688\ g\ CaSO_4 \cdot 2H_2O(s) + 427\ g\ Fe(OH)_3(s) \rightarrow 400\ g\ CaCO_3(s) + 351\ g\ FeS(s) + 220\ g\ CO_2(g) + 270\ g\ H_2O(l)$$

While chemically accurate, this equation does not fully present the associated physical changes (i.e., densification and volumetric reduction) that will occur during the process of converting hydroxides to sulfides in the mine workings. The approximate density of typical water treatment plant pond solids is historically found to be 1.07 grams per cubic centimeter (g/cm^3) with about 15% dry matter by weight. Solids conversion via the above listed chemical reaction with added carbon sources in time will reduce the anticipated volume of the inputs of newly formed in-place minerals by approximately 96 percent with a solids density of 3.41 g/cm^3.

In addition to the injection of a water treatment plant solids and an organic carbon source mixture, AKHM also plans to inject an organic carbon source into the mine pool as a pre-treatment step. This step will raise the carbon content of the adit water prior to reaching the adit bioreactor and improve its functionality.

5.2. CONTINUED PASSIVE TREATMENT

Once the operations of both the adit bioreactor and the Pond 2 bioreactor have stabilized, the water treatment system will be used only as necessary. The water quality prior to discharge to the Decant Box will be carefully monitored, and the successful operation of both bioreactors should be sufficient for the Bellekeno effluent to be within standards. It is likely that the mine pool pretreatment and the bioreactor in the Bellekeno 625 level will achieve treatment standards, and in that case the Pond 2 bioreactor will be kept in a standby condition to minimize the consumption of reagents. In that case, the pond will be bypassed.

During this time, AKHM plans to adjust the total organic carbon level within the discharged mine water prior to its entry into the adit bioreactor by injecting organic carbon into the mine pool as needed.

6. Calculated Residence Time

Within Section 5.3 Recirculation Dye Test of the Galkeno 900 bioreactor report (refer to Appendix C), there is a formula that can be used to calculate the residence time of the treated water within the bioreactor based on the calculated volume, estimated void space, and estimated inlet flow rate.

The dimensions of the Bellekeno 625 Adit bioreactor are estimated to be approximately 3 metres by 3 metres and 600 metres in length. The Pond 2 bioreactor is estimated to be 16 metres by 42 metres and 3 metres in depth. Assuming an estimated porosity of 0.35 for both bioreactors, the volume of both bioreactors is calculated to be roughly:

- **Bellekeno 625 Adit Bioreactor = 3m x 3m x 600m x 0.35 = 1,890 m^3 or 1,890,000 litres**
- **Pond 2 Bioreactor = 16m x 42m x 3 m x 0.35 = 706 m^3 or 706,000 litres**

- **Combined Total of 2,596 m^3 or 2,596,000 litres**

At 4.0 lps, assuming the total volume of available porosity within the bioreactor is utilized, approximately 7.5 days of residence time is available. The historic discharge rate of the Bellekeno mine was less than 4 liters per second, and when the mine pool is allowed to re-equilibrate, it is likely that this flow rate will be achieved again. The residence time of 7 days was observed to be sufficient to achieve the treatment objectives, and therefore this residence time is planned as the basis for the Bellekeno system.

7. Estimated Construction and Operation Costs

The estimated cost to modify the existing Bellekeno 625 water treatment facility and construct the bioreactor systems proposed for the Bellekeno Bioreactor per the closure plan are identified in Table 1.

Estimated Construction Costs					
Activity	**Materials**	**# Unit**	**Unit**	**Unit Rate**	**Subtotal**
Detailed Engineered design and license modification submittal		140	hr	$ 135.00	$ 18,900.00
Vacuum pump and clean sludge from the bottom of Ponds 1 & 2		40	hr	$ 125.00	$ 5,000.00
Install solution distribution piping along the bottom of Pond 2	$ 1,500.00	60	hr	$ 40.00	$ 3,900.00
Install divider walls in Pond 2 for proper flow distribution	$ 3,500.00	150	hr	$ 40.00	$ 9,500.00
Fill current Pond 2 with placer gravel/peat/wood chips for bio-substrate		2,016	m^3	$ 8.00	$ 16,128.00
Place geotextile layer over top of bio-substrate fill	$ 2,000.00	20	hr	$ 40.00	$ 2,800.00
Place 2 meters of cover soil over top of bio-substrate for freeze protection		1,344	m^3	$ 8.00	$ 10,752.00
Modify Pond 2 discharge piping (Release)	$ 1,000.00	40	hr	$ 40.00	$ 2,600.00
Peat, wood chips, and other carbon based matrl for BK625 adit		1,800	m^3	$ 8.00	$ 14,400.00
Placer gravel and other matrl for bio-substrate in BK625 adit		3,600	m^3	$ 8.00	$ 28,800.00
Shotcrete/rock fill, fine sand, or clay to create tortuous path		54	m^3	$ 125.00	$ 6,750.00
Install bulkhead and pipe collection system from BK625 adit to treatment	$ 8,000.00	160	hr	$ 40.00	$ 14,400.00
Install alcohol storage tank within treatment system	$ 1,500.00	15	hr	$ 40.00	$ 2,100.00
Install pump loop from mine pool to bioreactors for commissioning	$ 5,000.00	120	hr	$ 40.00	$ 9,800.00
Install automated monitoring system	$ 6,500.00	40	hr	$ 120.00	$ 11,300.00
				Total	**$ 157,130.00**

TABLE 1 - BELLEKENO BIOREACTOR CONSTRUCTION COSTS

In addition, AKHM expects that the reagents used within the water treatment system for commissioning the bioreactors will be minimal. The monthly operational costs for operating the Bellekeno bioreactors are estimated in Table 2.

Estimated Monthly Operating Costs with a minimal Lime Treatment System/Alcohol Addition							
Activity	**(mg/L)**	**Treated Water (L)**	**Materials**	**# Unit**	**Unit**	**Unit Rate**	**Subtotal**
Alcohol/Freight (treatment system)	10.0	10,368,000	$ 50.00	130	litres	$ 1.00	$ 180.00
Treatment Labour			$ -	8	hrs	$ 30.00	$ 240.00
Maintenance & Repair Supplies			$ 250.00				$ 250.00
Electrical/Remote Access			$ 75.00	1,188		$ 0.20	$ 312.60
Monitoring (included above)							$ -
						Total	**$ 982.60**

TABLE 2 – BELLEKENO BIOREACTOR MONTHLY OPERATIONAL COSTS

In addition to the monthly operational costs, AKHM plans to perform in-situ organic carbon additions to the mine pool over the first few years of bioreactor operations. These in-situ treatments may include the injection of one or more tanker trucks filled with methanol or ethanol. Table 2 shows that the estimated cost of alcohol is $1.00/litre and a tank truck holds roughly 20,000 litres per load.

8. ALTERNATIVE PASSIVE TREATMENT OPTIONS

Alternative passive treatment options to the bioreactor design presented here include mine pool treatment technology, which is included in this report as a pretreatment option. The use of mine pool treatment as a pretreatment or stand alone treatment has been used at similar underground mine pools to reduce metals' concentration prior to external mine treatment. The best example of this is the Platoro mine, in Colorado, where for over a decade alcohol and molasses has been added to the mine pool to stimulate sulfate reduction within the mine pool, resulting in a

Two other passive treatment options have been considered in the Keno district, which are natural attenuation, where mine water is discharged on a hillside and allowed to aerate, then pass through natural peat bogs prior to entry into the receiving environment and constructed wetland systems, where mine water is passed through wetland cells where plant-based removal of metals, both by uptake into plants, and microbes associated with the plant roots sorb or precipitate metals within the wetland cells. Both of these approaches would require passage of water to locations where the mine discharge is not immediately proximate to Lightning Creek. Alexco proposes to first employ the bioreactor technology, with the optional pretreatment of the mine pool, as the treatment approach to be used during mine closure. In the future, with the further development of other passive technologies it is possible that the water treatment approach at Bellekeno may be refined.

9. REFERENCES

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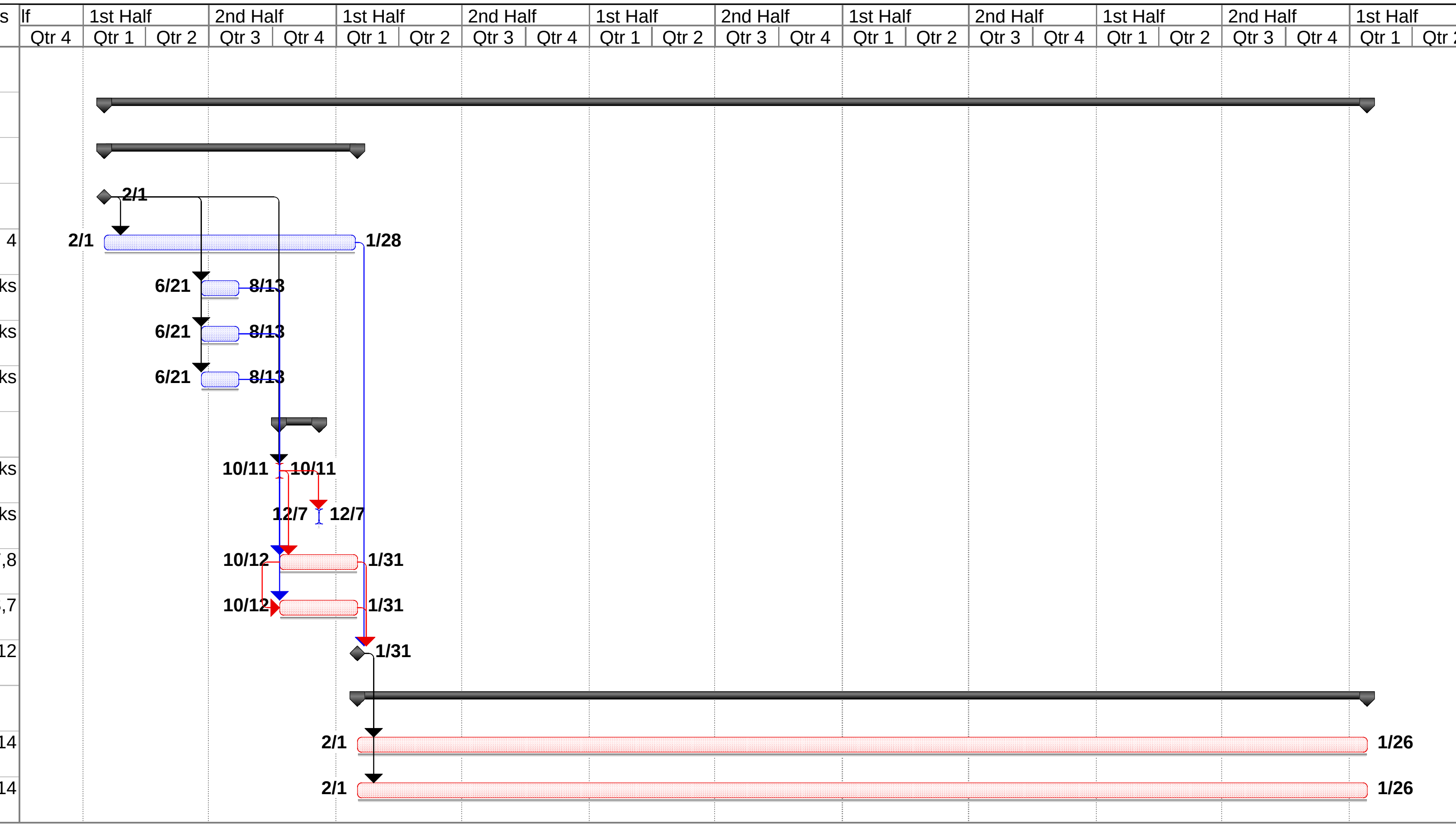
Bellekeno Bioreactor Schedule

ID	Text1	Task Name	Duration	Predecessors
1				
2		**Bellekeno Bioreactor Closure Schedule**	1301 days	
3		**Initial Closure Effort**	261 days	
4		Bellekeno dewatering pumps shut down	0 days	
5		Bellekeno Mine Pool Forms	52 wks	4
6		Bellekeno 625 Adit filled w/ bioreactor material behind a hydraulic plug	8 wks	4FS+20 wks
7		Existing Bellekeno WWTP upgraded w/ ferric chloride/alcohol tanks	8 wks	4FS+20 wks
8		Bellekeno Pond 2 converted to 2nd bioreactor	8 wks	4FS+20 wks
9		**In-situ Bellekeno Mine Pool Pre-Treatment**	42 days	
10		Mine Pool Pre-Treatment	1 day	4FS+36 wks
11		Mine Pool Pre-Treatment	1 day	10FS+8 wks
12		Bioreactor flow started with water pumped from pre-treated Mine Pool	16 wks	10,6,7,8
13		Bellekeno WWTP used as necessary to ensure effluent standards	16 wks	12SS,7
14		Bellekeno Mine floods, water drains through bioreactors	0 days	5,13,12
15		**Continued Passive Treatment Operation**	1040 days	
16		Active WWTP exists in stand-by mode	208 wks	14
17		Bellekeno mine water passively treated via bioreactors	208 wks	14

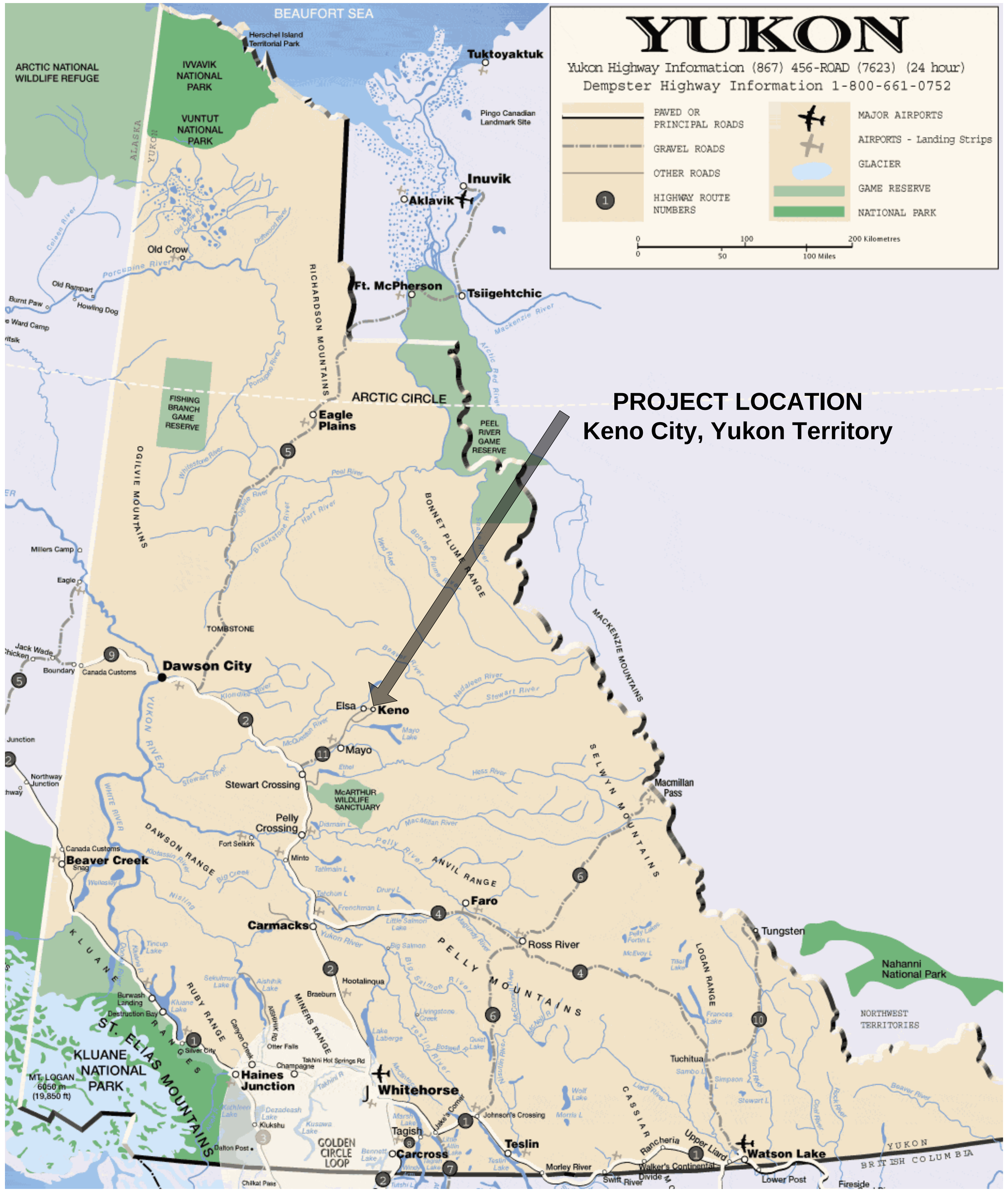


REV.	DESCRIPTION	DATE	BY
A	INITIAL RELEASE	8/19/11	EJL

APPENDIX B

ALEXCO

Alexco Resource US Corp
7720 East Belleview Avenue, Suite B-104
Greenwood Village, CO 80111
Office: 303.862.3929
www.alexcoresource.com



LOCATION MAP

SCALE: NONE

DESCRIPTION
COVER SHEET

Scope:
Design of a water treatment system that becomes operational during the decommissioning of the Bellekeno 625 mine. Water treatment system eventually becomes entirely passive with minimal required oversight and operational costs.

Rev. Date
8/19/2011

NOT TO SCALE

BELLEKENO 625
Bellekeno Bioreactor Design & Operation Plan

Alexco Resource US Corp
Water Treatment System Designer: Eric Lancaster, PE - Project Manager
Reviewer: Jim Harrington – President of Engineering

SIZE	FSCM NO	DWG NO	REV
B		2011-05	A
SCALE	N/A	SHEET	1

REV.	SHEET	DATE	BY
A	2	8/19/11	EJL

LIST OF DRAWINGS

DISCIPLINE	SHEET NO.	TITLE	REVISION NO. & DATE
GENERAL	1	COVER SHEET	Rev. A (8/19/2011) ALL DRAWINGS
	2	LIST OF DRAWINGS	
	3	WATER SPECIFICATIONS	
	4	SITE MAP	
MECHANICAL	5	ADIT BIOREACTOR X-SECTION	
	6	PROCESS FLOW SHEET	
	7	PIPING AND INSTRUMENTATION LEGEND	

DESCRIPTION
LIST OF DRAWINGS

8 7 6 5 4 3 2 1

REV.	SHEET	DATE	BY
A	3	8/19/11	EJL

Bellekeno 625

Current Water Licence Specifications

	Effluent Quality Standards	
		Existing Water Licence
		(QZ09 - 092)
Item #	**Deleterious Substance**	**Maximum Concentration in a Grab Sample**
1	pH	6.0 - 9.5 pH Units
2	Total Suspended Solids	25 mg/L
3	Ammonia Nitrogen	5 mg/L
4	Arsenic (total)	0.1 mg/L
5	Cadmium (total)	0.01 mg/L
6	Copper (total)	0.1 mg/L
7	Lead (total)	0.2 mg/L
8	Nickel (total)	0.5 mg/L
9	Radium 226	0.37 BQ/L
10	Silver (total)	0.01 mg/L
11	Zinc (total)	0.5 mg/L
	Acute Toxicity Testing	
12	96-hour Rainbow Trout	Non-Toxic, LC_{90} (100%)

Average Bellekeno 625 Discharge Rate

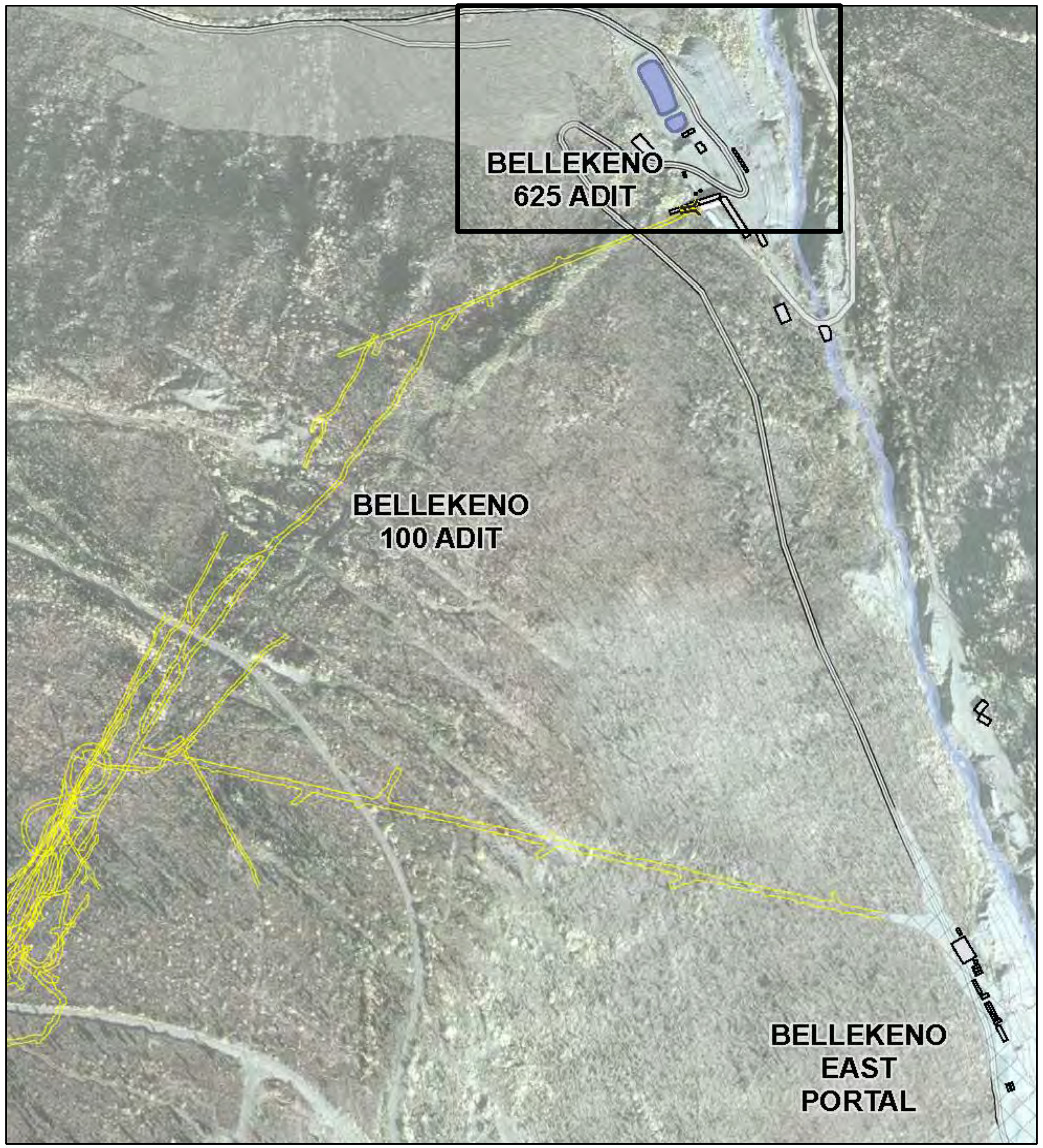
4.0 l/sec

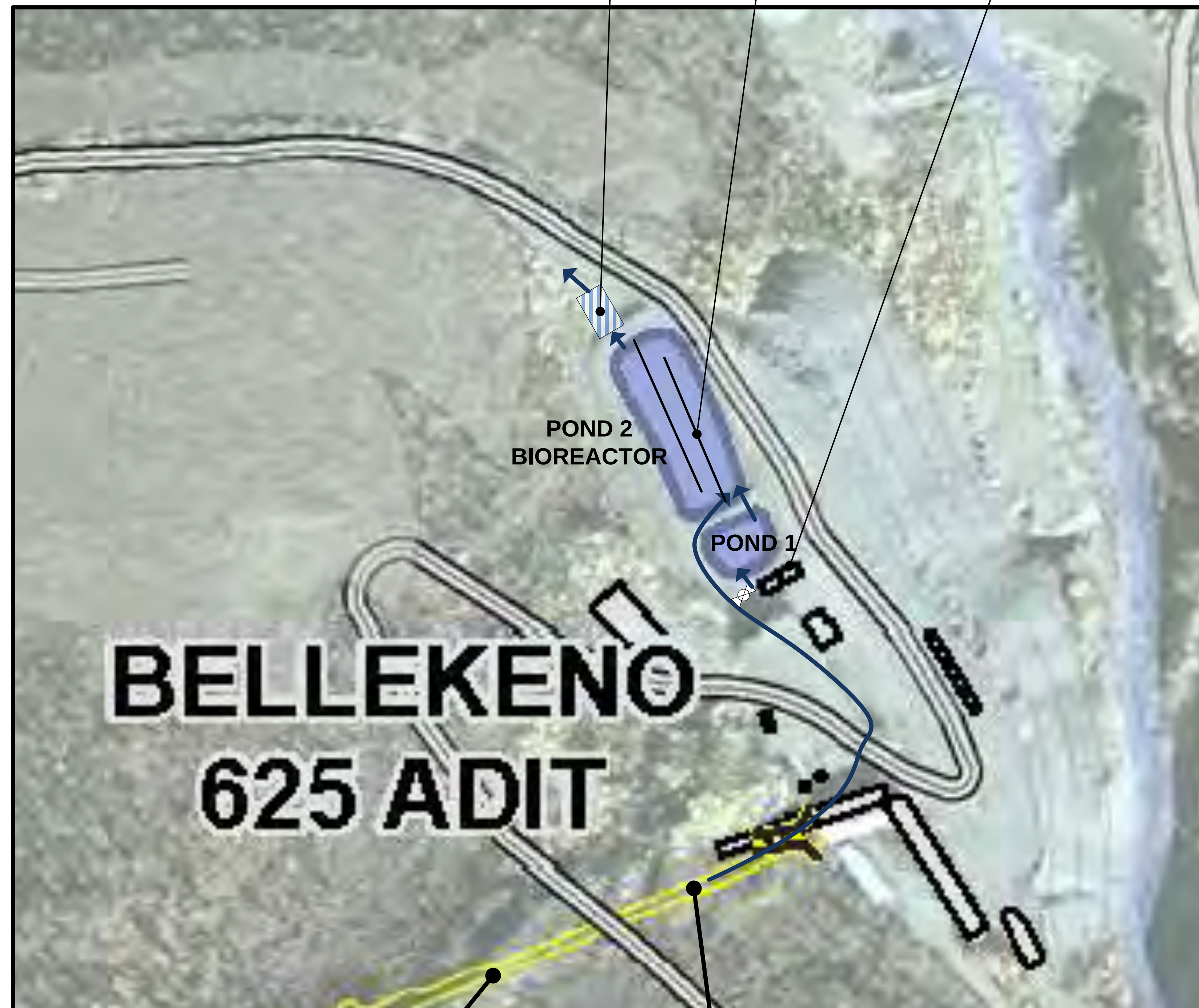
DESCRIPTION
WATER SPECIFICATIONS

8 7 6 5 4 3 2 1

REV.	SHEET	DATE	BY
A	4	8/19/11	EJL

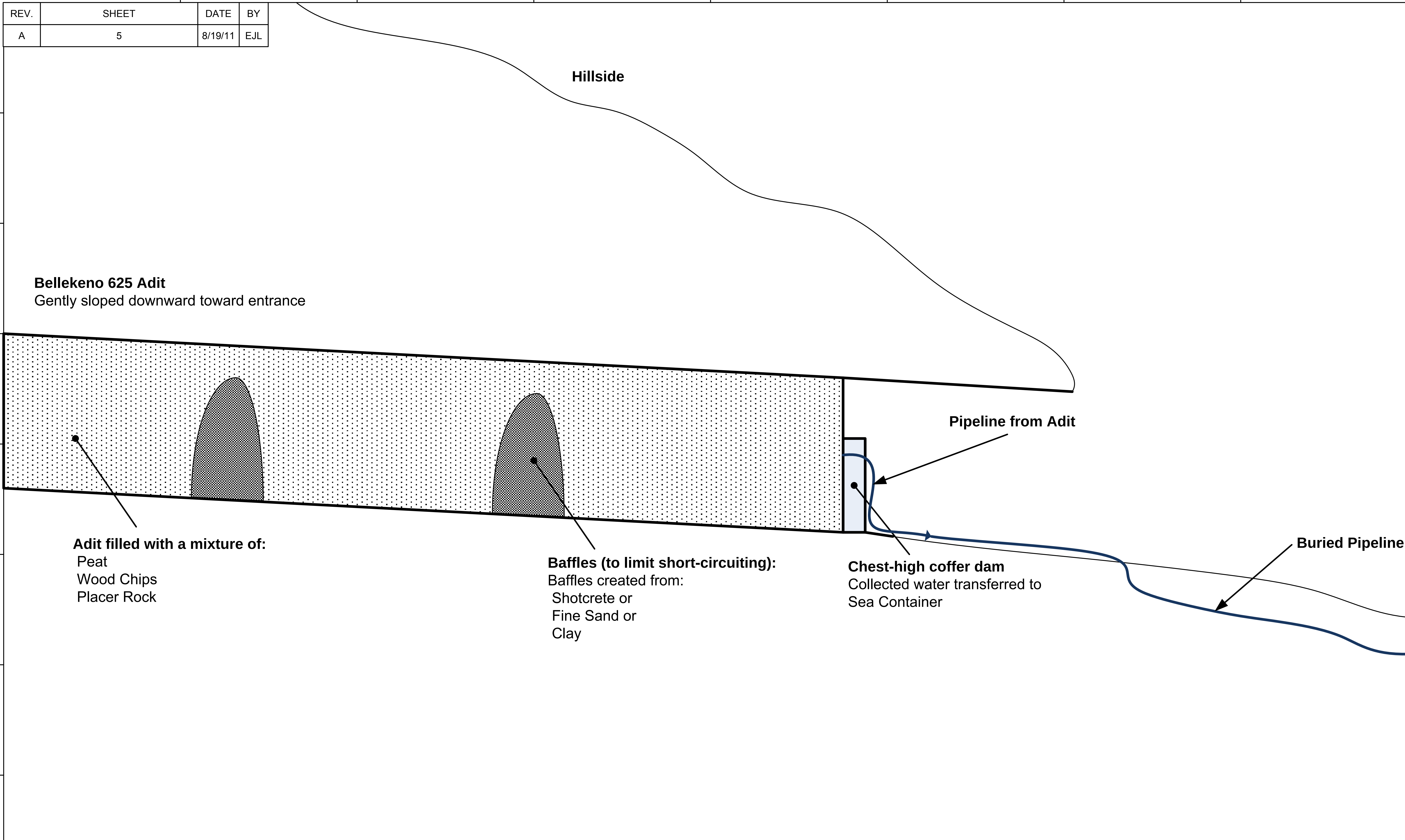
DIMENSIONS:
POND 1: 15m x 12m
POND 2: 16m x 42m
ADIT X-SECTION: 3m x 3m





DESCRIPTION
BELLEKENO LAYOUT PLAN

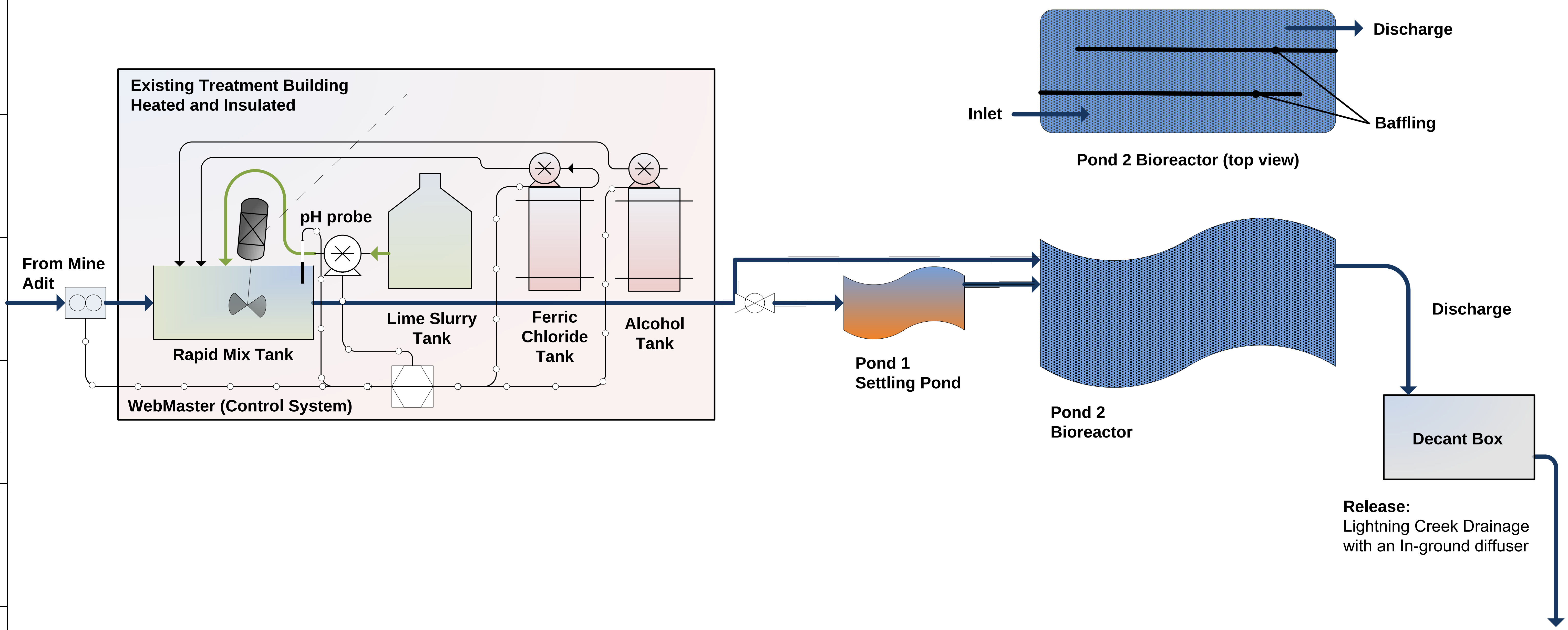
REV.	SHEET	DATE	BY
A	5	8/19/11	EJL



DESCRIPTION
ADIT BIOREACTOR

REV.	SHEET	DATE	BY
A	6	8/19/11	EJL

BELLEKENO 625
Process Flow Sheet



DESCRIPTION
PROCESS FLOW SHEET

REV.	SHEET	DATE	BY
A	7	8/19/11	EJL

PRIME MOVERS FOR MOTOR DRIVEN EQUIPMENT

- SUBMERSIBLE PUMP
- AGITATOR OR MIXER
- METERING PUMP
- pH PROBE

INSTRUMENT LINE SYMBOLS

- DATA LINE
- 120V A/C 1-PHASE
- 240V A/C 1-PHASE
- 575V A/C 3-PHASE
- HEAT TRACE / INSULATION

PIPE LINE DESIGNATIONS

- ALCOHOL ADDITION TUBE
- 2" HDPE
- 3" HDPE
- LIME SLURRY

PIPING ACCESSORIES AND DETAILS

- 45° IPS Fab Lateral

SYMBOLS FOR VALVE ACTION IN THE EVENT OF ACTUATOR POWER FAILURE

FO

SYMBOL LOCATED BY VALVE – USED ONLY WHERE NECESSARY TO INCREASE UNDERSTANDING OF THE SYSTEM.

FO = FAIL OPEN

FC = FAIL CLOSED

FL = FAIL LOCKED

FI = FAIL INDETERMINATE (LAST POSITION)

INSTRUMENTATION

- L — LEVEL SENSOR/ FLOAT SWITCH
- FLOW METER
- CONTROL PANEL
- P — PRESSURE GAUGE

VALVE SYMBOLS

- GATE
- GLOBE
- BALL
- BUTTERFLY
- CHECK

ADDITIONAL COMPONENTS

- RAPID MIX TANK
- LIME SLURRY STORAGE TANK
- INSULATED 40' SEA CONTAINER

DESCRIPTION

PIPING & INSTRUMENTATION LEGEND

APPENDIX C

DRAFT

Galkeno 900 Sulphate-Reducing Bioreactor 2008-2011 Operations Final Report

Prepared by:

Alexco Resource US Corp
For ERDC

May 2011

ERDC

TABLE OF CONTENTS

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LIST OF ABBREVIATIONS

AKHMC.................................Alexco Keno Hill Mining Corporation
AVS..Acid Volatile Sulphides
BK..Bellekeno
COC ....constituent of concern
gal...Gallons
KHSD.....................................Keno Hill Silver District
kg..Kilogram
l ....Litres
lb ....Pounds
lpm ....Litres Per Minute
lps...Litres Per Second
SRR..Sulphate Reduction Rate

1. EXECUTIVE SUMMARY

Alexco Environmental Group has operated a test bioreactor at the Galkeno 900 mine site since October 2008. Bioreactor technology is considered a closure option for some adit drainage sites in the Keno Hill Silver District (KHSD) and this closure pilot study has been performed to validate the effectiveness of this treatment technology with special consideration of engineering a stable bioreactor for the KHSD climate. In general, once sulphate reduction onset occurred after a commissioning period, effective treatment (significant mass reduction averaging over 90% during operational periods, and achieving discharge criteria at lower flow rates) was accomplished with a test flow rate range of 0.5-1.0 litres per second (lps). The configuration of the bioreactor was suboptimal due to the very limited footprint available near the Galkeno 900 adit, and the regulatory requirement to operate the bioreactor upstream of the lime treatment system. However, the key objectives of the study were accomplished; specifically sulphate reducing rates were determined across year-round operation, and it was demonstrated that the sulphate bioreactor technology could achieve under some operational flow rates discharge water quality standards as set under the existing water licence QZ06-074. The primary failure mode of the bioreactor was failure of the pumping systems due to power outages, which happened several times during the study, which led to freezing of the antisiphon valves and loss of water by siphoning from the bioreactor.

During the operational treatment phase at 0.5 lps, results showed removal of close to 99.8% zinc was achieved (5-6 mg/L reduced to 0.011 mg/L). During the operational treatment phase at 1.0 lps a maximum of 97.8% removal was occasionally achieved. Section 6, Bioreactor Performance, provides additional information concerning other metals that have also been substantially removed in the bioreactor at flow rates between 0.5 lps and 1.0 lps respectively. While zinc is the primary Constituent Of Concern (COC), 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 had good removal during the recirculation phase (99% for both metals) showed a dissolution and production from the bioreactor during the reduction onset and initial through flow phases. Manganese currently 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, demonstrating that dilution is not a significant factor causing metal removal in the reactor.

2. BACKGROUND

A bioreactor was constructed and operated in the Keno Hill Silver District (KHSD) at the Galkeno 900 adit beginning in May 2008. The bioreactor is still in operation as of May 2011, but the results of the bioreactor operations discussed in this report only include data through to March 2011. These results demonstrate the viability of sulphate reduction technology for the removal of metals, especially zinc and other metals that react with aqueous sulphide, in the KHSD.

The bioreactor solid phase substrate utilized to construct the bioreactor was coarse rock from a nearby placer mining operation. Solid organic carbon forms were not utilized to allow for the simplest assessment of metals removal due to sulphate reduction only. The organic substrate supplied to the bioreactor included dissolved organic carbon forms, with sugars, alcohols and complex carbohydrates and proteins from milk used during the growth phase of the bioreactor operation, and sugars and alcohols used during the maintenance phase. The purpose of the organic substrate was initially to support microbial growth until sulphate reduction became the predominant microbial activity in the reactor, and during the treatment phase to support microbial sulphate reduction. Sulphate reduction is a chemical transformation performed by microbes that transfers electrons from organic carbon to sulphate, causing sulphate to be reduced to sulphide. Sulphide then reacts with many dissolved metals, forming very insoluble metal precipitates. The reactor also had 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 part of a multipurpose program to assess the potential of adding an organic substrate to mine adit water to support metals removal, whether within 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 sulphide- and carbonate-based mineral precipitation that occurs in a bioreactor is similar to what would occur in a mine pool or natural sulphate reduction zone outside of a mine pool. The sulfate reduction rate observed in the bioreactor is similar to what would be achieved in these other settings.

Alexco has extensive experience with these types of in situ sulphate reduction systems, and 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 sulphate reduction.

Several adit discharge locations are being considered in the Closure Option assessment process for treatment in a bioreactor (Alexco Environmental Group, 2011). At this time, Silver King 100, Bermingham 200, Ruby 400, No Cash 500, Galkeno 900, Onek 400, Sadie Ladue 600 and Keno 700 are all considered as possible locations where bioreactor technology could be employed. Galkeno 900 has water chemistry and flow characteristics that are typical of these other adits in the KHSD. This test was of sufficient scale and operated long enough to provide design information that allows for the design of either a large scale bioreactor or an in-situ reduction field at several other adit drainage locations in the KHSD. The test was operated in a lined bioreactor allowing for the performance of the technology to 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 continued through the winter season to demonstrate durability of metals removal mechanisms. During the course of the bioreactor demonstration, the conventional lime treatment system was maintained to ensure water license discharge compliance criteria were met.

3. GALKENO 900 TREATMENT LAYOUT

Figure 1 shows the piping and instrumentation setup of the bioreactor and treatment facility at Galkeno 900.

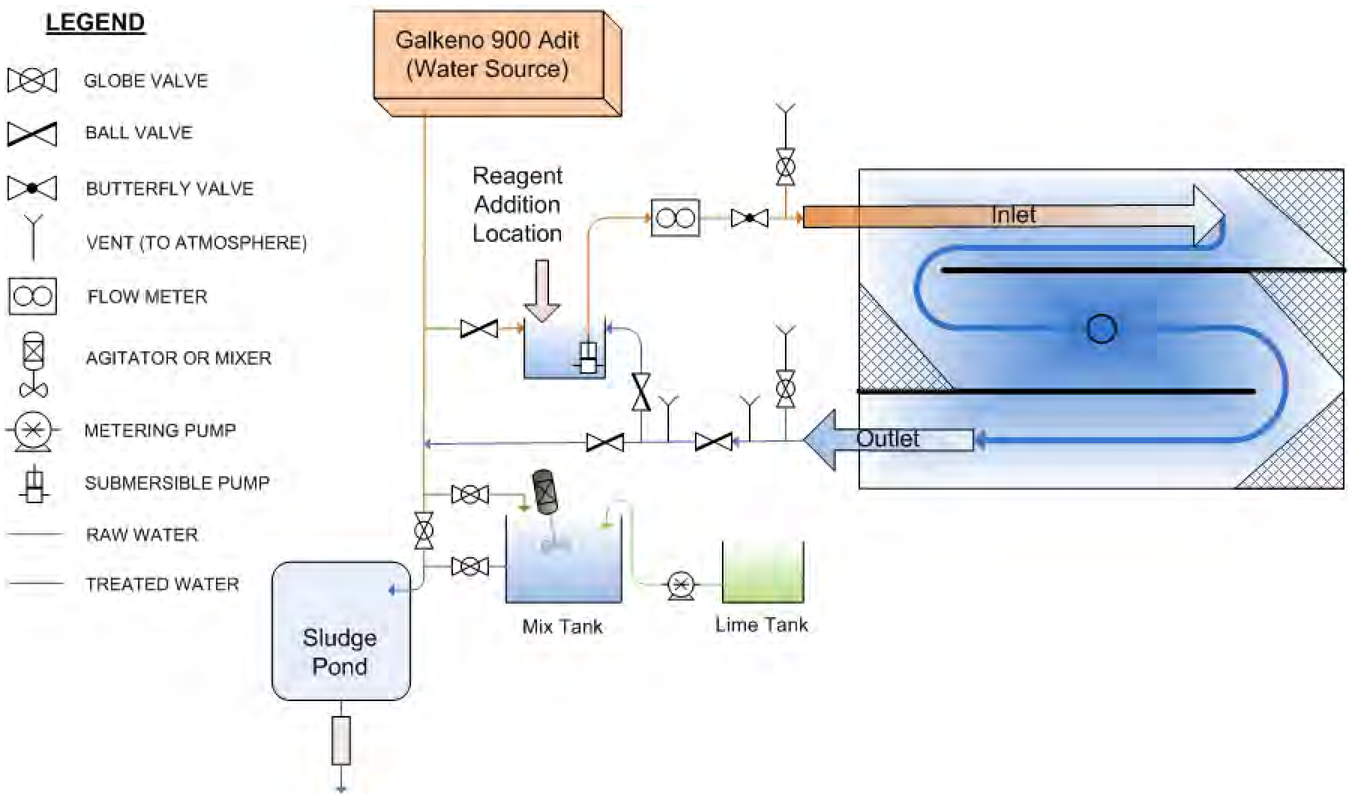

FIGURE 1 - GALKENO 900 LAYOUT

Water drains from the Galkeno 900 adit at an average annual rate of 4 litres per second (lps). This water is collected in a pipe and gravity flows away from the adit. Before the bioreactor system was installed, the water traveled directly to the treatment facility where it was mechanically agitated in a mix tank and dosed with lime slurry through a metering pump. Then the water was discharged to a sludge pond where the heavier particles where allowed to settle at the bottom in the form of sludge, and clean water was decanted and released. When the bioreactor treatment system was installed, additional valves and piping were added upstream of the lime treatment system so that a portion of the untreated adit water could pass through the bioreactor system for the purposes of this study.

FIGURE 2 – INLET VALVE

Water is supplied to the bioreactor through an initial valve that when opened allows water to travel to the bioreactor's influent sump. Because of the harsh conditions in the Yukon, this valve, and all piping used in this setup was buried over 1 meter below surface, thereby reducing the possibility of freezing. Figure 2 shows the buried vertical pipe that contains this initial valve. In this figure, water travels downward from the adit to the lime treatment area. Opening this valve allows water to flow into the bioreactor's inlet sump.

The bioreactor inlet sump, shown in Figure 3, has a 48 inch diameter and is also located below surface. It is accessed through a cover that allows for reagent addition and water sampling as needed. Normal operation of the bioreactor requires the frequent dosing (constant dosing up to as infrequently as every two weeks, depending on flow rates) of a carbon source such as sugar, ethanol, or methanol. These reagents are slowly added to this sump via a metering pump for the liquids, or as dry powder for the sugar. During initial start-up, and on a few other occasions, an addition of milk sugars/protein as dry milk powder was required to aid the growth of microbes in the bioreactor. These reagents were also added at this location.

FIGURE 3 – BIOREACTOR INFLUENT SUMP

FIGURE 4 – BIOREACTOR INLET

Within in the bioreactor inlet sump is a 1-horsepower submersible pump. The cable seen in Figure 3, stretching from lower left to upper right, attaches to a chain allowing the pump to be removed from the mix tank for servicing and/or replacement. The discharge from this pump is shown in Figure 4.

From the bottom of Figure 4 moving toward the top is a blue datalogger attached to the black Magnetic Flowmeter (Magmeter), a throttling globe valve, and finally a vertical anti-siphon standpipe. The datalogger records and stores the flow rates from the magmeter, allowing the system's operation rate to be tracked and analyzed. The globe valve is used to adjust the flow rate into the bioreactor. The vertical anti-siphon standpipe is exposed to the atmosphere. The system is designed so that in the event of pump failure, air will be pulled into the pipe and breaks the siphon. This series of instruments and valves is also located below grade in an insulated box and can be accessed through a cover.

The bioreactor is roughly 90 feet by 100 feet and has a liquid-filled portion that is 10 feet deep. It was dug partially into the native ground with an excavator, and the remaining depth was created by forming a berm around the excavated area. The bermed/excavated area was lined with 0.060 inch thick HDPE liner to form a pond, and then filled with waste rock recovered from a local placer mine. Figures 5 and 6 were taken during construction of the bioreactor and Figure 7 shows the overall design.

After the pond was filled with placer oversize rock, a geofabric was laid across the bioreactor, and soil from the excavated area and hillside was used to provide a 4 foot soil cover over the bioreactor. This soil cover layer acted as an insulating layer, minimizing the amount of ice formation in the top layer of the bioreactor. When the bioreactor solids were sampled in March 2011, the ice layer was approximately 18 inches to 2 feet thick.

Water enters the bioreactor through an inlet pipe that transports water to the far side of the bioreactor (see Figure 7 for an overall view of the layout). The last half of the pipe is perforated with ¾" holes, allowing water to fill the bioreactor and flow back and forth before final release.

FIGURE 5 - BIOREACTOR CONSTRUCTION

FIGURE 6 – BIOREACTOR STANDPIPE

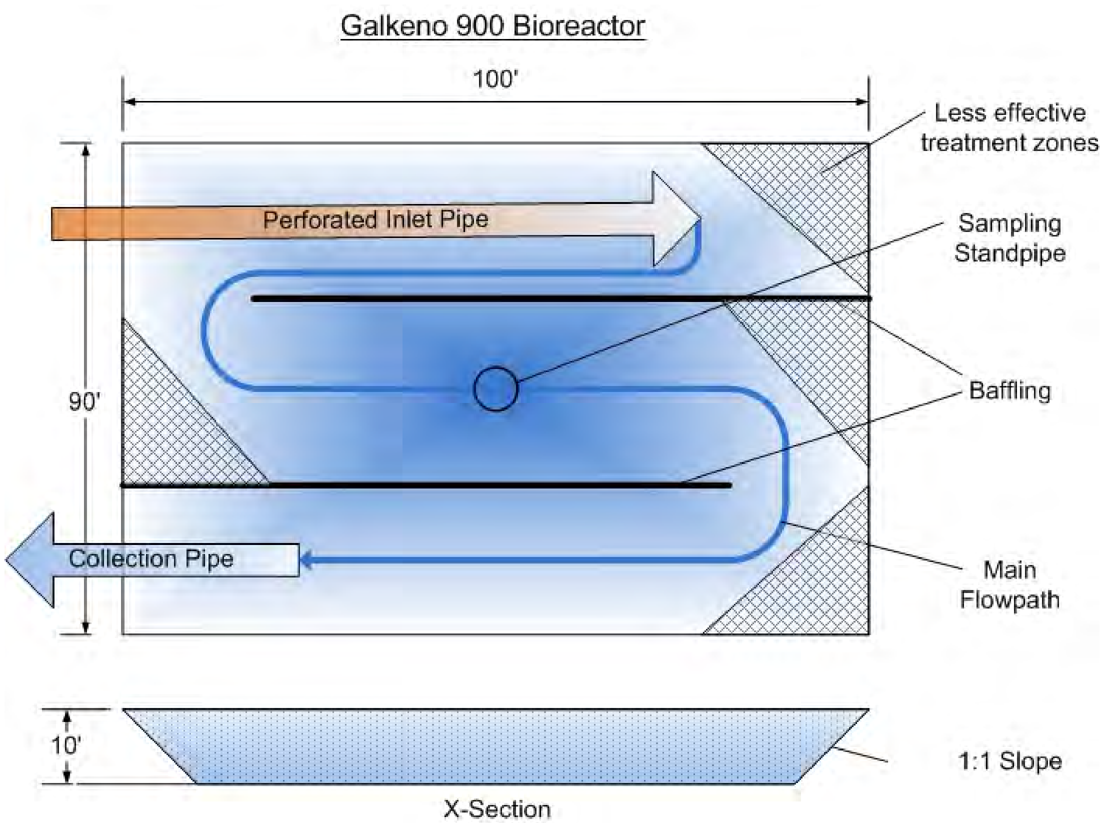

FIGURE 7 – BIOREACTOR LAYOUT

Baffling was installed in two locations to create a torturous flow path and increase the contact time of the water with the media within the bioreactor,. This forces the water to travel a greater distance within the bioreactor before final release and to contact a greater fraction of the media. Also present at the center of the bioreactor is a sampling standpipe that can be seen in Figure 6. This allows samples to be collected and analyzed once water has passed midway through the bioreactor.

The discharge from the bioreactor is collected in a pipe and can then be either sent back to the bioreactor influent sump for recirculation or mixed with untreated adit water from the Galkeno 900 adit. This co-mingled water then passes through the lime treatment system mentioned earlier and is released into a sludge pond where heavy particulate settles and clean water is decanted and released. Figure 8 is the bioreactor discharge valve set-up. Water travels from the bioreactor on the right (not shown) and can either be sent up (as shown in the photo) to the bioreactor influent sump or to the left (as shown in the photo) to be co-mingled with adit water from the Galkeno adit. This setup is below surface grade and is accessible through a cover.

FIGURE 8 – BIOREACTOR DISCHARGE VALVES

Overall, the system was constructed to provide the operator with the maximum amount of flexibility to study the performance of a bioreactor without introducing the risk of releasing untreated water from the adit. Based on the positions of several valves, the system could be run in one of the following operation modes:

1.) Bioreactor influent valve closed – collected adit water bypasses the bioreactor and is treated at the lime treatment facility.
2.) Bioreactor influent valve and discharge valve closed – water pumped from the bioreactor influent sump fills the bioreactor and once filled, this mode allowed the water in the bioreactor to be continuously re-circulated. This was important to allow for the initial

growth phase of the bioreactor, allowing the carbon source to be consumed in the bioreactor rather than being released from the discharge.

3.) Bioreactor influent valve open and discharge valve open – untreated adit water was pumped into the bioreactor, sampled along several key locations, then discharged from the bioreactor and co-mingled with the untreated adit water where it was transferred to the lime treatment facility.

The water from the adit was a significant heat source for the bioreactor; therefore some amount of influent water from the adit was desired even during the initial growth phase of the bioreactor. In a full scale installation without the requirement of the downstream secondary treatment plant, these valving systems would not be required other than to provide a bypass from the adit if desired, and a temporary recirculation loop to allow discharged water to be sent back to the influent sump.

4. BIOREACTOR OPERATIONAL SUMMARY

Operational notes are included in this report to capture a few of the issues experienced during construction and operation of the bioreactor. The bioreactor construction began in the summer of 2008 with operation starting soon after. The following timeline outlines milestones, as well as issues, that were noted during operation:

- July-August 2008: Pond constructed and lined (see Figures 5 & 6).
- September 2008: Pond filled with oversize rock from a local placer mining operation (some small amounts of fines were present).
- October 4th, 2008: Start filling the bioreactor with untreated adit water.
- October 10th & 11th, 2008: Started recirculation of bioreactor water, added 182 kg sucrose to support microbial sulfate reduction.
- October 16th, 2008: 110 gal methanol and 1.8 kg dried milk solids added.
- October 2008: Bioreactor covered with geofabric and several feet of topsoil.
- October 2008 through May 2009: Occasional "top up" of untreated mine water to maintain full conditions in bioreactor. Make-up water averages ~ 1 m^3/day or approximately 1 liter per minute average.
- January 23rd, 2009: 110 gal methanol added.
- January 2009: Determination of slow leakage rate from bioreactor ~ 1.09 m^3/day.
- **February 19th, 2009**: Anti-siphon valve on the return recirculation line iced over, draining the bioreactor and flooding covers/box. Estimated ~135 m^3 water was lost from the bioreactor through overflow of the tank.
- April 8th, 2009: Bioreactor standpipe blocked with ice – unable to sample.
- May 17th, 2009: Began adding methanol at the bioreactor influent sump at a rate of 1.0 litre per day.
- July 11th & 12th, 2009: Added 10 kg sucrose each day to jumpstart reduction, continued methanol addition at 1.0 litre per day.
- August 25th, 2009: Installed totalizer and flowmeter on the inlet to the bioreactor.

Once methanol was added at a constant rate, the bioreactor began through-flow operation. During that time, the following events occurred:

- October 8th, 2009: Initiated flow-through at a rate of 0.5 litre per second.
- December 18th, 2009: Initiated flow-through at a rate of 1.0 litre per second.

- January 7th-20th, 2010: Valve box flooded and frozen, thawed and repaired on January 20.
- February 15th, 2010: Power loss to submersible and metering pump.
- **February 16th - 18th, 2010**: Power loss while anti-siphon frozen which resulted in the loss of approximately half the bioreactor water volume through the sump; power restoration and line thawed; refilled bioreactor.
- August 6th, 2010: Reduced flow rate to 0.75 l/s to improve treatment.
- March 17th &18th, 2011: Return line frozen.

A review of the operator's log provides some important details that will guide future design. On February 19th 2009 and February 16th 2010, loss of power and a lack of continued pumping of water, which maintained heat in the bioreactor lines, resulted in ice formation in the anti-siphon valve. With the transfer pump stopped, the bioreactor siphoned water into the sump, which overflowed on the ground around the sump.

5. METALS REMOVAL MECHANISMS IN BIOREACTOR TREATMENT

The removal of metals from mine waters by bioreactors is done around the world, utilizing a variety of approaches. Doshi (2006) summarizes the many different types of bioreactors that are in operation, and discusses the relative advantages and disadvantages of these different bioreactor systems. The bioreactor utilized at Galkeno 900 is one type of reactor, where the only carbon source added to the bioreactor was added in a dissolved form semi-continuously during the operation of the bioreactor. Bioreactors are often constructed utilizing a mixture of substrates which either act as a carbon source for microbial reactions, or these substrates can act as sorptive surface for metals precipitation. However, bioreactors with solid phase carbon sources are often limited in their sulphate reduction rates by the availability of soluble organic carbon (Buccambuso et al, 2007) indicating that the constant supply of a carbon source as was done in Galkeno 900 bioreactor will tend to prevent microbial limitations on treatment.

For context of this discussion, the operation of the Galkeno 900 bioreactor can be divided into three distinct time periods. They are:

- **Recirculation Phase – Operation Mode 2 (October 2009 - July 2009):** During this period, the bioreactor was placed into service with water from the adit entering at an average rate of one litre per minute (1 lpm), which provided makeup water to replace slow leakage, and also to provide some heat from the adit water during the cold season. An initial carbon source addition consisting of (1.8 kg) milk powder and (182 kg) table sugar (sucrose) and (110 gal) methanol was added to provide an energy and nutrient source for an initial microbial growth phase. No source of microbes other than what was present on the placer rock and what is carried in the mine water was added to the bioreactor. However, researchers studying mine water and sediment at the Penn Mine Church et al (2007) showed that mine water even in an pH 4 mine drainage with high concentrations of heavy metals contained sulphate reducing bacteria and accounted for metals removal processes. The water in the bioreactor was re-circulated at a rate of one to two liters per second to mix and distribute water in the bioreactor. The water was periodically sampled to evaluate microbial growth and activity indirectly by evaluating water quality changes that could be inferred to be caused by microbial action. During this period there was incomplete formation of reducing conditions and the bioreactor likely had both aerobic and anaerobic zones. During the recirculation phase, metal concentrations were decreased over several months (discussed more below) and the removal mechanisms during this time may have included oxidative mechanisms (iron and manganese oxide formation) with metal co-precipitation on the iron and manganese oxides, carbonate mineral formation, and microbial sulphate reduction and metal sulphide precipitation.

- **Reduction Onset Phase – Operation Mode 2 (July 2009 – September 2009):** During this period, water within the bioreactor continued to be re-circulated while additional carbon sources were added at the bioreactor influent sump. This resulted in elevated carbon concentrations and the onset of more strongly sulphate-reducing conditions. During this time, the development of stronger reducing conditions were observed, characterized by greater sulphate reduction, the dissolution of manganese and iron from the reactor solid phase (likely manganese and iron oxides formed during initial bioreactor operations, as well as structural iron and manganese minerals in the placer rocks), and greater metals removal as sulphides.

- **Operational Treatment Phase – Operation Mode 3 (October 2009 – March 2011):** An initial flow rate of 0.5 litre per second (lps) was established into the reactor, and after stable metal removal conditions were observed this flow rate was maintained for several consecutive bimonthly samples. Soon after, the flow rate was increased to one litre per second (lps) in December 2009. In August 2010, the flow rate of the bioreactor was reduced to 0.75 lps, or approximately 19% of the adit flow. This flow rate was then maintained for the remaining operation of the bioreactor.

The results displayed in this report focus primarily within the operational treatment phase. The other phases, while important, are reflective of treatment performance during the transition of the bioreactor from construction to operation.

5.1. LITERATURE REVIEW AND BACKGROUND DISCUSSION

The formation of metal precipitates in a bioreactor that has carbon sources added to or present in the solid phase of the bioreactor has been extensively studied for 30+ years. There are several different styles of bioreactors, both in terms of carbon sources and flow dynamics. Some very large bioreactors have been created to treat flows as large as 20 lps or greater, and some bioreactors are designed to treat very acidic or concentrated metal-containing mine drainage. Each bioreactor must be designed to reflect the environmental conditions, the water chemistry of the mine water being treated, and other relevant variables as discussed in this report.

To understand the processes that occur in bioreactors many studies have attempted to identify directly by examination of mineral formation or by inference from water chemistry signatures what primary mechanisms are responsible for metals removal. When complex carbon sources are added as a solid phase in the bioreactor construction (i.e., peat, straw, compost, wood chips, etc.), a broad range of mechanisms has been documented (Gusek, 2002; Doshi, 2007; Gusek et al, 2008), that include:

- Sorption of metals on organic matter.
- Precipitation of iron hydrous oxides including ferric and mixed valence minerals, which then provide mineral surfaces for sorptive removal of metals, or metals can also be co-precipitated within the iron mineral matrix.
- Precipitation of manganese oxides including manganese (IV) oxides and mixed valence (III/IV) oxides and manganese carbonates, which then provide mineral surfaces sorptive removal of metals, or metals can also be co-precipitated within the manganese mineral matrix.

- Precipitation of metal sulphides, including primary metal sulphides such as ZnS or CdS, as well as precipitation of iron sulphides such as amorphous FeS and co-precipitation of metals within the FeS matrix. Depending on the pH of the bioreactor and the availability of structural iron, a very large amount of FeS minerals can be formed by aqueous sulphide formed by microbes reductively dissolving iron from the rock matrix, creating a "bank" of amorphous sulphide which has reactivity toward dissolved metals.
- Precipitation of some metals in their reduced forms, for example selenium reduction from a Se(VI or IV) anion to elemental selenium precipitates Se.
- Precipitation of metals as carbonate minerals. Some of the relevant metals have somewhat soluble carbonate minerals (e.g., zinc carbonate minerals including smithsonite, and hydrozincite) which are relatively more soluble than sulphides. When sulphide is not present, these minerals may provide a precipitation-removal mechanism.

Sorption of metals on organic matter is not a relevant metals removal mechanism in the Galkeno 900 bioreactor because only coarse rock was used as a solid substrate. The metal removal mechanisms in this reactor appear to initially relate to removal of iron and manganese during the recirculation phase, and then over time the removal mechanism transitioned to a metal sulphide removal mechanism (inferred because metals removal continued to occur when iron and manganese ceased being removed and actually increased in concentration during flow through the reactor). The precipitation and removal of metals in their reduced forms is not a significant potential mechanism for most of the metals present in Galkeno 900 adit water, with the potential exception of uranium which was only present in very low concentrations in the influent water. Consequently, the formation of sulphide from sulphate, which is a chemical reaction that is catalyzed by microbes and relies on the availability of organic carbon, is the primary performance variable that is relevant in the Galkeno 900 bioreactor performance evaluation. In typical evaluation of bioreactors where sulphate reduction/sulphide precipitation is a dominant mechanism, the Sulphate Reduction Rate (SRR) is determined as a primary design variable.

In a bioreactor with available sulphate and a soluble carbon source added, Dar et al (2007) showed that sulphate reducing bacteria (SRB) are the dominant microbe that accumulates in the bioreactor, and by inference the vast majority of the carbon consumption is performed by SRB. In their study, only a few different strains accounted for the majority of the cells present, indicating that microbes capable of utilizing the carbon source and reduce sulphate will become dominant in the bioreactor.

After the bioreactor entered stable operation, metals removal mechanisms appear to have shifted from the mixed reaction that were discussed in the prior report (Alexco Resource US Corp, 2009) to primarily a sulphide-based precipitation process. The stability of metals removed as sulphides are consequently an important consideration for the performance of the bioreactor. Jong and Perry (2004) studied the form of metals that were precipitated from solution as a result of the sulphate reduction process, and determined that arsenic, copper, iron, nickel, and zinc were primarily bound up in a sulphide phase that was also associated with residual organics, and that carbonate or hydroxide phases were relatively minor phases that held the metals removed from solution. The United States Environmental Protection Agency SITE program studied the stability of these sulphate-reducing bioreactor precipitates at the Leviathan Mine, in California. Using a series of different tests, the EPA determined that the metals in the bioreactor precipitates were below regulated total metals thresholds (California standards), the WET extraction test showed that the metals in the bioreactor did not leach above regulated soluble threshold standards, and that as defined by TCLP extraction testing the bioreactor solid materials were not hazardous.

The effectiveness of this sulphate reduction bioreactor process is sensitive to important variables including the hydraulic residence time in the bioreactor, the sulphate reduction rate, and the filtration capacity of the media.

Because the products of the sulphate reduction reaction include both sulphide 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 sulphide precipitation mechanism appears more likely because sulphide precipitates are less soluble than the carbonate precipitates of these elements. Thus the sulphate reduction reaction is the primary reaction that we will focus on optimizing in the bioreactor operations.

5.2. DETERMINATION OF THE SULPHATE REDUCTION RATE

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

4 moles methanol + 3 moles sulphate ➔ 3 moles sulphide + 4 moles bicarbonate

The rate of the reaction is nearly the same at temperatures in natural environments where the long-term 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 for the Galkeno 900 bioreactor to reach maturity so that it could sufficiently treat mine water. However, once the bioreactor was competent to perform sulphate reduction (as evidenced by net sulphide concentrations leaving the reactor in the 1 to 10 µM range, indicating that there is excess aqueous sulphide created above what was required to react with the soluble and solid phase metals) then the bioreactor SRR could be assessed. (Note: it was possible to add more organic carbon to the reactor and support additional sulphate reduction, however it would result in higher dissolved sulphide which would not be required for metals precipitation, and could result in reduction of oxygen in the surface receiving streams. At the amount of sulphide precipitation that was achieved (1 to 10 µM range) dissolved oxygen consumption would be less than 1 mg/L, or less than 10% of what is normally in surface water.)

The SRR is measured in terms of mM sulphate reduced per m^3 of bioreactor substrate per day. The influent sulphate compared to the effluent sulphate is compared to determine the amount of sulphate removal. The average sulphate removal amount during the treatment 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 lps, the total sulphate 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 the bioreactor has 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 dividing the amount of sulphate reduced by the volume of the entire bioreactor. However, less effective treatment zones or “dead zones” are identified in Figure 7 and were expected based on the sub-optimal configuration that was available at Galkeno 900. These areas can limit the exchange of organic carbon and therefore it is likely that minimization or elimination of these dead zones will improve the performance of the bioreactor.

5.3. RECIRCULATION DYE TEST

The volume of the bioreactor voids needed to be determined independently to assess residence time and other performance characteristics of the bioreactor. The dimensions of the reactor were measured to be approximately 100 feet by 90 feet and 10 feet in depth. Assuming an estimated porosity of 0.35, the volume was calculated to be roughly 890 m^3 or approximately 235,000 gallons. Starting on August 25th, 2009, a dye test was completed to independently assess the volume in the reactor.

Roughly eight ounces of rhodamineWT dye was added to the bioreactor on August 25 2009, and water was re-circulated in the bioreactor at a rate of two litres per second. After equilibrium conditions were reached in six days, a final dye concentration of 0.25 ppm dye was measured. The volume of the bioreactor was determined by the following formula:

$$\text{Volume of reactor } = \text{mass of dye added} \div \text{concentration measured}$$

Using this formula, the volume of the bioreactor was calculated to be approximately 909 m^3, or 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.

Understanding the volume of the bioreactor is necessary to understand the potential hydraulic residence time for water passing through the reactor. At 0.5 lps, assuming the total porosity of the bioreactor is utilized, approximately 21 days of residence time is available, and at 1.0 lps, approximately 10.5 days of residence time is available. A 2 lps flow rate should result in a residence time of approximately 5.25 days.

The dye test was run under re-circulating conditions at a relatively fast rate (2 l/s). 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 lps 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 9 shows conceptualization of flow in the bioreactor.

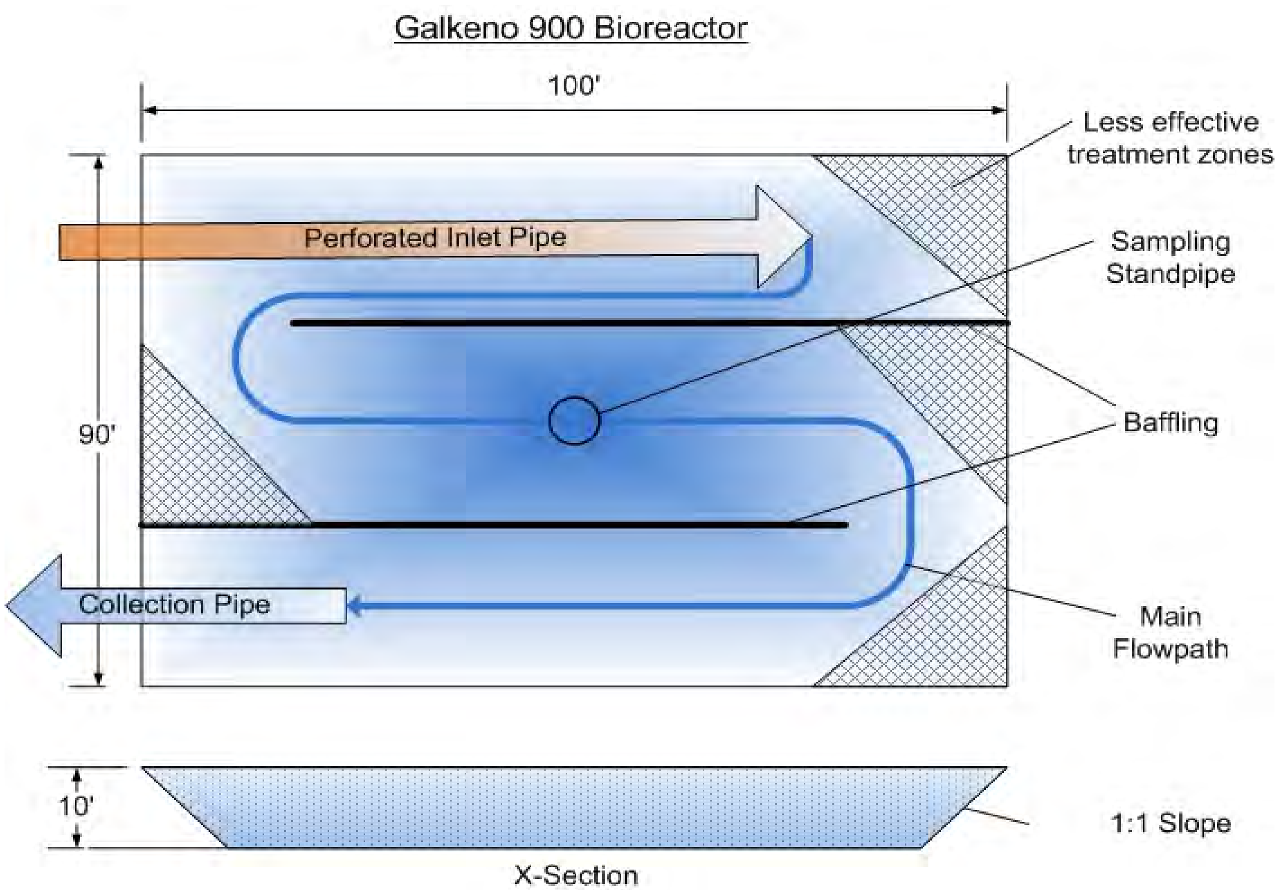

FIGURE 9 - CONCEPTUALIZATION OF FLOW PATHS IN THE BIOREACTOR

The "less effective treatment zones" are where water entering the bioreactor does not interact as much with the media and hence these zones are likely to only minimally contribute to the treatment performance. The activity in these areas is dependent on the availability of carbon sources diffusing from the actively flowing areas to support sulphate reduction. The practical residence time in the bioreactor can be estimated as two 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. For the design of bioreactors these less effective zones cannot be relied upon for treatment and hence the 2X dye peak is used for design purposes.)

Flow rate	Residence time (total porosity)	Residence time (active porosity)
0.5 lps	21.0 days	9.00
1.0 lps	10.5 days	4.50
2.0 lps	5.25 days	2.25

TABLE 1 - RESIDENCE TIME WITHIN THE BIOREACTOR PER FLOW RATE

6. BIOREACTOR PERFORMANCE

The performance of the bioreactor with respect to water chemistry is summarized in the following tables, graphs, and discussion. To better understand the treatment goals, Table 2 provides the Galkeno 900 effluent quality standards per the Conditions of Water Licence QZ06-074. In order to release water from any adit in the KHSD that is currently under the Care and Maintenance of ERDC, the water discharge must meet these standards. It is important to note that some sites such as Keno 700 do not need to meet discharge standards in order to attain aquatic standards in the receiving environment (Lightning Creek) Targeting a mass reduction goal of 90% may be more relevant for some sites of this nature.

Parameter	Maximum Concentration in a Grab Sample Measured in mg/L
pH	6.5 - 9.5 pH units
Suspended Solids	25.0 mg/L
Arsenic (total)	0.50 mg/L
Cadmium (total)	0.05 mg/L
Copper (total)	0.30 mg/L
Lead (total)	0.20 mg/L
Nickel (total)	0.50 mg/L
Silver	0.10 mg/L
Zinc (total)	0.50 mg/L

TABLE 2 – EFFLUENT QUALITY STANDARDS PER WATER LICENCE

6.1. 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 10 illustrates the pH of the influent and effluent from the reactor.

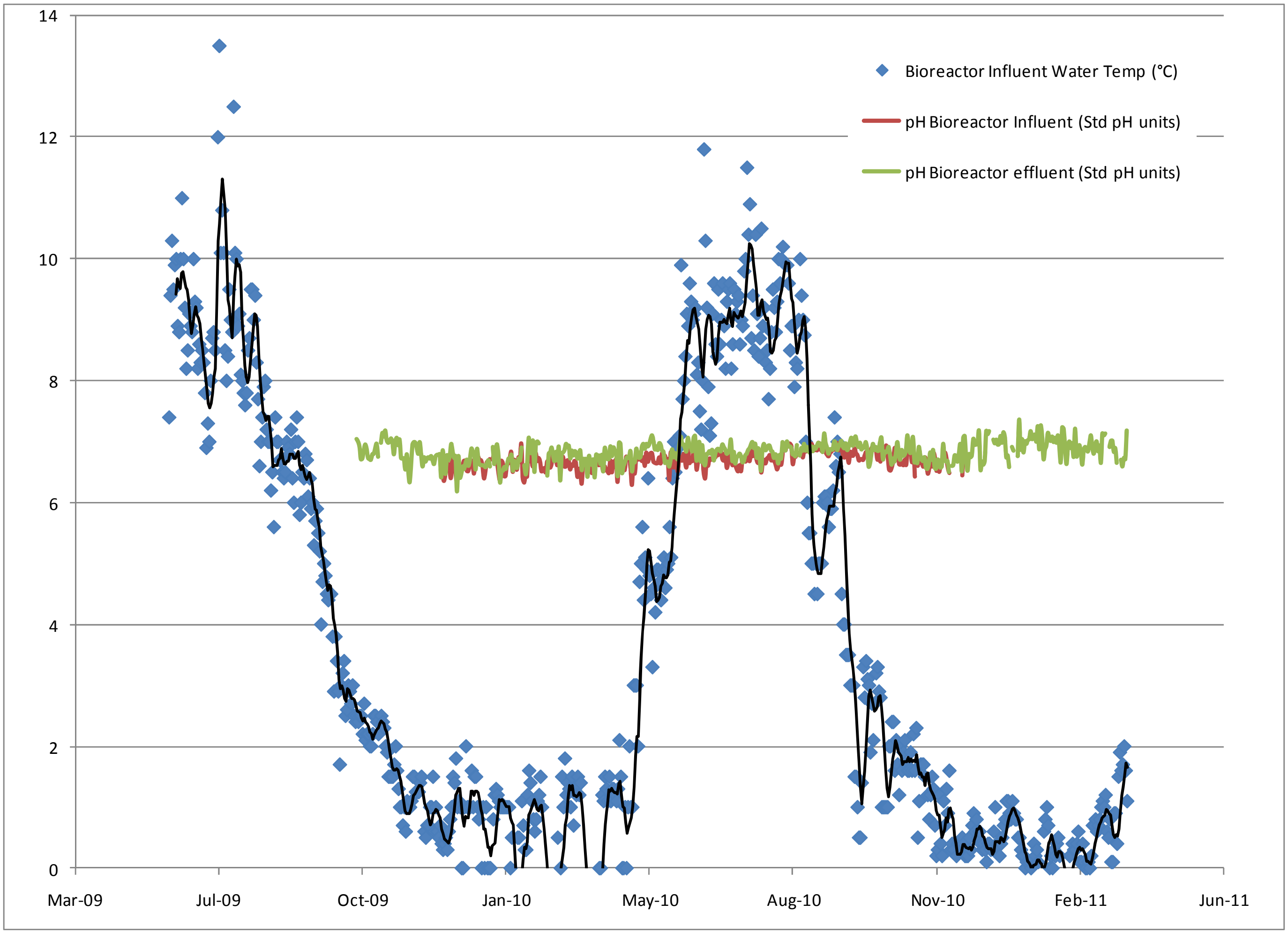

FIGURE 10 - COMPARISON OF GALKENO 900 ADIT PH AND BIOREACTOR PH VS. TEMP

In addition to pH, Figure 10 also displays water temperatures of the bioreactor influent water recorded during operation. Notice how the influent water temperature decreases to less than 2°C from October through April each year. This emphasizes how important it is to keep water moving through both the bioreactor and the piping systems at all times to avoid freezing.

6.2. DISSOLVED METALS

The primary metal that exceeds discharge criteria at the Galkeno 900 adit is zinc, which is true of most of the adit discharge locations in the KHSD. There are other metals that potentially contribute to the toxicity of water and this and other discharge locations, and hence the water chemistry of all dissolved metals present in the Galkeno 900 water has been evaluated.

To better understand the performance of the bioreactor during operation, several graphs have been generated that plot each constituent of concern. These graphs display the results of samples taken at the adit, midway through the bioreactor, and at the discharge from the bioreactor. Within each graph, a blue and green transparent box was added to signify flow rates during operation. Within the blue box, the average flow rate through the bioreactor was 0.5 lps. Within the green box, the flow rate was increased to 1.0 lps or subsequently 0.75 lps.

6.2.1. Zinc

The concentrations of zinc in the bioreactor were approximately 90% reduced during the recirculation phase where only minor additions of water (approximately one litre per minute) 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 lps in October 2009. Figure 11 illustrates the removal efficiency of the bioreactor during both treatment periods, including the 0.5 lps flow rate (blue rectangle), and the 1.0 lps flow rate(green rectangle). During the 0.5 lps time period approximately three pore volumes were exchanged (calculated on a total porosity basis) and when calculated on a reactive volume estimated by 2X the dye peak, nearly eight 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 lps treatment phase, approximately six pore volumes (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: data from the period after refilling the bioreactor indicates that the removal efficiency dropped to closer to 60-80% in the period immediately after the bioreactor siphoned out and was refilled, indicating that the pipe freeze-up and refilling of the reactor has temporary negative effects for a period of a few weeks after an upset.)

The conclusions that can be reached from the bioreactor's operation, before the pump failure, are that dissolved zinc can be effectively removed at 0.5 lps flow rate with an effective residence time of nine days, or a total residence of 21 days, and the first two months of operation at 1.0 lps 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 3 outlines the difference between dissolved and total zinc removal during the different operational phases.

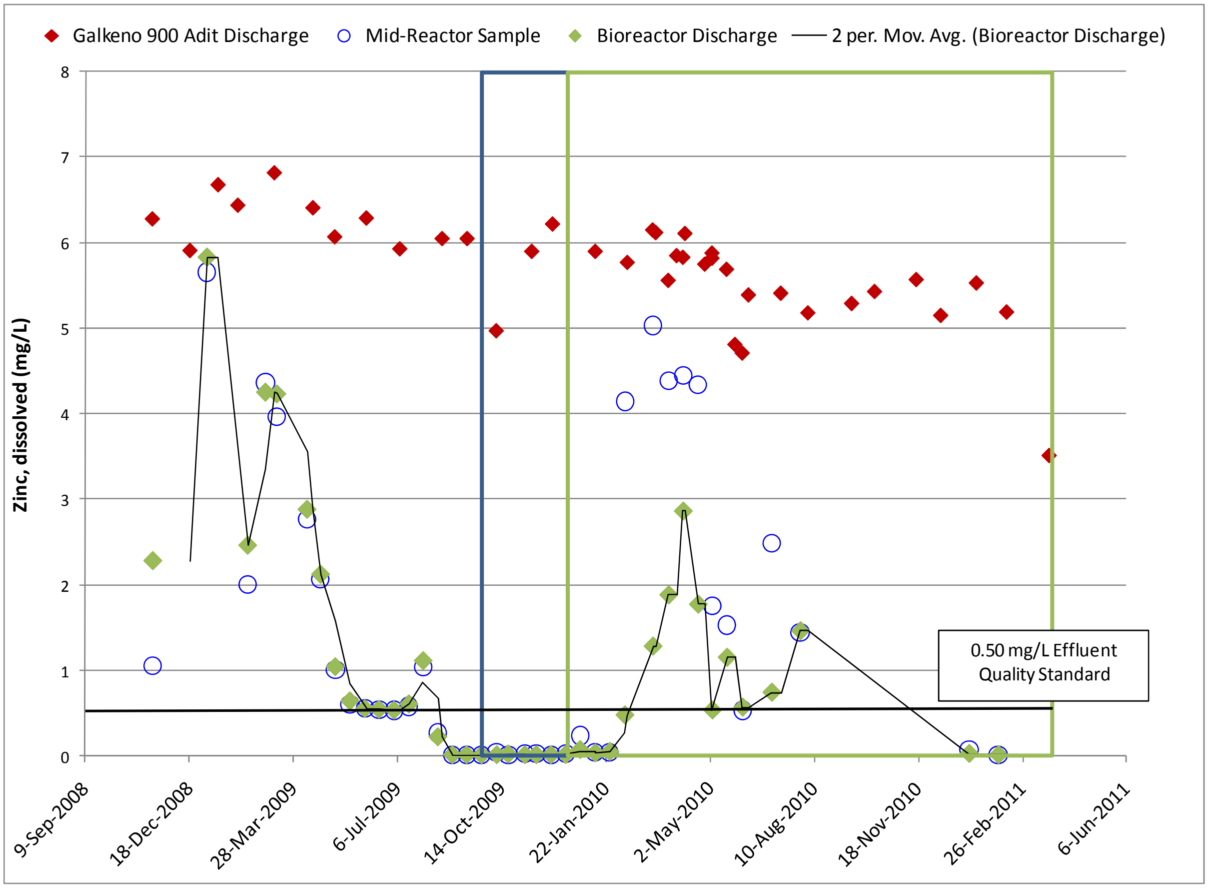

FIGURE 11 – Zinc removal by the Galkeno 900 Bioreactor

	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 lps treatment phase	0.28	0.012	4%
1.0 lps treatment phase	0.74	0.13	17%
0.75 lps treatment phase	0.29	0.018	6%

TABLE 3 – TOTAL VS. DISSOLVED ZINC PER OPERATION PHASE

The difference between total and dissolved zinc is that total zinc can be filtered out, i.e., it is the particulate zinc in the bioreactor samples that has been reduced from the soluble phase and become a solid zinc phase. Because of the coarseness of the bioreactor rock (see Figure 5) the media does not act as a very good filter. This is consistent with what was observed at a bioreactor in Montana (Gammons and Frandsen, 2001), where fine ZnS particulates passed as colloids through the reactor but could be filtered out with a 0.45 µm filter. As discussed later, design of future bioreactors would include finer grained rock than coarse oversize placer rock to encourage some filtration. In addition, freshly formed sulphides 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 lps treatment regimes. However, the treatment objective was not achieved for total zinc for the higher flow rate (1.0 lps) regime (0.74 mg/L) except for the final two data points collected in January and February 2011. This indicates that additional residence time may be required in the bioreactor to filter the particulate materials, or a subsequent filtration treatment 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. Active semi-passive or passive filtration systems such as sand filters, multimedia filters, or sedimentation ponds are other alternatives that could improve filtration.

6.2.2. Antimony

Antimony concentrations declined approximately 80% during the test (0.0025 mg/L reduced to below the detection limit (0.0005 mg/L) for most of the phases of the test (See Figure 12). Antimony removal in an organic carbon-rich reducing system is typically attributed to an antimony sulphide phase, or by sorption to iron or manganese oxides, carbonates, or sulphides that are stable in reducing conditions.

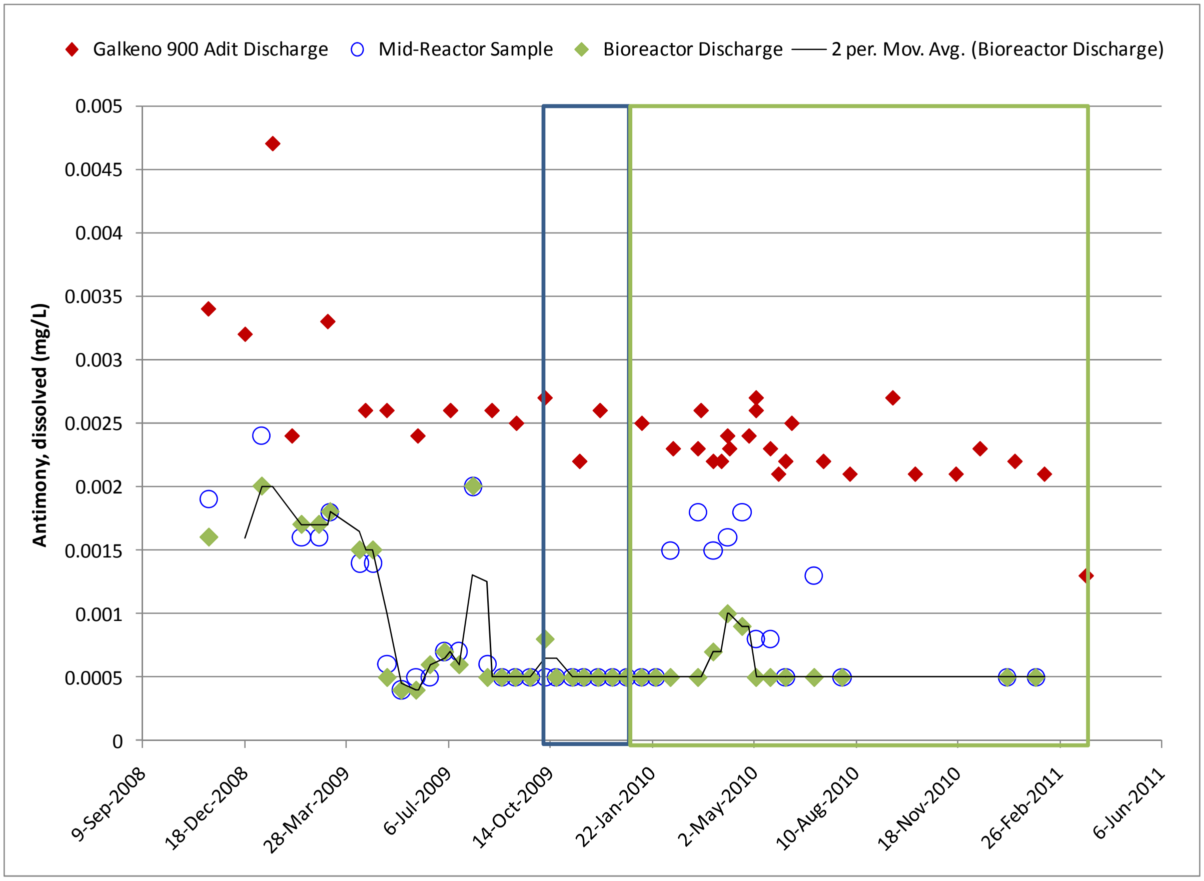

FIGURE 12 – Antimony Removal by the Galkeno 900 Bioreactor

6.2.3. Arsenic

Arsenic concentrations declined approximately 97% (0.068 mg/L reduced to 0.0015 mg/L average of last two months) during the recirculation phase (See Figure 13). 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, arsenic removal increased again as sulphate reducing conditions were established. During the treatment phases, arsenic removal averaged 58% for the 0.5 lps period, and 80% during the 1.0 lps. The performance during the 0.5 lps 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 lps performance.

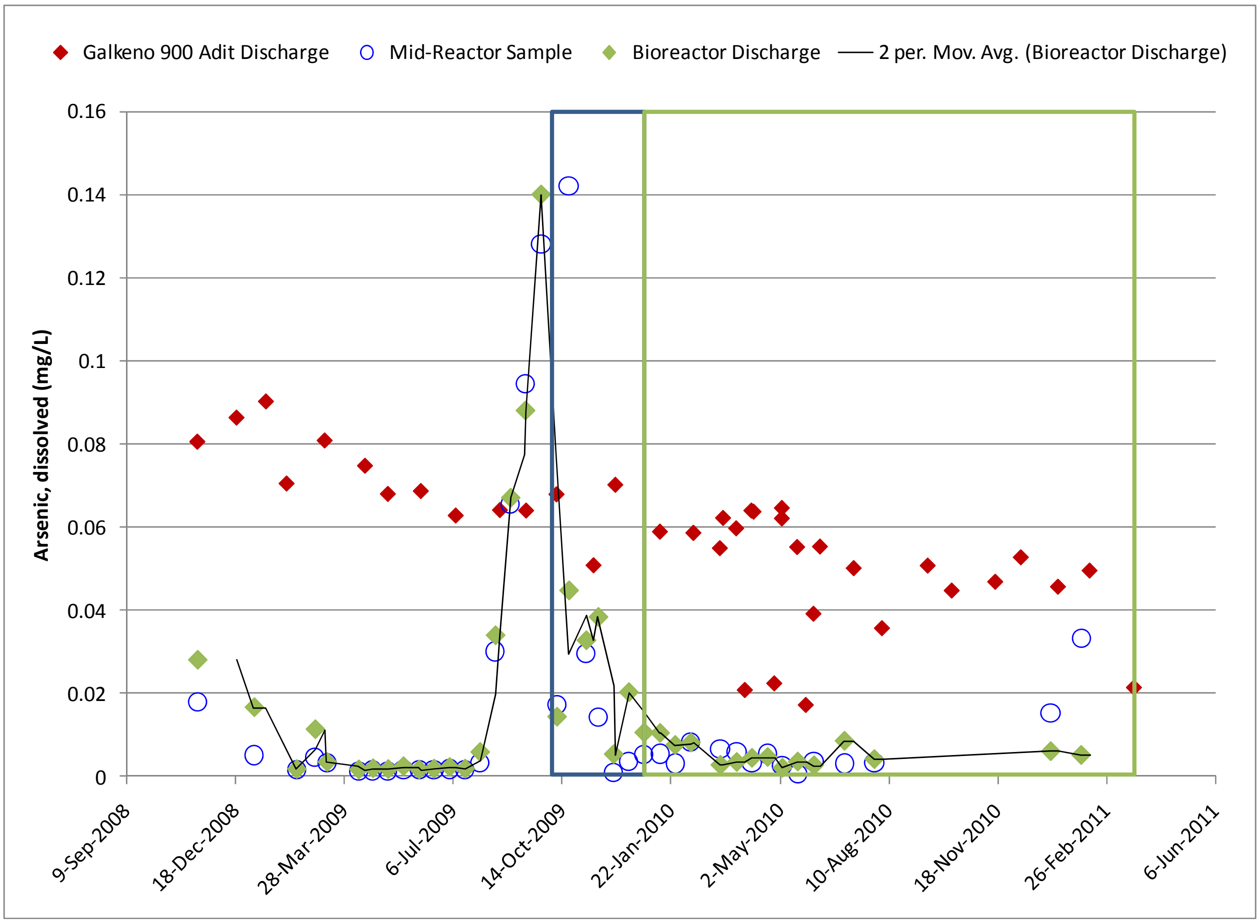

FIGURE 13 – ARSENIC REMOVAL BY THE GALKENO 900 BIOREACTOR

6.2.4. Cadmium

Cadmium concentrations declined approximately 60% (0.0015 mg/L reduced to 0.0005 mg/L average of last two months) during the recirculation phase (See Figure 14). After the beginning of the reduction onset phase, cadmium has been removed to below the detection limit and has remained at those levels during all the recirculation phases.

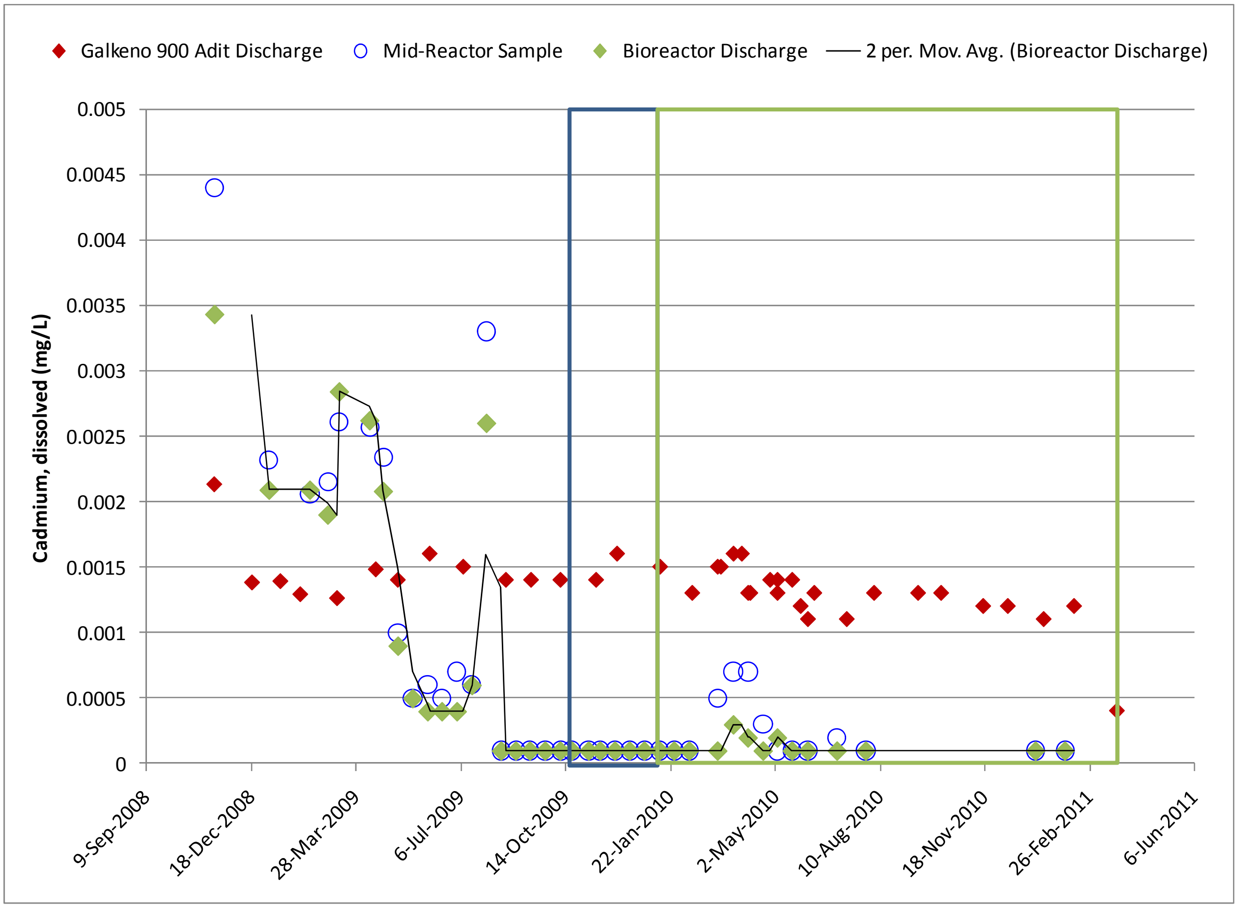

FIGURE 14 – Cadmium removal by the Galkeno 900 Bioreactor

6.2.5. Iron

Iron concentrations declined approximately 97% reduction (1.75 mg/L reduced to 0.032 mg/L average of last two months) during the recirculation phase (See Figure 15). 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 co-precipitation phases for other trace metals removal during the recirculation phase. Some of the iron was likely also removed as sulphides in their initial amorphous precipitate form (operationally called Acid Volatile Sulphides 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.

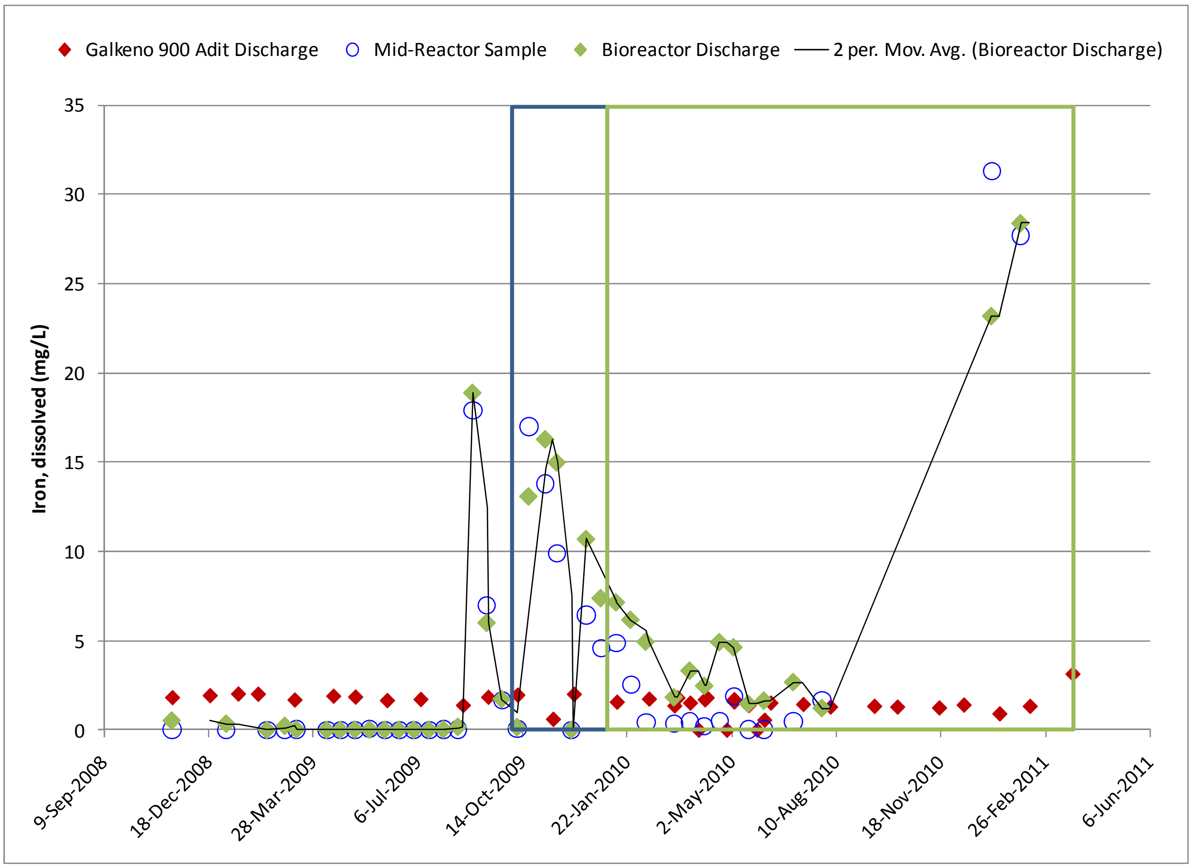

FIGURE 15 – Iron removal by the Galkeno 900 Bioreactor

6.2.6. Manganese

Manganese concentrations declined approximately 98% (18 mg/L reduced to 0.25 mg/L) during the recirculation phase (See Figure 16). 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 through flow 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.

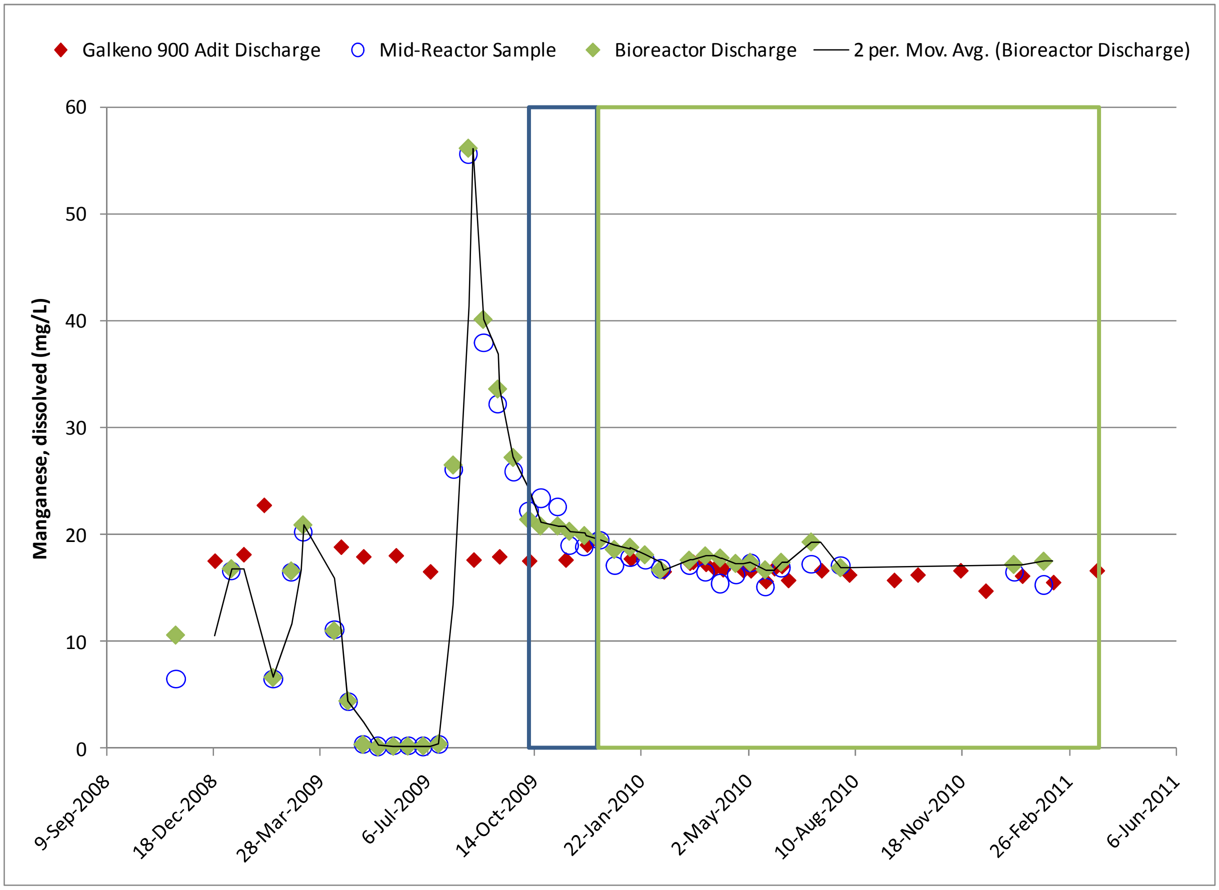

FIGURE 16 – Manganese removal by the Galkeno 900 Bioreactor

6.2.7. Nickel

Nickel concentrations declined approximately 80% (0.2 mg/L reduced to 0.04 mg/L average of last two months) during the recirculation phase (See Figure 17). During the reduction onset, a portion of the nickel was returned to solution, but during the slower flow periods, the nickel concentrations decreased to detection limits. Nickel removal during the 0.5 lps was 97.5%, but declined during the 1.0 lps flow rate. 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. However, the transition back to 0.75 lps improved the nickel removal.

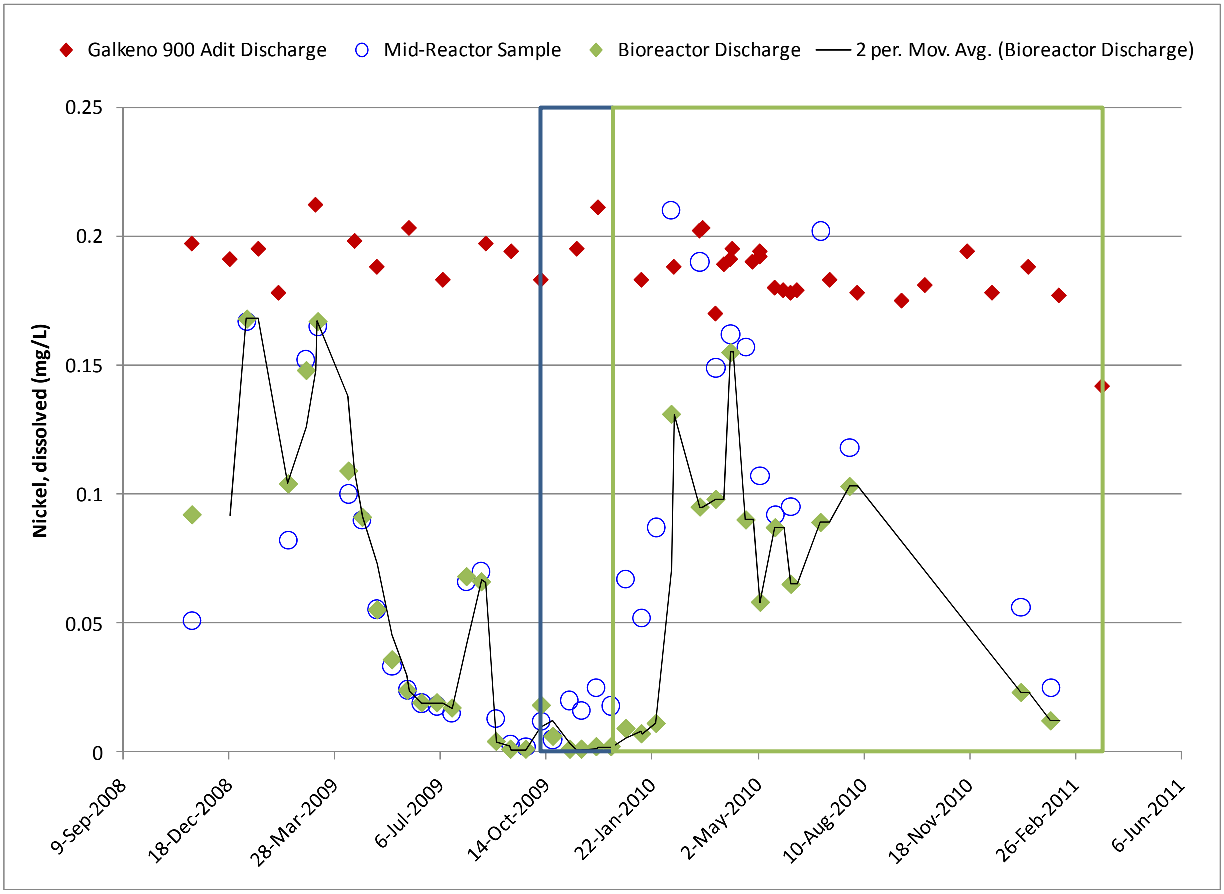

FIGURE 17 – Nickel removal by the Galkeno 900 Bioreactor

7. BIOREACTOR ENGINEERING DISCUSSION

Evaluation of the metals removal obtained in the bioreactor and determination of the SRR that can be achieved in the wintertime at the 0.5 and 1.0 lps flow rates enables an evaluation of the potential scaling factor for the size of the bioreactor that could treat the entire flow from the Galkeno 900 adit. Design improvements would focus on increasing contact with all of the bioreactor, and decreasing 'dead zones'. Experience at other sites has shown an elongated rather than square bioreactor has better contact parameters and fewer dead zones. In rough parameters, the flow from the Galkeno 900 adit is approximately 4 lps and remains consistent throughout the year and with the improvements and balancing the appropriate conservatism in design an approximate scale factor of four times the volume of bioreactor media would be used to design and cost a bioreactor for a full scale at Galkeno 900.

The minimum goal of 0.5 mg/L zinc was consistently achievable during normal operation of the bioreactor as long as the system remained in operation without interruptions. As shown in the data, a pump failure and/or pipe freezing can have a detrimental effect on the water quality results. This experience has shown the improvements to the design must focus on ensuring flow at all times, not dependent on power availability, and further improvements to insulation could also achieved.

The removal of other metals was also consistently achieved with the exception of a short period when reduction onset occurred, when some metals were released with the reductive dissolution of iron and manganese.

7.1. GENERAL BIOREACTOR DESIGN IMPROVEMENTS

The following is an assessment of the Galkeno 900 design components that worked well and design components that did not work well. This information will provide the basis of design and inform the construction of future bioreactors within the district.

The following components worked well and should be repeated in future designs:

1.) **Torturous Path -** Creating a torturous path within the bioreactor using liner for baffling was needed with the Galkeno 900 design to minimize short-circuiting and increase residence time. However, the use of baffling created zones that did not provide effective treatment and these zones should be minimized or eliminated in future designs if possible. One way to do this is to create a bioreactor that is laid out as a long, gently sloping trench sections. Finding land where trenches could be constructed near adits in the Keno Hill area may be difficult in some areas.

2.) **Bioreactor Dead Zones -** As discussed earlier, approximately 60% of the media appears to be actively participating in treating the water as it passes through the bioreactor. The remaining volume is for practical purposes considered as dead zones. These dead zones can be minimized by creating longer and narrower flow paths. This design improvement should be considered for future bioreactors.

3.) **Flowing Water -** Water must be kept flowing - This is critical during the winter months in the Keno Hills district. Mine drainage and groundwater is above freezing, and the water temperature must be maintained while passing through the bioreactor. As long as the pump was working and water was continuously flowing through the bioreactor, freezing was avoided. Every freezing failure of the bioreactor was caused by power failures which lead to cessation of pumping and a loss of the heat capacity of the adit influent water. In future bioreactor designs, allowing adit water to flow via gravity through a bioreactor will eliminate the potential for pump failure and maintain flow through the bioreactor. The exact design for each bioreactor will be carefully considered to minimize power usage and prevent the potential for power interruptions to cause treatment failures.

4.) **Back-up Treatment System** – During this study, the discharge from the Galkeno 900 bioreactor was co-mingled with the untreated raw water from the adit. This combined water was then treated with a lime slurry and allowed to decant from a settling pond. It is possible to have a mobile system to treat water while the bioreactor until the discharged water meets the applicable standards or performance objectives. Once the bioreactor can demonstrate effective treatment with discharged water meeting standards, the treatment system could be removed or placed on stand-by.

The following components were sources of problems and should be eliminated or redesigned for future bioreactors in the district:

1.) **Fill Material -** The fill material used in the Galkeno 900 bioreactor was too coarse. As seen in Figure 5, the material was a mixture of larger, broken rocks mixed with smaller pebbles and sand. By using a consistent fill material that is a smaller, crushed rock (between 3/8" to 2" diameters) additional surface areas will be available for bio-growth and will help avoid short circuiting.

2.) **Metering Pump -** If the metering pump that provided a carbon source to the bioreactor stopped working, there was at best a limited stored carbon source available within the media. For future bioreactor designs, a limited amount of solid phase carbon source such as course sawdust or wood chips, and/or peat should be mixed with the media to provide a secondary source of carbon to sustain the bioreactor if the soluble/primary carbon source is interrupted.

3.) **Pumps and Heat Trace -** As mentioned earlier, power failures were not planned for in the existing design. Inclusion of heat trace lines and backup power to pumps could have avoided the problems experienced in the Galkeno 900 bioreactor. In most cases, the location of the bioreactors could be placed in a downgradient location where power would only be required for the addition of a soluble carbon source. The carbon source could be designed to not require power by using an educator system where flow from the adit would draw in the carbon substrate by a venturi force. If utilized for backup power, a generator would be a very minimal size. The design would also consider placing the valves and controls inside the adit to minimize freezing.

Neither iron nor manganese were removed by the reactor during through flow operational phase. The natural attenuation studies in the district shows that these are readily removed in a very short distance by turbulent flow creating a natural oxidation system. This could be a designed as a cascading discharge or could be performed in a natural setting such as an existing stream.

8. DISCUSSION AND CONCLUSIONS

When continuous flow was maintained to the bioreactor at acceptable flow rates, effective treatment was maintained. At higher flow rates the transformation of metals from their dissolved forms to an insoluble form was accomplished, but the filtration efficiency of the coarse rock in the bioreactor did not filter the insoluble precipitates effectively. Full scale application of the sulphate reduction bioreactor technology appears feasible if slight design modifications are made to ensure gravity flow from the adit, avoidance of siphoning due to freezing, and improved sizing of the bioreactor media.

Evaluation of longer term bioreactor studies have been conducted at the Leviathin mine since 1997 by the US EPA. The US EPA SITE program (2006) ranked the bioreactor technology for metals treatment at the Leviathan mine using the criteria shown below. The Discussion of the Galkeno 900 bioreactor in terms of how it performed is presented relative to the same evaluation criteria.

- *For Overall Protection of Human Health and the Environment,* it was determined that the sulphate reducing bioreactor was effective for reducing metals concentration, and produced non-toxic and stable precipitates. A similar conclusion can be reached for the Galkeno 900 bioreactor; confirmation of stable non-toxic precipitates is underway in additional mineralogical studies, but with lower influent metals concentration in the Galkeno 900 bioreactor it is reasonable to believe similar results will be determined.
- *For Compliance with Applicable or Relevant and Appropriate Requirements (ARAR),* it was determined that the bioreactor generally produced compliant discharge, and with minor adjustments compliance was improved further. Similar conclusions can be stated

for the Galkeno 900 bioreactor.

- *For Long Term Effectiveness and Performance*, it was determined that the bioreactor consistently met the applicable standards over many years, and suggested that with additional engineering a more passive (wind and/or solar powered) system appeared to be feasible. The strength of this conclusion for Galkeno 900 reactor is weakened primarily due to power and freezing issues, but these issues can be engineered in future applications to be less significant and thereby increase the long term effectiveness and performance.
- *For Reduction in Toxicity, Mobility, or Volume through Treatment*, it was determined that the bioreactor concentrated the metals in a stable form. Similar conclusions can be reached for the Galkeno 900 bioreactor: on average over 90% of the metals were removed from solution and filtered out of the bioreactor during operational times.
- *For Short Term Effectiveness*, it was determined that the bioreactor effluent was protective of human health, and that the chemicals required for bioreactor operation could be handled safely with the appropriate engineering controls. Conclusions for the Galkeno 900 bioreactor are that it had short term effectiveness when operating at lower flow rates, and consequently that by appropriate sizing and cold weather engineering a bioreactor can have high short term effectiveness in the KHSD.
- *For Implementability*, it was determined that the technology is simple, could be operated with limited operator involvement, and that it was stable over a long time. For the Galkeno 900 bioreactor, the technology is very simple and required little operator involvement, and if pumping and siphoning the bioreactor could be avoided through gravity feed, the Galkeno 900 bioreactor process has a high implementability ranking.
- *For Cost*, it was determined that it cost approximately $15 per 1000 gallons to operate the Leviathan bioreactor. By way of comparison, the Galkeno 900 bioreactor costs are in the range of $5 per 1000 gallons. The main difference is the lower level of reagent requirements due to lower metals concentration and neutral pH at the Galkeno 900 bioreactor.
- *For Community Acceptance*, it was determined that the operation of the bioreactor presented minimal risk to the community, with diesel generation and transportation of chemicals to the bioreactor being the main risks. With the lower chemical usage required for a bioreactor in the neutral drainages in the KHSD, and the availability of line power the Community Acceptance criteria should be even better in the KHSD.
- *For State Acceptance*, it was noted that California has allowed it to be the only water treatment technology used year-round at the Leviathan Mine site. The Galkeno 900 bioreactor is currently approved for pilot scale trials on the Keno Closure program and was approved as part of the environmental assessment of the Bellekeno Mine.

It is recommended that the Galkeno 900 bioreactor cease operation after the metals stability study is complete, and that a subsequent study utilizing a buried trench design without pumping be considered for a next phase of testing.

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