BENCH-SCALE TESTING OF A SULFATE-REDUCING BACTERIA TREATMENT OF COPPER BASIN, TN MINE DRAINAGE ¹

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Abstract. Glenn Springs Holdings, Inc. (GSH) has begun remedial actions in the Lower North Potato Creek watershed of the Copper Basin, TN that will reduce the pollutant load to receiving streams and encourage recovery of aquatic life. Demonstration activities have identified that removal of problematic materials adjacent to streams will dramatically reduce concentrations of contaminants of potential ecological concern, but that the potential exists for these parameters to remain at levels of concern. After implementation of Phase I waste removal, the benefits of the removal and the remaining sources of acidic drainage will be evaluated and a course of action selected to further reduce those contributions, as necessary. The actions may include implementation/installation of appropriate systems to reduce the metals loadings and acidity to the receiving streams. Passive treatment systems have proven to be effective within the watershed in neutralizing acidity and removing metals from McPherson Branch and McPherson mine water. Additional study of passive systems was conducted to improve the understanding of the function and efficacy of their components under site-specific conditions, particularly low flow with high metals loadings. Static bench-scale studies of passive treatment systems (Task 1) completed in 2005 identified successful material combinations. The Task 2 study utilized two of those materials in a 'flow through' dynamic testing arrangement. This 27 week dynamic testing phase focused on determining system efficacy, longevity, and operational constraints. Both material combinations were tested at three aggressive metals and hydraulic loading rates using actual mine water. Both combinations neutralized influent acidity, raised pH, added alkalinity and removed some metals (measured as toxicity reduction) at each loading rate over the study period. Alkalinity was generated abiotically through the dissolution of limestone and biologically by the reduction of sulfate.

Additional Key Words: Ducktown TN, acid mine drainage, sulfate reducing bioreactors

http://www.glennsprings-copperbasinproject.com/basin.htm

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Introduction

Barge, Waggoner, Sumner & Cannon, Inc. (BWSC), Bratton Farm, Golder Associates, Inc., and Secaps Environmental, Inc. have been retained by Glenn Springs Holdings, Inc. (GSH), a subsidiary of OXY USA, Inc., to assist with the development and implementation of passive treatment system solutions for acid mine drainage (AMD) in the Lower North Potato Creek (LNPC) watershed in Eastern Tennessee. Static tests were previously conducted in accordance with Task 1 - Selection of Candidate Materials to identify material combinations that showed evidence of sulfate reduction, alkalinity addition or neutralization, and metal sulfide precipitation. These results were used during the preparation of the Task 2 - Bench-Scale Dynamic Testing work plan which was implemented from July 2006 to January 2007. Task 2 activities and results are part of a sequential process which will facilitate the design of passive treatment components appropriate for implementation in the watershed. GSH is implementing remedial actions intended to mitigate impacts to the LNPC watershed so that biodiversity should generally increase downstream. Waste materials will most likely be relocated from recharge areas and along streams and/or problematic materials will be covered. These actions, accompanied by effective land reclamation and other appropriate measures, will likely reduce the chemicals of potential ecological concern (COPEC) in the streams.

Waste material removal in 1998 along McPherson Branch demonstrated that in-stream metals and acidity could be reduced, but concentrations may remain above levels of potential concern. It is anticipated that there may be diminishing environmental improvement returns from subsequent removal and remedial actions in the Copper Basin. In addition, comprehensive removal or capping of marginally acidic materials is impractical and the availability of suitable regrading material is limited due to widespread erosion over many decades.

Passive systems have been proposed as a means of providing effective treatment with limited operations and maintenance requirements for seeps and other non-point sources along stream corridors. Research in passive treatment of acid mine drainage has indicated that proper selection of passive systems components is critical in optimizing performance. Therefore, a means of identifying potential passive system components appropriate for this watershed is needed. Bench-scale testing to identify promising passive system components and to determine removal rates for parameters not documented in other accepted research will provide this information so that the design of appropriate passive systems might be readily implemented during or shortly after any removal, remedial and regrading operations. Significant time is needed for the performance of bench-scale and demonstration systems testing to evaluate efficacy and longevity. Passive systems are limited in applicability by a host of variables, including flow rate and hydraulic conductivity, as well as concentration of metals in the influent to the system. These variables, perhaps unique to the study site, are among the data evaluated in this study. Bench-scale testing is quicker, more economical, and less risky than full-scale or pilot testing, but still requires a substantial commitment of time and resources.

An existing demonstration passive treatment system (anaerobic wetland – aerobic wetland – rock filter- restored stream segment) along McPherson Branch is designed for and has successfully mitigated relatively high flow, low metals/acidity load drainage. It is anticipated that small flows or seeps from residual waste materials following land reclamation will exhibit much higher

metals concentrations. This anticipated drainage represents a challenge much different from the McPherson demonstration. While removal of high concentrations of metals from low flows has been documented in bench-scale and full-scale projects at other mine sites, it is prudent to refine this technology specific to the unique drainage and site conditions of the Copper Basin before pilot- or full-scale implementation.

Summary of Task 1

Bench-scale static studies of passive treatment systems were initiated in November 2004 by combining various mixtures of locally available organic materials (including sawdust, apple mash, soybean hulls, hay and manure) with limestone and limestone kiln dust in containers with various strengths of acid drainage from the site. Results of this month-long, static testing indicated some components were clearly more efficient than others in providing conditions and bacterial populations that reduced COPECs. Additionally, this static test indicated that proper inoculation with sulfate reducing bacteria (SRB) is important for rapid efficacy. To provide additional information needed to refine component composition and ratio requirements, a second eight week static test of additional components was initiated in February 2005.

Suitable materials were identified that should provide alkalinity additions and reduction of COPEC concentrations in drainage that can be anticipated following initial waste removal at the site. Two candidate combinations were found to be most promising. Additionally, trials with 7 humic strata combinations in funnels tested the hydraulic conductivity, pH, oxidation reduction potential (ORP) specific conductance and alkalinity for one year. Weekly addition of 100 ml of McPherson Mine water was introduced to each one liter funnel for 52 weeks. Results indicated all combinations maintained an alkaline effluent with low ORP and neutral pH. Four manure sources were similarly evaluated for 53 days to identify SRB inoculants.

Task 2 Experimental Design

In Task 2, the promising materials identified in Task 1 were used. This task included flowthrough bench-scale simulations. Two material combinations, one surrogate water source (McPherson Mine), and three hydraulic/mass loading rates were evaluated in parallel test units, along with a control unit containing only inert material.

Materials required to construct the bench-scale passive treatment systems were obtained from local suppliers. These materials included alkalinity sources (crushed limestone and lime kiln dust), organic sources (hay and sawdust), microbial inoculum (aged equine manure), and an 'all in one' spent mushroom compost.

Two different alkalinity sources (crushed limestone and lime kiln dust) were utilized with the primary purpose to raise pH and alkalinity. The materials differ only in the expected dissolution (neutralization) rate where the more finely grained kiln dust will provide more immediate results. Both were mixed with the organics and inoculum to create the humic strata layer. The CaCO₃ equivalence of both alkalinity sources was confirmed to be over 100%. Lime kiln dust was analyzed for TCLP-leachable target analyte list metals to determine potential contributions to 'effluent' samples in Task 1. Three different organic sources were used. Each was intended to

provide a carbon source for SRB, although they differ in the rate and timing of availability. It was believed that spent mushroom compost (decomposed chicken litter and wheat straw) would provide a readily available carbon supply, and would also inoculate the humic strata with SRB. Hay represented an intermediate source. Sawdust was generally viewed as a long-term carbon source with limited initial input due to relatively slow decomposition. Each of the materials may chelate some metals although this means of removal is typically secondary to the formation of relatively insoluble sulfide complexes via SRB activity. See Table 1 for the proportions of the various components used in the Best Bet medium mixtures.

The microbial inoculant (aged equine manure) was intended to provide SRB 'seed' to the second combination. Manure has the added effect of providing an additional organic source. This variable is the difference between the two "Best Bet" mixtures. In Task 1, the difference in performance of the two mixtures indicated this component may be necessary for adequate SRB activity.

McPherson Mine water was selected from Task 1 results as representative of drainage which could be ameliorated by passive means. Further, suitable facilities to house and operate a bench-scale setup were located proximate to the McPherson Mine shaft. Literature revealed that effective dynamic bench scale testing is often challenged by the availability of an on-demand, chemically consistent water source (Watzlaf 2000). Anaerobic mine water with high dissolved metals typical of seepage from waste materials in the Copper Basin is inherently unstable. When minimally exposed to the atmosphere or oxygenated waters, metal oxidation and precipitation reactions occur rapidly. To maintain low to no oxygen conditions and minimize metals variability or precipitation, a dedicated stainless steel submersible pump was installed 150 feet below the McPherson shaft collar, approximately 120 feet below the fluctuating water level. One-inch polyethylene pipe was plumbed to the McPherson Hoist House basement, fitted to a PVC manifold, and returned to the mine shaft. A relief faucet at the collar allowed the regulation of the water pressure in the basement to approximately 10 pounds per square inch. Refer to Figure 1 and Figure 2 for the Set-Up Diagram.

The manifold supplied a 350-gallon reserve tank on the main floor of the Hoist House capable of feeding the treatment system via gravity for two weeks in the event of power failure or unacceptable influent water conditions. The reserve tank was drained and refilled weekly after field monitoring but was never used as the influent source. The manifold also supplied a sample port for the mine water and fed a battery-operated commercial water timer set to open four times per twenty four hour period for four minutes to a second manifold. The second manifold fed seven valves directing flow to seven polyethylene cans ('feed tanks') which had been fitted to overflow at predetermined volumes. The volume was determined by estimating average molar loading based on several McPherson Mine water samples collected over many months. The control drum and "a" drums were to receive nominal base metals load of 0.3 moles/m³/day, the "b" drums 0.6 moles/m³/day, and the "c" drums 1.2 moles/m³/day. The design flow rates are provided on Table 1.

Each feed tank was fitted with a polyethylene spigot and perched above a new 55-gallon plastic test drum. Silicon hose drained the feed tanks to water timers set to open ten minutes after the timer on the manifold filled them allowing overflow to stabilize. These lower timers then closed

after twenty minutes, preparing for the next cycle. Each drum had an 18-inch long, ³/₄-inch diameter perforated polyethylene drain pipe plumbed within 3-inches of the bottom and fitted to a polyethylene effluent tube. The effluent tubes were secured to the outside top of the drum and looped back to the floor where they entered the neck of a one gallon plastic jug. The loop was pierced at its highest point to prevent siphoning. The tube ended at the bottom of the jug which would overflow out its neck. Additional silicon tubing was run from each jug to a labeled end at a peristaltic pump to allow for sampling of the effluent without disturbing the apparatus. Care was taken to exclude any ferrous fittings or other reactive components which might influence chemical analysis.

Materials were mixed according to Table 1 by carefully weighing individual components to prepare a Best Bet humic strata batch approximately twice the volume necessary to fill the drums to ensure homogeneity. Before mixing, hay was ground with a lawnmower to ensure homogeneity in the drums. Each drum (except the control) was filled with a uniform mass of pea-sized limestone to cover the perforated drain pipe. A uniform mass (about 134 liters) of Best Bet humic strata was then placed in each drum and covered with a shallow layer of spun fiberglass insulation and a plastic disk (5 gallon bucket lid) to distribute the flow. Representative samples of each humic strata were retained for future analysis. The control drum was filled with spun fiberglass insulation. All drums were filled with 30 gallons (~114 liters) of McPherson Mine water which brought the water level in each drum over the surface of the humic strata or insulation and distribution device and initiated a discharge to the gallon sample jug. Drums were filled starting the incubation period on June 20, 2006 and daily hydraulic loading was initiated on July 18, 2006.

The secure four hundred forty square feet room was fitted with a positive pressure blower to vent any hydrogen sulfide gas buildup. Keyed entry occurred each day by personnel wearing a hydrogen sulfide monitor after completion of a daily safety check. After three months of operation with no hydrogen sulfide detected, the blower was turned off to limit outdoor air exchange as cooler ambient temperatures began to prevail.

Daily visual observations to ensure integrity of the system were accompanied by documentation of water pressure and mine water specific conductance for twenty seven weeks. The sampling and analysis program was followed with deviations noted. All field instruments were calibrated each week. Weekly field measurements made using portable Hydrolab[®] instrumentation included pH, specific conductivity, ORP, and temperature. A fresh sample of the influent mine water was monitored for pH depression with the addition of 10% by volume 3% hydrogen peroxide. Mine water ferrous iron was measured with a Hach DR-850 colorimeter to confirm characteristics before the reserve tank was emptied and refilled each week. Field alkalinity was measured using Hach alkalinity strips. Each week, a scheduled fill cycle was observed to ensure the integrity of the system and to measure the volume of water delivered to the drums. Other than resetting and synchronizing the time of day of the water timers, very little system maintenance was necessary.

Effluent samples were collected from the one-gallon sample jugs using a peristaltic pump, analyzed in the field for ferrous iron (where possible), and submitted to the laboratory for acidity, hardness, and sulfate analysis. Filtered (0.45 μ m filter) samples for dissolved metals analysis were also collected. Laboratory samples were collected from the sample ports at Weeks

0, 1, 2, 4, 8, 12, 16, 20, 21, 23, 25, and 27. Sampling of the control vessel was suspended for the remainder of the study beginning Week 8. All samples were collected in properly preserved containers, handled under strict chain of custody and shipped to STL Laboratories, Pittsburgh, Pennsylvania for analysis.

At Week 27, all drums except drum 1a were opened, examined, sampled and decommissioned. Drum 1a was fitted with thermostatically controlled heat pads, insulated and left on line for an additional two weeks during which it underwent daily observation and weekly monitoring and sampling before its contents were similarly sampled and decommissioned.

Field and laboratory data collected as part of this effort were subject to data quality assessment review. No data quality issues were identified that would place significant limitations on the intended data end uses. For comparative purposes, the experiment is summarized in Table 2.

While reviewing the study on-site, Dr. Robert Hedin suggested further investigation of the microbial population by enlisting the help of Dr. Linda Figueroa of the Colorado School of Mines. Arrangements were made with CSM for Phospholipids Fatty Acid Analysis (PLFA) and Carbohydrate Compositional Analysis (CCA) of select samples of the humic strata after the experimental run.

RESULTS – Field Analyses (Table 3)

The quality of influent water was relatively consistent throughout the entire Task 2 monitoring period. Influent pH fell within the 3.5 s.u. to 4.2 s.u. range through November 14, 2006 (Figure 3). Thereafter, wider fluctuations were noted ranging from 2.8 s.u. to 4.5 s.u. Changes in influent characteristics after November 14, 2006 are attributable to reduced control over the water source. Waters from other sources were inadvertently directed to the McPherson Mine around this same time. The increased pumping rates to purge these waters and non-equilibrium conditions likely account for the observed variability in influent water quality. Influent specific conductance and ferrous iron remained above minimum target levels throughout the study.

Based on experimental design, loading rates were expected to vary by as much as +/- 25% from the study optimum. Actual administered hydraulic loading rates were consistent throughout the study and were within the expected range of variability. Target volume per cycle was estimated at 1890 ml, 3780 ml, and 7560 ml for 'a', 'b' and 'c' trials, respectively based on a medium volume of 178 liters. As previously stated, the actual typical medium value was 134 liters. Average hydraulic loading rates over the study period were within approximately 12% (or less) of the design values.

At the base design flow rate, the hydraulic retention times were less than those typically targeted for SRB reactors (20-25+ days). This indicates that, consistent with Task 2 objectives, the units were 'stressed' relative to traditional design rates.

The molar metals loadings were higher than the design specifications $(0.3, 0.6 \text{ and } 1.2 \text{ moles/m}^3/\text{day}$ for low, intermediate and high loading rates) throughout the study period. Loads

are presented in Table 5. The target $(0.3 \text{ moles/m}^3/\text{day})$ was exceeded by 30 to 50% at base design flow. An exception was noted during the December 7, 2006 sampling event. This coincided with the period when the water source was recovering from an upset condition. Iron load (at 0.00138 gpm) over the surface area of the humic strata (20-inch diameter or 0.20268 m²) was 2.49 g/d. This represents a surface loading of 12.3 g/d/m²; somewhat higher than what might be used to size an aerobic wetland (4 to 10 g/d/m²) with less intense water.

Figure 3 shows pH trends over the study period in each treatment unit. Irrespective of hydraulic loading, each material combination provided neutralization raising pH from below 4 s.u. to above 5.7 s.u. for the entire study period. On average, the treatment effect was an over 2 s.u. pH improvement between influent and effluent. Neutralization was maintained despite the high variability in influent pH observed during the latter half of the study period.

ORP was the key field parameter intended to provide an indication of SRB activity in the units. ORP results are presented in Figure 4. Although results varied widely week to week, all treatment units saw an initial drop in ORP to levels in the -100 to -300 mV range over the first month. Trial T2-BB1-McPa most consistently sustained ORP below -100 mV. This pattern continued through Week 13 at which time an abrupt rise in ORP was observed in all units. This was approximately coincident with a drop in total organic carbon (TOC) and chemical oxygen demand (COD) in the cell effluents.

From Week 14 through study completion, ORP readings generally remained negative but were above -75 mV indicating only mildly reducing conditions. The sustained ORP levels during the latter half of the study were above the threshold established in the work plan as indicative of strong SRB activity. As a result, it was concluded that the units did not behave as expected for the entire study period. While the lack of hydrogen sulfide odors emanating from the units during the study and unit autopsies raised some concern that SRB activity was limited, absence of olfactory evidence is typical for cells with metals loads in excess of the sulfate reduction rate.

The rise in ORP levels coincided with a drop in mine water influent and effluent temperatures from greater than 15° C to less than 10° C (Figure 4a).It was suspected that the declining temperature may have had an inhibitory effect on SRB activity. The McPherson Hoist House basement has been used for storage of tree seedlings for the last few years, and anecdotal reports indicated the temperature stayed "above freezing" during winter months. Therefore, no supplemental heat source was provided for this test space to maintain temperatures above mean ground temperature (13° C).

Because of the variance from expected temperatures, trial T2-BB1-McPa was run for an additional two weeks (January 16-31, 2007) with an artificial heat source. The target trial core temperature of between 12° C and 15° C was met (effluent temperatures were lower owing to acclimation with ambient conditions after discharge). During this two week period, metals and acidity loading was also considerably lower as evidenced by ferrous iron levels well below the historical average. As shown in Figure 4, no appreciable ORP response was observed with heating despite the reduced loading. Other factors were suspected to affect microbial activity and are addressed in the Discussion section.

Based on field results (specifically pH and ORP), no clearly superior material combination was identified for any loading rate. Best Bet 1 did, however, sustain moderately reducing conditions for a longer period at the lowest loading rate. None of the units performed as expected with respect to maintaining strongly reducing (ORP < -100 mV) conditions for the study duration.

RESULTS - Laboratory analyses (Table 4)

As outlined in the work plan, laboratory data were used to evaluate metals removal using a hazard quotient method applying the decision rule that *If a material (or combination) does not reduce the ecological hazard index by* >50%, *then associated laboratory analysis will be terminated and it will not be considered for further testing.*

Each effluent metal result was divided by its corresponding ecological screening value (EcoSV) to produce hazard quotients on a sample-specific basis. The hazard quotients were then summed to produce a hazard index (HI) for each sample. The hazard index reduction (%) was computed by subtracting the effluent hazard index from the hazard index for the corresponding influent water, and dividing by the influent water hazard index. Hazard index reduction comparisons between trials and over time were used to gauge relative performance and treatment sustainability. The lower the hazard index, the lower the predicted effluent toxicity. As a point of reference, a hazard index of 1 or less would characterize an effluent that poses no risk to aquatic organisms.

Net sulfate removal (%) was calculated by subtracting the effluent concentration from the influent, and dividing by the influent concentration. This calculation reflects removal (via complexation or reduction) as well as dissolution/oxidation of previously precipitated sulfide. Alkalinity addition was also evaluated based on laboratory results. The total alkalinity addition was computed as the effluent result plus the influent acidity (which was eliminated during treatment) on a concentration basis. The following discussions evaluate hazard index reduction, sulfate removal, and alkalinity addition performance for each trial over the study period.

Table 4 summarizes laboratory results for all effluent samples from each trial. Hazard indices and HI reduction findings are depicted in Figure 5. Sulfate reduction and effluent alkalinity results are presented in Figures 6 and 7, respectively. The following discussions focus on effluent characteristics on a concentration or toxicity reduction basis compared to influent water composition.

Control (T2-C-McPa)

As expected, the control trial provided little treatment. Hazard index reductions were initially below 10% but rose to stabilize around 20% after two months. The observed reductions were due almost exclusively to iron removal via oxidation and precipitation. Sulfate was not removed and no alkalinity was added in the control. In fact, the effluent sulfate result was higher than the influent in many cases.

Best Bet 1

All Best Bet 1 (BB1) trials provided high HI reduction rates (96% or more) for the first month of the study. Effluent HI were below 30 during the early stages with minima during Week 3 at less than 15. The bulk of the HI reductions were associated with aluminum and iron removal.

After the first month, metals removal began to decline. Consistent with expectations, the BB1units receiving the highest loading were the first to show diminished treatment followed by those with intermediate loading. Trial T2-BB1-McPa (lowest loading) sustained greater than 99% HI reductions through early October before treatment began to decline. HI reduction declines occurred in relatively consistent increments through November 27, 2006 with higher and more stable metals removal thereafter. By the end of the study, effluent HI from BB1 units ranged from 140 to over 280; due almost exclusively to waning iron removal rates. Removal of other metals (cadmium, copper, lead, selenium, and zinc) was almost complete in all trials throughout the study.

The lowest HI reduction observed (72%) in T2-BB1-McPa corresponded to the November 27, 2006 sampling event. The other trials showed a similar pattern. This sampling event followed a brief period during which stronger than normal influent was introduced to the units. The diminished treatment efficiency indicated by these samples is suspected to be associated with undocumented, short-term overloading conditions.

Sulfate removal rates were initially greater than 60% in all trials. Although variable, sulfate removal showed general improvement over the first month of the study with almost complete elimination indicated for a few T2-BB1-McPa samples. Thereafter, removal rates declined, apparently associated with loading rates, through November 2, 2006. The November 27 and December 7, 2006 sample results suggested sulfate additions although it is suspected that these data reflect an undocumented spike in influent sulfate between November 2 and November 27, 2006 or dissolution of sulfide minerals formed during preceding weeks. From December 7, 2006 through study completion, the trials removed some sulfate; generally less than 25%. Section 4.4 provides details regarding the potential causes of the observed pattern.

As anticipated, alkalinity additions showed a large initial spike (up to 6,000 mg/L) due to lime kiln dust and fresh crushed limestone effects. These levels were not sustained beyond Week 2 with alkalinity additions stabilizing at the two month mark. As with other parameters, the rate and incremental magnitude of alkalinity addition declines was higher for the higher loading rate trials. Throughout the study, each unit was able to produce sufficient alkalinity to neutralize influent acidity and provide at least some surplus under effluent ORP conditions. An exception was noted for the higher loading rate samples collected on December 7, 2006. As previously discussed, it is anticipated that this departure was associated with undocumented introduction of higher acidity influent when the water source was disrupted.

As previously discussed, T2-BB1-McPa was allowed to operate two additional weeks with an artificial heat source. Heating did not cause any appreciable improvement in alkalinity addition or metals and sulfate removal after January 16, 2007. In fact, sulfate removal declined during this period with net addition indicated in the last sampling event. As a result, it was concluded that temperature may not be responsible for diminished performance after early October 2006.

Best Bet 2

Comparable to BB1, all Best Bet 2 (BB2) trials provided high HI reduction rates (96% or more) for the first month of the study. Effluent HI were below 30 during the early stages with minima during Week 3 at less than 10. The bulk of the HI reductions were associated with aluminum and iron removal.

After the first month, metals removal began to decline in all trials. Consistent with expectations, the BB2 units receiving the highest loading showed the most rapid onset of diminished treatment followed by those with intermediate and design loading, respectively. Trial T2-BB2-McPa (lowest loading) sustained greater than 90% HI reductions through early October before treatment began to decline further. HI reduction declines occurred in relatively consistent increments through November 27, 2006 with higher and more stable metals removal thereafter. By the end of the study, effluent HI from BB2 units ranged from 195 to almost 270; due almost exclusively to waning iron removal rates. Removal of other metals (cadmium, copper, lead, selenium, and zinc) was almost complete in all trials throughout the study.

The lowest HI reduction observed (64%) in T2-BB2-McPa corresponded to the November 27, 2006 sampling event. The other trials showed a similar pattern. This sampling event followed a brief period during which stronger than normal influent was introduced to the units. The diminished treatment efficiency indicated by these samples is suspected to be associated with undocumented, short-term spike in influent concentrations.

Sulfate removal rates were initially greater than 80% in all trials. Although variable, sulfate removal generally remained at greater than 60% over the first month of the study with complete elimination indicated for one T2-BB2-McPc sample. Thereafter, removal rates declined, apparently associated with loading rates, through November 2, 2006. As with BB1, the November 27 and December 7, 2006 sample results suggested sulfate additions although it is suspected that these data reflect an undocumented spike in influent sulfate between November 2 and November 27, 2006 or dissolution of sulfide minerals formed during preceding weeks. From December 7, 2006 through study completion, the trials removed some sulfate; generally less than 30%. Section 4.4 provides details regarding the potential causes of the observed pattern.

Similar to Best Bet 1 trials, alkalinity additions showed a large initial spike (up to 6,000 mg/L) due to lime kiln dust and fresh crushed limestone effects. These levels were not sustained beyond Week 2 with alkalinity additions stabilizing at the two month mark. As with other parameters, the rate and magnitude of alkalinity addition declines was higher for the higher loading rate trials. Throughout the study, each unit was able to produce sufficient alkalinity to neutralize influent acidity and provide at least some surplus under effluent ORP conditions. An exception was noted for the higher loading rate samples collected on December 7, 2006. As previously discussed, it is anticipated that this departure was associated with undocumented introduction of higher acidity influent when the water source was disrupted.

• If strength of evidence (field measures/analysis, lab analyses, and general observations) indicates a certain material combination is clearly superior in terms of performance (metals removal, neutralization, SRB activity), then it will be considered a candidate for pilot-scale testing (Task 3). Determinations will be made by comparing between trials conducted under the same hydraulic/mass

loading conditions. If no clearly superior material combination is identified, then additional criteria may be used to make the final selection.

All material combinations were able to provide HI reductions of 50% or greater for the duration of the study. At low and intermediate loading rates, BB1 had the highest removal rates on average but at the highest loading rate, BB2 was superior. A similar pattern was observed for sulfate removal. For alkalinity addition, BB1 provided the most benefit at the lowest loading rate but BB2 introduced more net alkalinity at intermediate and high loading rates.

Effluent Special Study

As iron removal and alkalinity addition rates began to decline, concerns developed that the passive treatment process may provide little residual benefit to receiving waters. Impromptu studies were conducted on December 7, 2006, January 4, 2007 and January 16, 2007 to gauge the potential interactions of effluent ferrous iron and residual alkalinity after discharge. Hydrogen peroxide was added to aliquots of T2-BB1-McPa effluent to provide instantaneous oxidation.

As evidenced by the residual alkalinity and minor pH effects upon oxidation, the December 7, 2006 and January 4, 2007 samples indicated that the system may produce sufficient excess alkalinity to counteract iron oxidation reactions in the receiving water or a subsequent aerobic wetland system. In other words, the cells appeared to function like vertical flow reactors (or successive alkalinity producing systems – SAPS) rather than sulfate-reducing bioreactors. Although anaerobic iron removal was meager, over 95% was lost to precipitation reactions upon oxidation. The January 16, 2007 sample showed a different pattern. Although iron removal post-oxidation remained high, very little alkalinity remained. This suggests that the unit's capacity to provide excess alkalinity may be insufficient to substantially buffer the effluent against downstream oxidation reactions. Furthermore, the system effluent would be unlikely to provide any lasting benefit to receiving waters apart from reduced metals loading (assuming ferrous iron is removed prior to stream discharge).

Hydraulic Performance

No indications of diminished hydraulic conductivity were noted during the study in any trial. Upon introduction of influent water, water was rapidly discharged to each sampling jug even after 180 days. As expected, plugging with aluminum (average influent concentration of 31.4 mg/L) precipitates did not become a problem.

Unit Longevity Estimation

The longevity of each unit could be estimated based upon two factors: alkalinity source depletion and carbon source depletion. For Task 2, alkalinity source depletion was based on the initial calcium carbonate content of the treatment matrix and the net efflux of calcium over the study period. Longevity associated with alkalinity sources was computed based upon the remaining calcium carbonate content, average daily influent volumes, and a depletion rate estimated from the 'near steady state' net calcium additions observed over the last month of the study. Unit longevity estimates based on lime kiln dust and limestone depletion ranged from 15 years at the highest load (2c) to 30 years for the lowest load (1a).

Based on these conservative projections, the service life for each unit would be acceptable for passive treatment applications. Longevity was not estimated based upon carbon source depletion. Due to the apparent limited amount of SRB activity during the last two to three months of the trial, it was determined that such estimates could not be made with any certainty.

Post-Study Treatment Unit Examination

At the completion of the study, treatment units were examined for color, precipitate and evidence of SRB microbial activity. Findings are summarized below.

- *Color* Color was evaluated through visual examination of the materials in each drum. In all drums containing humic strata, the color prominence was moderate to complete. Moderate color prominence was noted in drums 2a and 2b due to limited volumes of unreacted matter which suggested preferential flow paths through these drums. The matrix color was mostly black (potentially ferrous sulfide) with some brown and gray with a relatively shallow (approximately 3-inches) upper gray layer. In drums 2a and 2b, unreacted material retained the characteristic brown color of the original organic mixture. The spun fiberglass insulation in the control drum was stained orange.
- *Precipitate* The presence of black chemical precipitates was evaluated through visual examination of the materials in each drum. Heavy (>50%) to complete (>75%) coating of the organic material and limestone was noted in each drum. Aggregated or voluminous masses of precipitates were absent. There was bright orange precipitate on the fiberglass insulation in the control drum, and on the thin distribution layer atop each humic strata.
- *Microbial Activity* Microbial activity was evaluated based on evidence of SRB or other activity in each container. Headspace hydrogen sulfide was not detected in any of the drums using silicon tubing placed inside the sealed drum and evacuated with a peristaltic pump to the hydrogen sulfide monitor. No hydrogen sulfide smell was evident when the drum contents were removed. Both observations are consistent with other SRBR units ranging from bench to full scale. The predominant odor in all drums (except control) was that of pine tar or asphalt. All organic components were somewhat degraded except for small amounts where short-circuiting was noted in drums 2a and 2b.

DISCUSSION

As outlined in the preceding text, the passive treatment units were designed to provide the following benefits:

• Increased pH;

- Acidity removal and increased alkalinity;
- Strongly reducing conditions (as indicated by ORP) due to SRB activity, and
- Metals removal.

Each unit consistently raised pH to 5.7 s.u. or higher with effluent pH typically exceeding 6 s.u. Metals removal (as HI reduction) exceeded 60% in all trials except during upset conditions. In recommended (low) loading rate trials, metals removal stabilized in the 75 to 85% range. Acidity removal was complete in all trials irrespective of loading.

There was no attempt to restrict oxygen from the loosely vented drum heads. Mine water dripped freely into the drum and likely saturated with oxygen while standing in the top of the drum. Flow from the sample jugs was immediate as "fresh" water entered the drum during a scheduled cycle. Observation at decommissioning indicated the presence of orange precipitates in the fiberglass material overlaying the humic strata. Apparently, some of the iron was precipitated as ferric hydroxides in this area. As the flow proceeded vertically through the drum, it is likely oxygen was removed by metal hydrolysis and the reducing environment resulting in very low dissolved oxygen readings in the sample jugs. However, some re-oxygenation may have occurred, especially on older samples (collected up to six hours after a timed cycle).

Alkalinity additions (effluent alkalinity plus influent acidity) dropped rapidly after initiation of the daily hydraulic loading. As shown in Figure 7 (inset), some excess alkalinity was typically present in effluent from each treatment unit. It is well established that alkalinity can be added abiotically through limestone dissolution and biologically through sulfate reduction. Comparing Figures 7 and 8, it is apparent that alkalinity trends mirrored those of calcium and magnesium additions. From this pattern, it may be concluded that the bulk of the alkalinity added was associated with limestone dissolution. As discussed for the Effluent Special Study, the excess alkalinity added at the end of the trial may be insufficient to counteract the effects of ferrous iron oxidation reactions upon discharge. Thus, sustained loading at even the lowest rate would not produce treatment effects typical of a SRBR or SAPS unit. In spite of the projected longevity of the units based on calcium carbonate depletion rates, associated alkalinity additions would have to be supplemented in order to provide any lasting in-stream benefits if overloading conditions were maintained for an extended period.

Biotic sulfate reduction adds alkalinity as follows as long as the reduction rate exceeds the metal sulfide consumption rate:

$$SO_4^{-2} + 2 CH_20 \rightarrow H_2S + 2 HCO_3^{-1}$$

 $H_2S + M^{+2} \rightarrow MS + 2 H^{+1}$

The analytical data for the last three full sampling events (December 20, 2006 through January 16, 2007) were initially believed to be representative of the long-term behavior of bench-scale SRBR cells. The inset of Figure 7 shows that alkalinity additions provided by "a" cells were higher than those exhibited by more heavily loaded "b" and "c" cells. This could be attributable to greater SRB activity and/or greater limestone dissolution associated with longer retention times in the "a" cells. When T2-BB1-McPa (with heating and reduced metals loading) was

monitored for an additional two weeks, however, increased alkalinity was accompanied by higher calcium and magnesium concentrations but low to no net sulfate removal.

The molar sulfate removal rate is typically estimated in moles per day per cubic meter of organic medium or substrate (moles/day/m³). Cell design protocol typically attempts to match the volumetric removal rates for metals and sulfate at 0.3 moles/day/m³. This benchmark value has been established over dozens of SRBR applications ranging from bench- to pilot- to full-scale systems (Gusek 2007 personal communication).

The sulfate reduction rates are closely related to the available amounts of dissolved organic carbon in the bioreactor medium pore space. Total organic carbon (TOC) and chemical oxygen demand (COD) concentrations provide a measure of food source readily available to the SRB. The more TOC available, the more prolific the SRB will be; for example, SRBR cells fed with ethanol or methanol ("bugs on booze" systems) typically exhibit sulfate reduction rates many times the benchmark rate.

During cell startup, the abundance of very labile organic matter from the animal manure, compost and hay typically creates an environment conducive to sulfate reduction. Once the labile sources are depleted, the rate of TOC generation is dependent on a suite of other bacteria that include cellulose degraders and methanogens (Seyler, 2003) that provide TOC the SRB can use. Ultimately, the rate at which cellulose is degraded controls the rate at which SRB reduce sulfate.

All units in the Task 2 bench tests initially exhibited sulfate removal two to 10 times the benchmark rate. Sulfate removal dropped precipitously after six to 14 weeks in each unit. Table 6 summarizes sulfate concentrations/removal rates. The abrupt decline in sulfate removal coincided with a similar trend in TOC concentrations. Examples (highlighted) for the T2-BB1-McPa cell show a drop in TOC from 457 to 24 mg/L in October 2006 and a coincidental drop in sulfate removal rate from 0.86 to 0.32 moles/day/m³ (Figure 9). The ORP values also changed in response to the labile organic depletion rising from -272 mV to about -70 mV in a month's time. Metals removal and hazard index (see Figure 5) suffered at the same time. A similar phenomenon was observed in the T2-BB2-McPa cell, only it occurred two months earlier, in August 2006.

By late November, TOC levels in both "a" cells had dropped to concentrations on the order of 10 mg/L to 20 mg/L and the sulfate reduction rates dropped to zero or negative values (sulfides may have been re-dissolved in portions of the cell mass). At this time, the cellulose-degrading bacteria (CDB) population may have attempted to fill the niche in the SRBR bacterial consortium as sulfate removal rates rebounded to the range of 0.12 to 0.27 moles/day/m³ (Figure 6). However, no corresponding increases in effluent TOC were observed. Remarkably, net sulfate removal in T2-BB1-McPa appeared to drop to below zero, after its initial recovery, despite heating. This may have been primarily due to the reported drop in influent sulfate concentration (995 mg/L) in the final sampling event (see Table 4). This value is well below the average influent sulfate concentration for the test period (1,545 mg/L), and inconsistent with the observed pH drop, ORP increase and only modest conductivity decrease (from 2,030 to 1,831 us/cm) observed coincidentally for this sampling event. As a result, it could not be determined if

the CDB, thought to be responsible for the initial sulfate removal recovery, would have been able to continue to sustain SRB activity for an extended period. Interestingly, the HI value appeared to rebound (Figure 5) in the final two "heated" sampling events and the effluent ORP dropped slightly (from -15 mv to -47 mv) despite a dramatic spike in influent ORP (Figure 4).

Sulfate removal rates did not track closely with ORP as an indicator of sulfate reduction and general bacterial activity. Some of the highest sulfate removal rates early in the trial corresponded with relatively high ORP (> -100 mV). Between August 9 and October 11, 2006, there were indications of higher reduction rates assumed to be attributable to SRB. The pattern was most notable in T2-BB1-McPa where ORP remained below -200 mV and sulfate removal in excess of 80% was sustained. None of the units performed as expected with respect to maintaining strongly reducing (ORP <-100 mV) throughout the study. During the sulfate removal recovery phase (after late November 2006), no concomitant decreases in ORP were observed that would indicate the reductions were bacterially-mediated to a significant extent.

In the absence of strong, sustained indications of sulfate reduction in most units, alternate or complimentary explanations for sulfate removal were sought. As first discussed by Thomas (2002), sulfate may have been consumed in the formation of aluminum hydroxy-sulfates or similar mineral phases associated with the dissolution of limestone. Although this may account for some of the observed sulfate removal, influent aluminum concentrations were not high enough to suggest this as the primary removal mechanism. It was noted that sulfate removal declined as effluent calcium levels dropped suggesting a possible link. Based on simple saturation indices (using influent sulfate and effluent calcium concentrations), it would appear that in situ conditions may be favorable for gypsum formation during early stages. Due to the complex chemistry expected in the treatment units, the saturation indices are not considered full proof evidence but they do provide a possible explanation for sulfate removal in the absence of significant SRB activity.

Based on observed sulfate, ORP, alkalinity and calcium trends, the following sequence of sulfate removal modes was postulated:

- Initial sulfate removal was due largely to abiotic reactions including precipitation (aluminum hydroxysulfate, gypsum) and other complexation reactions
- As ORP dropped, biotic (SRB) and abiotic processes accounted for removal
- When ORP increased, the primary mechanism reverted to abiotic removal with some biotic process-related removal sustained in T2-BB1-McPa for a longer period than in other trials.
- An undocumented influent sulfate spike or dissolution of precipitated sulfide minerals led to net negative sulfate removal for a period of approximately one month.
- Sulfate removal rates recovered to approximately design rates, attributable to abiotic (limestone dissolution) and biotic (CDB moderated TOC availability) factors after the apparent upset.

CONCLUSIONS AND RECOMMENDATIONS

Based on Task 2 results, Best Bet 1 appeared to provide the best overall treatment over the study period at low and intermediate loading rates. It consistently raised pH, neutralized acidity, and provided the greatest metals (in terms of toxicity reduction) and sulfate removal. After 10 weeks, however, metals (specifically iron) and sulfate treatment efficiency declined even at the lowest loading rate and alkalinity additions waned. Effluent iron concentrations during the latter study stages were well above water quality benchmarks and residual alkalinity may be insufficient to counteract anticipated 'downstream' oxidative processes. Despite early signs, SRB activity was either absent or very limited in BB1 (and BB2) trials after eight to twelve weeks based on ORP readings indicating only mildly reducing conditions in these heavily loaded trials. As a result, an unqualified recommendation to proceed with pilot scale studies using BB1 materials cannot be made. PLFA Analysis of the substrate before and after exposure to the mine water indicate that SRB bacteria were present, and that organic decomposers may indeed have been more prevalent in the exposed substrate (Figure 10) than the fresh substrate. Organic substrate analysis, not yet available at publishing time, may provide further insight to the bacterial consortium and degree of decomposition.

There are inherent limitations in designing bench-scale testing for refining passive treatment system design. The Task 2 system, as designed, was intended to illustrate the treatment capacity of one passive treatment component (SRB reactor). It is likely that better long-term treatment efficiencies could be achieved in the SRBR if loading rates were incrementally increased from below to above typical design rates rather than attempting to treat under 'overloading' conditions from the outset.

In an actual treatment system, this component could either precede or follow an area or structure providing oxidation and precipitation prior to water introduction or stream discharge and may be adequate to provide some mitigation of acid drainage and reduce COPECs. Bench-scale testing evaluating several different and sequential processes that may be utilized in a successful full-scale system would be quite complex and costly. Champagne et al (2005) bench tested synthetic mine drainage higher in acidity and metals concentrations than Task 2 influent utilizing a five stage apparatus and achieved >98% removal efficiency for all Task 2 metals parameters (except cadmium at 66% reduction).

A sequential arrangement, mimicking that of a multi-staged system such as the existing McPherson Branch demonstration, may indeed be necessary for a metal free, highly alkaline effluent. However, the need for and success of any passive treatment system will be dependent upon the specific treatment objectives (removal or addition needs), design requirements (source flow, local hydrologic conditions, receiving water quality) and field constraints (topography, land area available) associated with the residual seep. If and when a seep is identified that may be effectively addressed by an SRB-based anaerobic system, pilot-scale application of the technology may be proposed.

Finally, it appears that SRB reactors are quite sensitive to overloading under startup conditions, much like any newborn who would not be expected to run a marathon before its first birthday.

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Table 1

Material Combinations for Bench-Scale Testing AMD Passive Treatment System Demonstration – Task 2

		Solid and Liquid Amounts ¹												
Material/Combination	K	L	Organics	<u>Inoculum</u>	Flow Rate mL/day ⁽²⁾	Logic ⁽⁴⁾								
T2-C-McPa					7570	Base metals load								
T2-BB1-McPa ⁽³⁾	2%	28%	50% S, 10% H	10% C	7570	Base metals load								
T2-BB1-McPb ⁽³⁾	2%	28%	50% S, 10% H	10% C	15140	2x base metals load								
T2-BB1-McPc ⁽³⁾	2%	28%	50% S, 10% H	10% C	30280	4x base metals load								
T2-BB2-McPa ⁽³⁾	2%	28%	50% S, 5% H, 5% C	10% M	7570	Base metals load								
T2-BB2-McPb ⁽³⁾	2%	28%	50% S, 5% H, 5% C	10% M	15140	2x base metals load								
T2-BB2-McPc ⁽³⁾	2%	28%	50% S, 5% H, 5% C	10% M	30280	4x base metals load								

The water source will be from the McPherson Mine pump. Flow rates were selected to provide the following retention times and metals/acidity/sulfate loadings. Total volume will be in four equal aliquots at sixhour intervals. T2 = Task 2, BB = Best Bet, C = Control, H = Hay, S = Sawdust, C = Compost, M = Equine Manure, L = Limestone, K = Cement Kiln Dust. All % based on fraction of total treatment media mass.BB1 corresponds to BB8 from Task 1 and BB2 corresponds to BB10 from Task 1Metals (as well as acidity and sulfate) loading estimated from historical results from McPherson Mine pump/pipe sampling points.



Figure 2 Experimental Set-up Diagram

Return to McP Mine



TABLE 2

Preliminary Summary of a Bench Scale Test for Copper Mine Drainage Glenn Springs Holdings Copper Basin Project, Ducktown, TN investigators: Ben Faulkner, BratFarm@pol.net, Carrie Stokes - BWSC, Nashville, TN, Mark Bowers - Secaps, Jim Gusek - Golder Associates, Franklin Miller - Glenn Springs Holdings Following evaluation of local materials for suitability (static testing with four strengths of mine water), two humic strata mixes and one control were subject to three loadings from a copper mine for 182 days Results will be used to refine additional passive treatment systems considered as a part of this comprehensive land reclamation and water quality improvement project. http://www.epa.gov/superfund/programs/aml/tech/copperbasin.pdf http://www.epa.gov/superfund/programs/aml/tech/cuwetlands.pdf

Statistics for Task 2:

Task 2 bench scale test: 182 days

	7/18/06 to 1/16/07	1/16/2007	1/16/2007
		SELECT	outlet 1a
		outlet 1a	final
	inlet avg. McP-150	final	oxidized
flow: gpm	0.001387		
pH s.u.	3.74	6.40	5.3*
acidity mg/L	861	0	0
alkalinity mg/L	0	165	10
d. Fe mg/L	325.75	133.00	0.17
d. Mn mg/L	13.52	14.50	14.80
d. Al mg/L	31.40	0.02	0.02
d. Zn mg/L	7.79	0.00	0.01
d. Cu mg/L	0.1716	0.0009	0.0008
d. Cd mg/L	0.0032	0.0000	0.0000
d. Ca mg/L	156.50	326.00	333.00
d. Co mg/L	0.0849	0.0124	0.0050
d. Pb mg/L	0.0087	0.0000	0.0000
d. Se mg/L	0.0121	0.0005	0.0005
d. Mg mg/L	67.49	67.49	67.49
hardness mg/L	661	1180	1160
sulfate mg/L	1784	1260	1200
ORP mV	268	-15	-15
sc µmho	2277	2208	2208
Falk mg/L	0	120	120
COD mg/L	39	45	117
TOC mg/L	6*	10	4

FLOW RATE for 1a: 1882 ml per cycle * 4 times/day = 7528 ml/day = 0.00138 gpm 2a : 2143 ml per cycle = 0.00157 gpm 1c: 6628 ml/cycle = 0.00486 gpm 2c: 6959 ml/cycle = 0.00510 gpm

AREA, VOLUME

20" diameter = pi r squared = $100^{*}3.14159$ = 314.159 sq. in = surface area = 0.20268 m sq. 29" depth of humic strata (26") and limestone (3") * 314.159 = 9111 in cubed = 0.14930 m cubed

HYDRAULIC LOAD

For 1a: (lightest load)	
7.528 L/d / 0.20268 m sq. = 37.14 L/m2/day	363 hours or 15.1 days retention time
For 2c: (heaviest load)	
27.836 L/d / 0.20268 m sq. = 136.39 L/m2/day	98 hours or 4.1 days retention time

IRON LOAD

For 1a: (lightest load)

Fe load is 325.75 mg/l * 0.00138 gpm * 5.45 = 2.49 grams per day of iron

2.49 grams of iron per 0.20268 m sq. is 12.3 g/m2/day iron load

For 2c: (heaviest load)

Fe load is 325.75 mg/l * 0.00510 gpm * 5.45 = 9.0542 grams per day of iron 9.0542 grams of iron per 0.20268 m sq. is 44.67 g/m2/day iron load

TOTAL TARGET METALS LOAD (*excludes Mn and a portion of aluminum - proprietary) For 1a: (lightest load)

T*M load is 351 mg/l * 0.00138 gpm * 5.45 = 2.63 grams per day

2.63 grams of T*M per 0.20268 m sq. is 13 g/m2/day T*M load For 2c: (heaviest load)

FUI 2C. (Heaviest load) T_{1}

T*M load is 351 mg/l * 0.00510 gpm * 5.45 = 9.75 grams per day 9.75 grams of T*M per 0.20268 m sq. is 48 g/m2/day T*M load

* denotes TOC measured in control, pH of 1a oxidized interpolated from trend

Figure 3 - pH Trends



Date

Figure 4 - ORP Trends



Date

Figure 4 a Temperature Trends



Figure 5 - Hazard Index Reduction Trends



Figure 6 - Sulfate Removal Trends



Date

Figure 7 - Effluent Alkalinity Trends





Figure .8 - Calcium + Magnesium Added



Figure .9 - Sulfate Removal Rate and Effluent TOC Trends

Date

Table 3 - Field Da	ata Summary			<u> </u>																												
AMD Passive Trea	atment System L	Jemonstrati	on - Tasi	(2																											<u> </u> '	
Parameter	Trial/Source	Units	7/18/06	7/22/06	7/29/06	8/2/06	8/9/06	8/16/06	8/23/06	8/30/06	9/7/06	9/13/06	9/20/06	9/27/06	10/4/2006	10/11/2006	10/18/2006	25-Oct	2-Nov	8-Nov	14-Nov	22-Nov	27-Nov	7-Dec	13-Dec	20-Dec	26-Dec	4-Jan	11-Jan	16-Jan	24-Jan	31-Jan
Alkalinity	Control	mg/L	0			0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Mine Water	mg/L	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-	T2-BB1-McPa	mg/L	240			240	240	240	240	240	240	240	240	240	240	240	240	240	240	240	240	180	180	240	240	100	180	240	200	120	120	150
	T2-BB1-McPc	mg/L mg/l	240			240	240	240	240	240	120	240	240	240	240	180	240	150	120	120	80	120	100	80	120	80	120	80	100	80		
-	T2-BB2-McPa	mg/L	240			240	240	240	240	200	240	240	240	240	240	240	240	180	240	240	240	180	240	180	240	80	180	240	150	80		
	T2-BB2-McPb	mg/L	240			240	240	240	240	240	240	240	240	100	200	240	240	240	240	180	120	120	160	120	180	110	120	120	100	60		
	T2-BB2-McPc	mg/L	240			240	240	240	240	240	240	240	240	200	140	240	240	150	240	120	80	120	120	80	80	80	120	120	100	60		
Conductivity	Control	uS/cm	2371	0405	2420	2378	2494	2505	2540	2616	2660	2634	2600	2508	2667	2473	2589	2587	2647	2541	2801	2829	2928	2977	2898	2814	2591	2345	2332	500		
	T2 PP1 MoPo	uS/cm	2207	2185	2315	2192	5200	2239	2296	2292	2387	2293	2311	2280	2330	2264	2299	2270	2258	2138	4397	2203	2061	1970	2120	2129	2079	2145	2311	2256	2030	1821
	T2-BB1-McPh	uS/cm	9000	8217	4172	3025	2382	2152	2001	1954	2176	2128	2088	2004	2273	2495	2202	2287	2359	2297	2490	3294	3051	2259	2161	2110	2178	2072	2148	2208	2110	2078
	T2-BB1-McPc	uS/cm	8143		2771	2231	2178	2020	2056	2150	2292	2261	2292	2304	2424	2366	2349	2380	2445	2294	3293	3760	2598	2177	1978	2213	2259	1974	2236	2413		
	T2-BB2-McPa	uS/cm	10603		5971	4566	3499	2959	2729	2495	2387	2260	2258	2291	2312	2284	2298	2331	2369	2298	2857	3327	3042	2509	2271	2206	2264	2045	2148	2344		
	T2-BB2-McPb	uS/cm	11465		4098	3187	2584	2215	2038	2088	2354	2253	2204	2263	2361	2314	2344	2356	2430	2366	3112	3584	2950	2237	2146	2166	2269	2030	2166	2363		
Daliman Mahana	T2-BB2-McPc	uS/cm	10382	4360	3278	2674	2213	2134	2076	2191	1000	2324	2349	2324	2447	2371	2425	2424	2472	2379	3244	3924	2584	2178	1994	2238	2343	1915	2330	2411	\vdash	
Delivery volume	Control Mine Water	mi	1860	1860	1860	1870	1880	1880	1900	1960	1920	1960		1960	1960	1910	1860	1940	1920				1800	1810		1710.00				1500.00	—	
	T2-BB1-McPa	ml	1880	1840	1920	1790	1840	1820	1880	1900	1920	1900	1820	1900	1920	1840	1860	1840	2130				1850	1880		1900.00				1900.00	<u> </u>	
	T2-BB1-McPb	ml	3520	3430	3640	3640	3600	3520	2820	3520	3600	3620	3600	3540	3600	3560	3560	3600	3620				3600	3590		3600.00				3500.00		
	T2-BB1-McPc	ml	6960	6400	6700	6920	6860	6660	5860	7060	7000	7240		7030	7180	7160	5800	7050	7040				7250	4340		7140.00				4900.00		
	T2-BB2-McPa	ml	2140	2100	2160	2190	2100	2140	2200	2200	2100	2180	2180	2140	2160	2090	2060	2180	2045				2100	2190		2160.00				2200.00		
	12-BB2-McPb	mi	3830	3740	3840	3860	3800	3840	3820	3840	3740	3740	3760	3720	3760	3760	3800	3760	3640	I	 	l	3790	3770		3780.00			I	3800.00	—	
Dissolved Oxygon	Control	ma/l	2 08	0/20 4 82	1500	30	4 04	3 3 1	4 74	2 57	2 00	3.01	2 37	0940 4 37	2.54	7000	0700	2 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9	2 22	8 76	2.76	3 21	2 83	2 21	4.52	3 47	9.02	2.86	3.01	4 70	───	
Dissolved Oxygen	Mine Water	ma/L	0.5	4.02	4.39	5.9	4.5			2.01	1.85		2.31		2.04	0,59		2.32	0,65		2.70		2.03		2.72		3.32	2.00			<u> </u>	1.57
	T2-BB1-McPa	mg/L	0.85	2.35	4.33	3.21	0.88	1.75	2.21	0.38	0.81	0.55	0.44	0.4	0.25	0.43		2.12	2.69	2.22	1.40	2.72	2.68	2.95	1.65	3.32	4.72	5.03	2.66	3.30	2.49	2.49
	T2-BB1-McPb	mg/L	0.83	2.8	4.29	3.4	0.24	1.08	1.59	0.52	1.37	2.84	2.02	2.2	1.76	1.09		3.34	2.28	1.74	1.62	2.35	3.00	2.46	2.14	2.76	4.48	1.89	2.42	3.43		
	T2-BB1-McPc	mg/L	0.63	1.14	4.03	4.9	0.24	2.12	1.58	1.54	1.51	2.43	2.23	2.27	2.82	1.53		2.42	1.84	2.75	1.90	3.05	2.85	2.38	2.35	2.48	3.92	2.59	3.94	3.44		
	T2-BB2-McPa	mg/L	0.84	4.35	3.78	3.32	0.55	0.77	1.45	0.44	2.1	1.95	0.86	1.91	1.37	1.32		3.16	1.48	1.22	1.33	3.29	1.46	2.15	1.91	2.74	2.91	2.96	3.39	2.93	\parallel	1
	T2-BB2-McPc	mg/L	1.25	1.88	3.65	4.14	0.17	1.33	2.59	1.29	1.14	1.78	1.57	2 14	1.52	0.8		2.58	2.58	1.78	1.91	4.28	2.05	2.22	2.15	2.69	2.21	2.54	3.64	2.31	├ ───┤	
Ferrous Iron	Control	mg/L	1.50	1.57	2.12	3.49	548		1.20	1.52	3.4	2.21	1.0	2.14	1.04	1.07		2.49	2.70	1.34	1.70	3.31	1.04	2.15	2.15	2.90	2.19	177.50	3.01	2.03		
r onodo non	Mine Water	mg/L	328		362		1068	1072	370	365	376	420	385	355	385	365	435	370	322.5	307.5	645	370	330	189	288	270		325	390	318	185	11
	T2-BB1-McPa	mg/L																									-			-		
	T2-BB1-McPb	mg/L																														
-	T2-BB1-McPc	mg/L																														
	T2-BB2-McPb	mg/L mg/l																													<u> </u>	
	T2-BB2-McPc	ma/L																														
ORP	Control	mV	288	241	402	396	395	422	450	440	451	461	473	522	457	467	454	467	357	467	428	424	429	415	434	435	460	421	443	444		
	Mine Water	mV	197	202	207	221	212	276	262	222	281	224	242	210	216	266	536	<mark>191</mark>	262	196	279	214	233	416	156	246	438	280	258	166	411	534
	T2-BB1-McPa	mV	-154	-134	-50	-64	-228	-220	-222	-222	-161	-233	-235	-298	-252	-272	-72	28	-52	-27	-46	-18	48	-61	-52	-4	32	-43	-25	-15	-4	-47
	T2-BB1-McPb	mV mV	-152	-120	-75	-118	-270	-233	-224	-223	-78	-132	-134	-165	-165	-200	-78	13	-42	-21	-41	-17	-2	-63	-58	-9	8	-38	-33	-23		
	T2-BB1-MCPC	m\/	-134	-123	-101	-119	-200	-246	-141	-100	-42	-75	-110	-158	-167	-187	-43	-4	-40	-23	-50	-21	-10	-33	-00	-0	-4	-41	-33	-20		
-	T2-BB2-McPb	mV	-115	-31	-117	-22	-296	-153	-164	-177	-86	-75	-122	-154	-163	-190	-57	-8	-47	-17	-38	-28	-27	-71	-47	-20	-2	-46	-44	-30		
	T2-BB2-McPc	mV	-110	-85	-145	-120	-273	-240	-207	-170	-78	-59	-108	-131	-153	-180	-59	-14	-35	43	-38	-34	-31	-72	-45	-29	-13	-50	-48	-31		
pН	Control	s.u.	2.95	4.47	2.76	3.7	2.96	2.72	2.73	2.79	2.53	2.86	2.33	2.59	2.66	2.75	2.84	2.82	3.14	2.67	2.40	3.04	2.63	3.30	3.29	2.86	2.77	3.29	2.51	3.19		
	Mine Water	s.u.	3.77	4.17	3.7	4	4.06	3.74	3.5	3.77	3.64	3.73	3.58	3.92	3.85	4.07	3.77	4.13	3.69	4.13	3.39	3.81	3.77	2.82	4.52	3.90	2.95	3.83	3.60	4.34	3.13	3.00
	T2-BB1-McPa	s.u.	6.01	0.12 6	5./ 6.16	5./b	5.95	5.77	5.61	6.03	0.14 6.03	6.05	5.78	6.25	6.08	6.24	5.87	5.97	6.36	6.18	5.94	5.95	5.89	6.04	6.50	5.79	5.87	6.19 6.20	5.96	6.39	0.55	0.25
	T2-BB1-McPc	s.u.	6.09	7.11	6.05	6.31	6.18	5.91	5.9	5.99	6	5.98	5.76	6.18	6.15	6.4	6.13	6.04	6.25	6.14	5.83	5.80	6.04	6.18	6.54	6.08	6.05	6.18	6.07	6.38		
	T2-BB2-McPa	s.u.	6.23	6.74	5.95	6.03	6.08	5.91	5.92	6.1	6.14	6.12	5.88	6.25	6.13	6.36	6.15	6.07	6.28	6.24	5.97	5.90	6.09	6.24	6.53	6.20	6.18	6.25	6.15	6.49	·	
	T2-BB2-McPb	s.u.	6.26	6.45	6.02	6.35	6.21	5.93	5.92	6.09	6.08	6.01	5.77	6.23	6.07	6.28	6.22	6.13	6.31	6.2	5.92	5.98	6.14	6.27	6.56	6.20	6.16	6.21	6.16	6.44		
11 51 152 6 -	T2-BB2-McPc	s.u.	6.37	6.13	6.17	6.43	6.26	5.94	5.88	6.05	6.32	6.03	5.78	6.26	6.13	6.34	6.28	6.17	6.35	5.97	5.90	6.00	6.15	6.33	6.58	6.24	6.20	6.21	6.19	6.42]	
pH with H2O2	Control Mino Water	s.u.				2.00	2.05				2.00	2.00	2 50						2.00									2.00				257
	T2-BB1-McPa	5.U. S II	2.5		2.04	3.09	2.95	2.12	2.11	2.02	2.00	2.90	2.59	2.12	2.93	2.94	3.23	3.14	2.99	2.0/	2.24	3.12	2.09	2.00	3.47	2.95	3.00	3.00	2.00	3.24	2.90	2.57
	T2-BB1-McPb	s.u.																														
	T2-BB1-McPc	s.u.																														
	T2-BB2-McPa	s.u.																														
	T2-BB2-McPb	s.u.																													<u> </u>	
Temperature	Control	s.u. dea C	22.74	20.05	22.12	23.65	21.76	22.30	 21.27	21.52	 18 71	17 03	15 30			15.81	15 30	9.2	9.40	10.64	8.83	8 31	7 71	 5 32	7 97		7 00	 8 21	5.85	 11 08	<u> </u>	
Temperature	Mine Water	deg C	17.2	20.33	21.67	21.68	20.71	20.6	21.27	17.9	17.07	16.52	15.53	15.02	16.11	15.01	23.3	14 07	12 41	14 1	13.21	13.02	13.03	6.17	11.54	14 11	8.31	13 11	11 70	13.67	13.32	12.52
	T2-BB1-McPa	deg C	22.82	20.13	21.99	22.98	21.49	21.55	21.47	21.58	18.32	18.15	15.68	14.97	15.61	15.72	14.34	8.81	9.92	10.13	8.94	6.37	6.92	5.82	6.52	8.12	7.96	7.78	5.20	8.66	7.84	8.40
	T2-BB1-McPb	deg C	23.46	22.25	22.02	23.81	21.71	22.16	21.32	21.69	18.94	18.09	14.82	14.5	15.46	15.62	14.66	8.39	9.28	10.23	9.01	5.60	6.60	5.60	7.20	7.68	7.83	8.25	5.04	8.45		
	T2-BB1-McPc	deg C	24.14	22.2	22.13	23.92	21.82	22.34	21.23	21.64	18.67	18.02	14.35	14.28	15.44	15.61	14.5	8.33	9.68	10.18	9.04	5.49	6.74	5.65	7.10	7.58	7.88	8.19	5.13	8.45		
	12-BB2-McPa	deg C	23.61	21.82	22.15	23.6	21.72	22.12	21.38	21.65	18.47	18.19	14.93	14.47	15.42	15.64	14.39	8.04	10.03	9.95	8.85	5.53	6.55	5.31	6.57	7.41	7.73	7.90	4.90	8.39	<u> </u>	
	T2-BB2-McPb	deg C	23.84	21.51	22.2	23.37	21.84	22.16	21.32	21.7	18.3	18.03	14.33	14.26	15.44	15.72	14.11	7.9 8.05	10.2	9.73	9.02	5.49	6.52	5.25	6.24	7.31	7.60	7.10	4.80	8.26	<u> </u>	<u> </u>
	12-DD2-IVICPC	uey c	24.22	21.01	22.17	23.13	22.05	21.0	21.21	21.03	17.00	10.1	14.39	14.40	10.41	10.00	14.11	0.03	10.00	9.93	3.40	0.00	0.52	0.04	0.33	1.30	1.52	7.04	5.07	1.31	<u> </u>	<u> </u>
Notes:		1	1	1		1	1	1						1							1	<u> </u>							<u> </u>			
 Yellow shading in 	ndicates values t	that are sus	pect bas	ed on equ	upment p	oroblem	s or hun	nan error.																								
- Orange shading	indicates the me	easurement	was inac	lvertently	omitted.	1							1 -									1		1 -		1 -	-					

Table 4 - L	aboratory Data Su	mmary	alec **	Tool: C											
AMD Pass	ave i reatment Syst	em Demor	stration -	ask 2	. ·				07.1		0.5 5		40.1		0.1
Parameter Acidity	I rial/Unit MCP	18-Jul 941	22-Jul 882	29-Jul 872	9-Aug 1000	7-Sep 1000	4-Oct 1030	2-Nov 941	27-Nov 882	7-Dec 587	20-Dec 857	4-Jan 670	16-Jan 670	24-Jan 615	31-Jan 489
(mg/L) Alkalinity,	T2-C-McPa	NA	NA	NA	774	NA	NA	NA							
Total (As CaCO3)	MCP	NA	NA	NA	NA	NA	NA	5	NA	NA	NA	NA	NA	NA	NA
(mg/L)	T2-C-McPa T2-BB1-McPa	5 4010	5 4180	17.8 4100	5 3160	5 1920	5 1420	NA 325	NA 265	NA 190	NA 143	NA 161	5 165	NA 110	NA 198
	T2-BB1-McPb T2-BB1-McPc	4150 5030	3760 1480	1780 692	998 908	423 201	221 76.2	190 55	168 70.4	5 5	39.5 15.9	98.5 33.4	112 81.4	NA NA	NA NA
	T2-BB2-McPa T2-BB2-McPb	4930	4810	2930	1800	473	462	229	251	189	83.1 40.8	235	146	NA NA	NA NA
Aluminum	T2-BB2-McPc	4950	2350	1250	1030	276	136	113	80.6	5	45.6	42.5	104	NA	NA
(Dissolved)	MCP	30400	31000	31300	30500	34400	34200	31900	30600	32800	29700	29500	30500	31200	32000
(ug/c)	T2-BB1-McPa	858	770	668	447	299	204	48.6	46.3	55.3	23.7	15.6	24.9	15.6	18
	T2-BB1-McPb T2-BB1-McPc	769 706	659 381	461 256	220	139 41.7	17.8 35.2	36.9 52.4	21.8 60.5	40.1 51.7	27.8 46.5	15.6 15.6	45 61	NA	NA NA
	T2-BB2-McPa T2-BB2-McPb	699 697	651 621	553 418	323 243	131 110	99.5 78.6	24.3 33.4	25.5 23.8	43.2 23.5	21 40.8	36.8 15.6	46.3 17.6	NA NA	NA NA
Cadmium	T2-BB2-McPc	693	468	294	207	105	20.8	30.6	17.1	20.4	38.4	15.6	28.4	NA	NA
(Dissolved) (ug/L)	MCP T2-C-McPa	2.6	2.8	3.1	4.4 3.9	3.2 2.6	2.8	4.1 NA	2.8 NA	5.8 NA	1.8 NA	2.4 NA	2.2	6.8 NA	20.3 NA
	T2-BB1-McPa T2-BB1-McPb	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074 NA	0.074 NA
	T2-BB1-McPc	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	NA	NA
	T2-BB2-McPb	0.074	0.11	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	NA	NA
Calcium	12-BB2-MCPC	157000	161000	160000	155000	167000	164000	157000	152000	122000	155000	154000	162000	122000	112000
(ug/L)	T2-C-McPa	160000	161000	169000	157000	169000	167000	NA	NA	NA	NA	NA	151000	NA	NA
	T2-BB1-McPa T2-BB1-McPb	2120000	2040000	971000	459000	351000	335000	395000	422000	395000	274000	289000	283000	337000 NA	337000 NA
	T2-BB1-McPc T2-BB2-McPa	2190000 2100000	928000 2310000	576000 1360000	430000 787000	311000 406000	314000 388000	292000 353000	291000 459000	261000 420000	264000 296000	231000 308000	287000 315000	NA NA	NA NA
	T2-BB2-McPb T2-BB2-McPc	2260000 2190000	1900000 1250000	950000 753000	540000 430000	380000 379000	362000 345000	353000 325000	400000 306000	304000 261000	278000 269000	284000 232000	297000 299000	NA NA	NA NA
Chemical Oxygen															
Demand (COD)	MCP	40	45.7	45.1	44.8	34.5	39.5	40.1	38.1	17	40.9	39.8	44.7	15.8	10
(mg/L)	T2-C-McPa T2-BB1-McPa	46.7 12700	58 10200	39.2 9780	35.8 5480	24.4 2120	21.6 1130	NA 72.7	NA 71.4	NA 55.5	NA 64.2	NA 49.1	20.7 44.7	NA 38.8	NA 34.7
	T2-BB1-McPb T2-BB1-McPc	9950 548	10900 2370	2720 669	777 475	120 60.4	50.9 46.3	43.8 47.2	53.3 53.7	40.2 38.9	38.5 39.4	43.8 37.1	46.3 41.4	NA NA	NA NA
	T2-BB2-McPa	536	11100	5660 2200	2830	168	116	59.5	95.3	62.7	46.1	53.1	41	NA	NA
Cobelt	T2-BB2-McPc	532	3620	1410	548	66.7	54.8	55.5	66.6	45.5	42.5	35.8	44.7	NA	NA
(Dissolved)	MCP	82.1	86.5	83	82.6	97.8	95 81.0	84.1	80.4	90.2	78.4	77.4	80.7	93.9	106
(ug/L)	T2-BB1-McPa	9.8	18.5	84.5 19.6	10.1	5	4.1	6.8	18.3	11.2	6.4	9.4	12.4	5.4	8.9
	T2-BB1-McPb T2-BB1-McPc	10.2	21.9	9 5.4	6.5 7.5	б.7 11.1	/.8	12.4	26.8 25.4	19.1	16.3 17.7	14.9 16.9	15.4 21.6	NA	NA
	T2-BB2-McPa T2-BB2-McPb	17.1 20.2	19.5 10	8.2	10.2 6.2	8.3 8.9	4.1 6.8	9.8 15.7	19 22	12.8 19.9	11 15.7	7.5	14.9 16.9	NA NA	NA NA
Copper	T2-BB2-McPc	17.8	10.5	4.5	8.7	11.4	10.2	16.4	22.3	24.1	18.5	15.3	21.7	NA	NA
(Dissolved) (ug/L)	MCP T2-C-McPa	63.8 72.6	63 84.2	66.3 81.8	61.5 76.6	65.8 71.9	61 76.3	60.1 NA	87.6 NA	1240 NA	75.2 NA	151 NA	63.9 553	1130 NA	4230 NA
	T2-BB1-McPa T2-BB1-McPb	5.6 7	5.5	5.2 4.2	5.1	2	1.2	1.9	1.1	1.1	1.1	0.86	0.9	0.92 NA	0.9 NA
	T2-BB1-McPc	8.6	2.4	2	1.9	1.3	0.95	1.9	0.93	0.76	1.1	0.76	0.74	NA	NA
	T2-BB2-McPb	7.4	6.7	2.9	2.3	1.4	1.1	2	1.3	0.88	1.2	0.91	0.78	NA	NA
Hardness	MCP	8.9 700	3 580	2.3 680	2 800	1.6 680	1 674	1.9 680	0.88	0.82 600	1 640	0.79 640	0.78 660	600	NA 700
(mg/L)	T2-C-McPa T2-BB1-McPa	800 5400	640 5600	700 5400	800 3900	720 2180	740 1760	NA 1400	NA 1540	NA 1380	NA 1200	NA 1180	620 1180	NA 1220	NA 1180
	T2-BB1-McPb T2-BB1-McPc	5900 6100	5300 2600	2600 1900	1500 1400	1240 1160	1280 1200	1260 1120	1600 1120	1160 960	1000 980	1000 900	1060 1060	NA NA	NA NA
	T2-BB2-McPa T2-BB2-McPb	6200 6400	6000 4900	3000	2300	1360	1400	1320	1680 1480	1480	1080	1100	1160	NA NA	NA NA
Iron	T2-BB2-McPc	6200	3300	2300	1400	1320	1320	1240	1200	980	1020	840	1120	NA	NA
(Dissolved)	MCP	337000	344000	343000	333000	360000	348000	329000	324000	211000	322000	315000	343000	202000	92800
(09/2)	T2-BB1-McPa	11900	3110	14500	5360	190	140	74400	201000	129000	101000	97400	133000	106000	80100
	T2-BB1-McPb T2-BB1-McPc	15200 4340	16100 5280	3500 23200	409 2290	51200 172000	96800 196000	158000 264000	346000	198000 285000	220000	212000	225000	NA	NA
	T2-BB2-McPa T2-BB2-McPb	3420 14900	6070 11700	4210 1370	623 441	69600 90200	54300 106000	138000 167000	269000 318000	137000 215000	200000 223000	128000 160000	188000 246000	NA NA	NA NA
Lead	T2-BB2-McPc	4030	9360	657	747	120000	163000	227000	338000	275000	253000	197000	262000	NA	NA
(Dissolved) (ug/L)	MCP T2-C-McPa	4.7 15.8	6.6 8.1	7.2	5.5 11.6	4.9 8	4.6 6.7	6.6 NA	8.5 NA	32.8 NA	7.3 NA	9 NA	6.8 14.5	33.4 NA	119 NA
	T2-BB1-McPa T2-BB1-McPb	0.51	1	0.38	0.18	0.067	0.15	0.026	0.11	0.044	0.026	0.17	0.047	0.14 NA	0.075 NA
	T2-BB1-McPc	0.46	0.14	0.026	0.026	0.026	0.026	0.026	0.08	0.026	0.026	0.31	0.036	NA	NA
	T2-BB2-McPb	0.39	0.46	0.071	0.026	0.026	0.027	0.026	0.026	0.026	0.026	0.12	0.028	NA	NA
Magnesium	12-BB2-MCPC	0.33	0.2	0.053	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.12	0.053	NA	NA 40000
(Dissolved) (ug/L)	MCP T2-C-McPa	67900 69200	70200 69200	70200	68700 67900	75200	73600	67100 NA	63300 NA	55200 NA	65000 NA	64500 NA	69000 63600	56000 NA	46000 NA
	12-BB1-McPa T2-BB1-McPb	170000 189000	185000 186000	175000 82000	137000 63200	74600 89800	74700 91800	86300 93900	109000 124000	97500 87500	77700 79700	78200 75600	80400 85900	78600 NA	76800 NA
1	T2-BB1-McPc T2-BB2-McPa	180000 178000	76600 197000	72700 130000	70100 67500	91300 90600	92200 90300	90600 93500	95400 125000	81400 102000	83400 81600	74100 78600	94000 91100	NA NA	NA NA
1	T2-BB2-McPb T2-BB2-McPc	184000	170000	85200 71000	66200 70700	92100 97900	95700 95700	96600 94200	115000 96400	83300 80700	80700 85100	78000	91900 95400	NA NA	NA NA
Manganese (Dissolved)	MCP	13700	14100	13800	13600	14900	14500	13500	13000	11200	13000	13200	13700	11400	9270
(ug/L)	T2-C-McPa T2-BB1-McPa	13500 6170	13500 6310	14200 7980	13300 5660	14200 2740	14300 2660	NA 13900	NA 20700	NA 17300	NA 15200	NA 14500	12900 14500	NA 13800	NA 13100
	T2-BB1-McPb	7090	8760	4760	3200	12400	15400	16700	25600	17800	14300	13400	14100	NA	NA NA
1	T2-BB2-McPa	4040	5260	4110	2110	11900	10800	14500	23000	16000	13800	12500	14400	NA	NA
Poloniu	T2-BB2-McPc	3330 4000	3280 4090	2930	2540 5740	17000	16900	17100	23400 19300	14400	13500	13200	14300	NA	NA
(Dissolved)	MCP	12.2	11.3	12.1	12.5	6.8	9.8	17.3	12.1	12.7	8.7	16	14.2	13	12.9
(agric)	T2-BB1-McPa	5.5	4.8	3.2	2.6	1.1	0.7	1.3	0.8	0.56	0.53	1	0.5	0.76	0.79
1	12-BB1-McPb T2-BB1-McPc	6.1 6	4.3 0.96	1.3 0.67	0.98 0.6	0.51	0.32	1.3	0.82	0.34	0.46	0.81 0.85	0.72	NA NA	NA NA
1	T2-BB2-McPa T2-BB2-McPb	5.5 6.5	4.6	1.8 1.2	1.3 0.69	0.48	0.41	1	0.88	0.74 0.29	0.52	0.98	0.49	NA NA	NA NA
Sulfate	T2-BB2-McPc MCP	5.8 1590	2 1760	0.73	0.81	0.37	0.47	0.92	0.79	0.35	0.39	0.87	0.47	NA 1560	NA 995
(mg/L)	T2-C-McPa T2-BB1-McPa	1680 536	1860	1580	1800	1740	1570 308	NA 1190	NA 1580	NA 1270	NA	NA 1120	1540	NA 1270	NA 1060
	T2-BB1-McPb	631	86.5	604	460	876	1260	1360	1970	1390	1348	1170	1420	NA	NA
1	T2-BB2-McPa	290	19.4	383	302	943	1090	1330	1890	1360	1348	1050	1400	NA	NA
	T2-BB2-McPb T2-BB2-McPc	290 285	119 576	668 920	559	1010 1160	1330 1470	1400 1550	1850 1710	1380 1400	1360 1424	1140 1140	1490 1570	NA NA	NA NA
Total Organic															
Carbon (TOC)	T2-C-McPa	999	7.7	6	5.6	6.1	5.9	NA	NA	NA	NA	NA	1.1	NA	NA
(mg/L)	12-BB1-McPa T2-BB1-McPb	3130 3330	3230 3320	3000 828	1690 244	734 32	457 13.6	24.2 10.5	18.3 10.1	17.7 7.4	13.3 5.2	11.5 7.8	9.5 6.2	11.9 NA	8.4 NA
1	T2-BB1-McPc T2-BB2-McPa	3790 3750	759 3640	218 1680	136 685	12.7 50.9	9.7 34.2	6.5 15	4.5 17.8	4.2 18.4	2.9 7.5	4.2 5.3	3.1 5.3	NA NA	NA NA
1	T2-BB2-McPb T2-BB2-McPc	4050	2820	687 360	303 138	28.9 19.4	18.2	12.2	12.1	8.4	5.8	9.3 7	3.7	NA NA	NA NA
Zinc (Dissolved)	MCP	7650	7870	7690	7500	8530	8190	8010	7880	7960	7430	7350	7360	7880	9780
(ug/L)	T2-C-McPa	8400	8300	8400	7790	8100	7950	NA	NA	NA	NA	NA 2.2	7810	NA	NA
	T2-BB1-McPb	18	38	12.7	8.4	7.2	3.5	5.2	2.3	2.3	2.3	2.3	2.3	NA	NA
1	T2-BB1-McPc T2-BB2-McPa	17.2	21.1 29.3	8.5 19.6	13 18.4	2.3	25 5.1	2.9 4.8	2.3	2.3	2.3	2.3	2.3	NA	NA
			45.0	11.9	14.1	4.4	3.8	54	23	23	22	23	2.2		NA
	T2-BB2-McPb T2-BB2-McPc	26 12.4	25.2	12.6	13	2.8	5.8	3.8	2.3	2.3	2.3	2.3	2.3	NA	NA
	T2-BB2-McPb T2-BB2-McPc	26 12.4	45.2	12.6	13	2.8	5.8	3.8	2.3	2.3	2.3	2.3	2.3	NA	NA
Notes:	T2-BB2-McPb T2-BB2-McPc	26 12.4 hat trial an	40.2 25.2 d date	12.6	13	2.8	5.8	3.8	2.3	2.3	2.3	2.3	2.3	NA	NA

Table 5

TOTAL METALS LOADING in moles/day/m³

	18-Jul	22-Jul	29-Jul	9-Aug	7-Sep	4-Oct	2-Nov	27- Nov	7-Dec	20- Dec	4-Jan	16- Jan	24- Jan	31- Jan
Influent (moles/L)	0.0078	0.0080	0.0080	0.0078	0.0085	0.0083	0.0078	0.0076	0.0057	0.0075	0.0074	0.0080	0.0055	0.0036
T2-BB1-McPa	0.39	0.39	0.41	0.38	0.44	0.42	0.44	0.38	0.29	0.38	0.38	0.40	0.31	0.20
T2-BB1-McPb	0.74	0.74	0.78	0.75	0.82	0.80	0.76	0.74	0.55	0.73	0.70	0.75	NA	NA
T2-BB1-McPc	1.46	1.37	1.44	1.43	1.59	1.59	1.47	1.48	0.67	1.44	1.19	1.04	NA	NA
T2-BB2-McPa	0.45	0.45	0.46	0.44	0.48	0.48	0.43	0.43	0.34	0.44	0.43	0.47	NA	NA
T2-BB2-McPb	0.80	0.80	0.82	0.79	0.85	0.83	0.76	0.77	0.58	0.76	0.75	0.81	NA	NA
T2-BB2-McPc	1.48	1.44	1.61	1.49	1.58	1.56	1.45	1.42	1.07	1.39	1.28	1.28	NA	NA
T2-C-McPa	0.39	0.40	0.40	0.39	0.44	0.43	0.40	0.37	0.28	0.35	0.32	0.32	NA	NA

TARGET: $0.3 \text{ moles/day/m}^3$, $0.6 \text{ moles/day/m}^3$, $1.2 \text{ moles/day/m}^3$ RESULTS: $0.2 \text{ moles/day/m}^3$, to $1.6 \text{ moles/day/m}^3$

Table 6

Sulfate Concentration- mg/L and

Trial/Unit	18-Jul	22-Jul	29- Jul	9-Aug	7-Sep	4-Oct	2-Nov	27- Nov	7-Dec	20- Dec	4-Jan	16- Jan	24- Jan	31- Jan	Avg.
MCP	1590	1760	1600	1610	1650	1750	1670	1450	1280	1560	1510	1640	1560	995	1545
T2-BB1-McPa	536	227	13.8	57.3	103	308	1190	1580	1270	1232	1120	1260	1270	1060	
	0.62	0.88	0.95	0.89	0.92	0.86	0.32	-0.07	0.01	0.19	0.23	0.22	0.17	-0.04	0.44
T2-BB1-McPb	631	86.5	604	460	876	1260	1360	1970	1390	1348	1170	1420	NA	NA	
	1.05	1.79	1.13	1.29	0.87	0.55	0.35	-0.58	-0.12	0.24	0.38	0.24	NA	NA	0.60
T2-BB1-McPc	295	828	1050	518	1180	1520	1620	1670	1410	1460	1200	1540	NA	NA	
	2.80	1.86	1.15	2.33	1.02	0.51	0.11	-0.50	-0.18	0.22	0.58	0.15	NA	NA	0.84
T2-BB2-McPa	273	19.4	383	302	943	1090	1330	1890	1360	1348	1050	1400	NA	NA	
	0.88	1.14	0.82	0.85	0.46	0.44	0.22	-0.29	-0.05	0.14	0.31	0.16	NA	NA	0.42
T2-BB2-McPb	290	119	668	559	1010	1330	1400	1850	1380	1360	1140	1490	NA	NA	
	1.55	1.91	1.11	1.24	0.74	0.49	0.31	-0.47	-0.12	0.24	0.44	0.18	NA	NA	0.63
T2-BB2-McPc	285	576	920	0	1160	1470	1550	1710	1400	1424	1140	1570	NA	NA	
	2.86	2.48	1.59	3.59	1.06	0.61	0.26	-0.56	-0.26	0.29	0.74	0.13	NA	NA	1.07
T2-C-McPa	1680	1860	1580	1800	1740	1570	NA	NA	NA	NA	NA	1540	NA	NA	
	-0.05	-0.06	0.01	-0.11	-0.05	0.11	NA	NA	NA	NA	NA	0.05	NA	NA	-0.02

REMOVAL in moles/day/m³

