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March 13, 2013
133-20192-13004, Task 100

TECHNICAL MEMORANDUM

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U.S. Forest Service – Gallatin National Forest

FROM: H. C. Liang, James Maus, Kirk Miller - Tetra Tech, Inc.

SUBJECT: Final - Beal Mountain Mine Heap Leach Pad and Treatment Chemical Modeling - Contract AG-0343-B-12-0002

Background

The Beal Mountain reverse osmosis (RO) water treatment facility has been operated seasonally since 2008 to treat the heap leach pad water to a suitable quality for discharge. Because the RO reject has been recycled back to the heap leach pad since operations began, there is concern that a buildup of ions could lead to future operational problems, such as increasing scaling potential that would decrease the operational efficiency in the RO unit and prevent the water treatment facility from discharging the necessary amount of water or increasing contaminant concentrations that may lead to violations of discharge standards. Because of these concerns, detailed chemical modeling using the U.S. Geological Survey software PHREEQC was conducted to predict potential rises in major ion and trace metal concentrations from continued operation of the RO water treatment facility at Beal Mountain where the RO reject is recycled back to the leach pad. Data collected on the Beal Mountain heap leach pad, particularly data collected in 2012, after the heap leach cap at Beal Mountain was repaired and less recharge occurred from 2011 to 2012, were used in the chemical modeling work. Data from the water quality modeling was analyzed to determine potential impacts on RO recoveries and operability and on the treated effluent water quality from recycling the RO reject and decreasing the water volume in the heap leach pad.

Water Quality Modeling Activities

The water quality modeling was conducted in the following order:

1) Existing RO influent, effluent, and reject data were analyzed, and mass balance calculations using the spreadsheet Excel were conducted on the major ions, including ions that could lead to scaling on the RO membranes, such as calcium and sulfate, and on trace ions that are a concern for discharge water quality. These calculations were used to determine the mass balance flow in the system and to calculate historical removal efficiencies in the RO facility to use as a basis for the next steps in the chemical modeling. The data are shown in **Appendix A**.

2) The mass balance flows and removal efficiencies determined in the previous phase of the modeling were used to set up calculations of mass balances to model future water treatment activities at Beal Mountain, where it was assumed that 16 million gallons (MG) of fresh recharge water would be added to the leach pad over the winter months. The volume of 16 MG was derived from site data for the period November 2011 through November 2012 (i.e., after cap repairs made). It was also assumed that the recharge water would be pure water and would not add to the overall mass of ions in the leach pad. Using these assumptions, various scenarios of treating different amounts of water from the leach pad per 124-day operating season were calculated using an iterative process. Because the 16 MG of water has been assumed to be pure water, and because the modeling assumed that the only constituents that would be leaving the leach pad would be through the RO permeate, results of the modeling would not change significantly based on the timing of the input volume. The RO reject was modeled to mix totally with the water in the heap as a realistic worst-case scenario. If total mixing does not occur, then the RO influent should be of slightly better water quality (i.e. – lower concentrations of most constituents) than that modeled. Another assumption was that none of the water has been modeled as drain down.

3) In modeling future water quality, after each mass balance calculation, PHREEQC chemical modeling software was used to estimate the ions that would precipitate or dissolve. For example, in estimating the calcium and sulfate concentrations after recharge over the winter, a straight mass balance calculation was first performed in Excel. Then PHREEQC was used to model precipitation or dissolution of solids. An example is that PHREEQC was programmed to model the diluted water from the recharge equilibrating with solid gypsum in the leach pad to generate more realistic concentrations for calcium and sulfate. To model decreasing the volume of the leach pad over a treatment season, PHREEQC was programmed to allow for over-saturated species such as gypsum to precipitate. However, an important assumption was made to allow gypsum to dissolve to ~140% saturation during recharge and to precipitate at ~180% saturation when the leach pad's volume decreased to near its annual minimum volume at the end of the treatment season instead of using the standard 100% saturation value. These higher numbers were empirically derived based on analyzing historical data at Beal Mountain. It is thought that the gypsum saturation levels are significantly higher than 100% due to antiscalant buildup in the leach pad from recycling RO reject. This point will be discussed and elaborated in further detail below. The modeled data from this step are in **Appendix B**. Data from the PHREEQC chemical modeling are included in **Appendix C-1** through **C-10**.

4) After estimating the predicted water quality from future operations, historical contaminant removal efficiencies were used to calculate the expected RO effluent water quality, and values over the discharge limits were flagged as potential issues. These data are in **Appendix B**.

5) The RO antiscalant software Avista Advisor was used to estimate the likely impact of projected future ion concentrations on the recovery of the RO water treatment system when Vitec 7000 antiscalant, the antiscalant currently used at Beal Mountain, is applied to mitigate scaling. Other antiscalants, such as Vitec 1000, Vitec 2000, Vitec 3000, Vitec 4000, Vitec 5100, were also examined. However, out of these antiscalants, Vitec 7000 performs best in mitigating calcium sulfate scaling.

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Major Findings

Amount of Water Discharged and Ending Leach Pad Volume per Season Will Likely be Limited by Selenium Effluent Quality

Using the methods and assumptions outlined above, iterative modeling calculations were conducted to determine the volume of water that could be discharged from the leach pad without surpassing discharge standards for contaminants other than ammonia. Ammonia was allowed to exceed the discharge limit in the modeling work because there are other mechanisms for treating ammonia in the current treatment configuration at Beal Mountain, and higher ammonia concentrations will not lead to scaling issues for the RO membranes or decrease the RO recoveries.

For 2013, it was found that the Beal Mountain treatment facility would theoretically be able to process approximately 33.3 MG of water and discharge up to 20 MG of treated leach pad water, resulting in ~6.5 MG of water remaining in the leach pad, without running into major issues with scaling or with contaminants other than ammonia exceeding the discharge standards. The selenium effluent concentration would be close to the limit of 0.005 mg/L by this point, however. These estimates assumed that there would be 16 MG of recharge (current worst case scenario to result in higher concentrations), the total volume of the leach pad would be approximately 26.5 MG, and RO recoveries remain at approximately 60%. Under these assumptions,selenium was found to be the contaminant of concern that would likely go over the discharge limit if 16 MG or less recharge occurred and more than 20 MG of treated water is discharged in 2013. Furthermore subsequent modeling results showed that selenium would be the contaminant of concern that will keep the operations from being able to lower the volume of the leach pad to much below 7.5 MG over time (Table 1).

It is important to note, however, that the RO system is assumed to continue operateing at historical removal efficiencies for selenium and other contaminants. Because the total dissolved solids (TDS) is modeled to go up to approximately 14,000 mg/L as the level of the leach pad is drawn down to 6.5 MG and will hover around 12,000 mg/L when the volume of the pad is around 7.5 MG (in 2014 and 2015), these higher TDS levels compared to historical values of up to ~9,300 mg/L could lead to lower removal efficiencies of selenium and other contaminants due to the associated increase in the ionic strength of the water (Bartels et al., 2005). This is one of the data gaps in the study, in which it is unknown how well the RO will continue to reject ions at TDS levels anticipated in the future. The unknown effect of how much the higher TDS levels will negatively impact the ion rejection in the future is one of the key data gaps in being able to accurately predict whether treating down to 7.5 MG on a consistent basis in the leach pad is viable.

Table 1 presents chemical modeling results assuming 16 MG recharge per year into the Beal Mountain leach pad (major ions, potential scaling components, and contaminants of concern displayed). Volume of treated water discharged per season was determined iteratively by the maximum volume discharged above which a discharge standard would be violated based on calculations.

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Table 1. Predicted Chemical Model Results

	June 2013 Influent	October 2013 Influent	October 2013 Effluent	June 2014 Influent	October 2014 Influent	October 2014 Effluent	June 2015 Influent	October 2015 Influent	October 2015 Effluent
Volume Discharged (Volume Left in Leach Pad (MG))	0 (26.5)	20 (6.5)	20 (6.5)	0 (22.5)	15 (7.5)	15 (7.5)	0 (23.5)	16 (7.5)	16 (7.5)
pH (s.u.)	8.0	8.0	9.0	8.0	8.0	9.0	8.0	8.0	9.0
TDS (mg/L)	5,150	14,050	62	5,550	12,100	53	5,450	12,200	54
Total Alkalinity (mg/L as $CaCO_3$)	51	179	29	57	161	26	56	165	26
Arsenic (mg/L)	0.175	0.712	0.003	0.206	0.617	0.002	0.197	0.616	0.002
Chloride (mg/L)	324	1,318	6	381	1,141	5	364	1,139	5
Cyanide, Total (mg/L)	2.4	9.8	0.1	3.0	9.0	0.0	2.9	9.1	0.0
Cyanide, WAD (mg/L)	0.24	0.95	0.04	0.28	0.82	0.03	0.26	0.80	0.03
Fluoride (mg/L)	0.30	1.09	0.33	0.30	0.80	0.24	0.30	0.83	0.25
Nitrite-N (mg/L)	10.8	43.7	0.8	12.6	37.5	0.7	12.0	37.2	0.7
Nitrate and Nitrite-N (mg/L)	71	287	7	83	247	6	79	245	6
Phosphorus (mg/L)	0.05	0.19	0.04	0.05	0.14	0.03	0.05	0.14	0.03
Selenium (mg/L)	0.1320	0.4600	0.0047	0.1600	0.4780	0.0049	0.1500	0.4680	0.0048
Silica (mg/L)	3.7	3.6	0.1	3.7	3.6	0.1	3.7	3.6	0.1
Sulfate (mg/L)	2,782	6,421	4	2,816	5,340	3	2,805	5,451	3
Aluminum (mg/L)	0.028	0.002	0.000	0.030	0.002	0.000	0.030	0.002	0.000
Ammonia-N (mg/L)	13	50	6	15	43	5	14	42	5
Barium (mg/L)	0.003	0.002	0.002	0.003	0.003	0.003	0.003	0.002	0.002
Calcium (mg/L)	712	740	1	726	796	1	722	785	1
Iron (mg/L)	1	1	0	1	1	0	1	1	0
Magnesium (mg/L)	15	61	1	18	54	1	17	53	1
Manganese (mg/L)	0.070	0.280	0.005	0.080	0.240	0.004	0.080	0.250	0.004
Molybdenum (mg/L)	0.2	0.6	0.0	0.2	0.6	0.0	0.2	0.6	0.0
Potassium (mg/L)	17	68	3	20	58	3	18	55	3
Sodium (mg/L)	939	3,817	27	1,103	3,300	23	1,053	3,291	23
Strontium (mg/L)	3.8	8.3	0.0	3.8	9.1	0.0	3.8	9.0	0.0

As can be seen from Table 1, modeling for 2014 used the results from assuming treating the heap leach pad down to 6.5 MG in 2013 and again assumed 16 MG of recharge water. It was estimated that approximately 15 MG of water can be discharged in 2014, down to a heap leach pad volume of 7.5 MG. The same was found for 2015.

The results are consistent with the modeling assumptions that the only way for contaminants to permanently leave the heap leach pad system is through the RO permeate discharge. And because the two-pass RO system at Beal Mountain has historically rejected ~99% of most ions, this means that for all practical purposes, recycling the RO reject back to the Beal Mountain heap leach pad results in simply recycling constituents back into the leach pad water. Under this scenario, the concentrations of the ions are controlled mostly by the volume of the leach pad and the associated equilibria of relevant solids precipitating as they become supersaturated and of deposited solids dissolving as the water becomes undersaturated with respect to particular constituents, such as gypsum, when fresh recharge water is added to the heap leach pad over the winter months. In short, results from the chemical modeling analyses conducted suggest that the major controlling factor in ion concentrations in the Beal Mountain heap leach pad is the volume of water, and that selenium will likely be the limiting factor in allowing the leach pad volume to be decreased to below 7 MG over time under current operational practices.

One possible way to address the future potential of exceeding the selenium and other contaminant concentrations in the RO permeate due to higher TDS in the heap leach pad water is to conduct bench scale testing to simulate increasing TDS levels. The testing can be done using a flat sheet membrane RO bench scale testing rig and using simulated waters that can be made by taking RO reject from the Beal Mountain and diluting it at different blending ratios with deionized water to simulate various TDS levels. Then the simulated waters can be treated through the RO bench scale testing rig to see how changes in TDS impact the removal efficiencies.

Likely Impact of Calcium and Sulfate Buildup on RO Recoveries

Results from the modeling (Table 1) were used to estimate RO recoveries at the extremes of when the volume in the leach pad would be the lowest and the calcium and sulfate concentrations would be highest. All results showed theoretical RO recoveries of at least 59% using Vitec 7000, the antiscalant currently used at Beal Mountain (**Figure 1**):

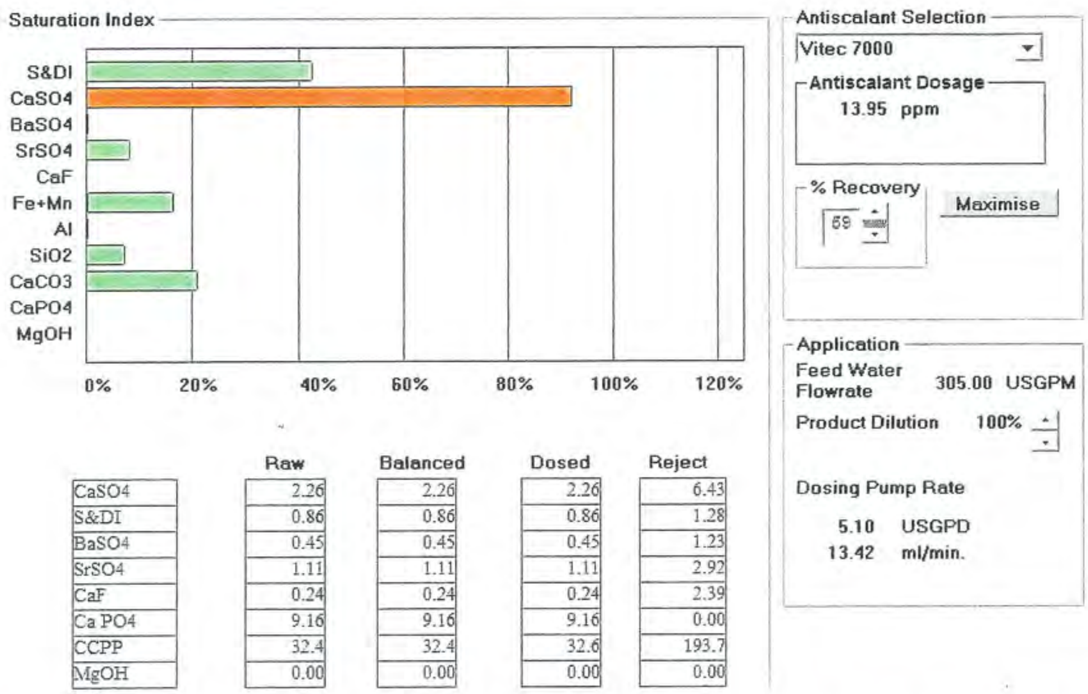

Figure 1. RO recovery projection using data from modeled October 2013 influent where 6.5 MG of volume would be left in the leach pad (**Table 1**)

The reason why the projected recovery does not decrease significantly even with increasing calcium and sulfate levels can be attributed to the fact that at higher TDS concentrations, the associated higher ionic strength of the water leads to lower activity coefficients for ions and higher solubilities for gypsum so that the saturation level for gypsum does not go up by much even as the concentrations of calcium and sulfate increase.

As stated above, though, a data gap is that the modeling work was conducted assuming 140% saturation levels of gypsum in the leach pad at the beginning of the season, after maximum recharge, and 180% saturation towards the end of the season. These numbers were based on historical trends derived from empirical observations of the gypsum saturation levels in the heap leach pad (**Figure 2**). The % saturation of gypsum at the various RO influent conditions was calculated using PHREEQC. Data from the PHREEQC modeling to calculate the historical % saturation of gypsum in the RO influent are in **Appendix D**, where PHREEQC was used to calculate the saturation index SI. From the SI, Excel was used to calculate the % saturation based on the relationship of $SI = \log(IAP/K_{sp})$, where IAP stands for ion-activity product and K_{sp} stands for solubility product constant.

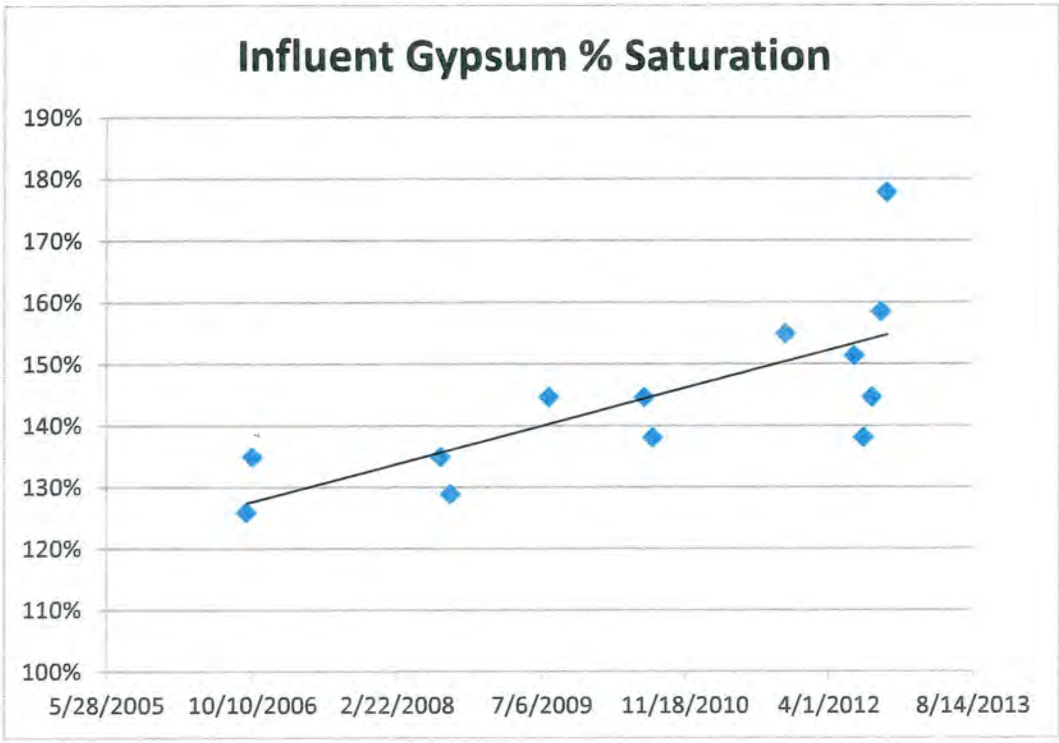

Figure 2. Rising influent gypsum % saturation at Beal Mountain RO Water Treatment Facility (Blue diamond data points correspond to calculated influent gypsum % saturation values at given dates)

In theory, the saturation level of gypsum in the Beal Mountain leach pad should remain relatively steady, near 100%. The escalation of the influent gypsum saturation level is consistent with the fact that antiscalant has been added to the leach pad over time. And it is likely that the antiscalant concentrations are building up because they are being added faster than they can be degraded in the heap leach pad. Typically, organic polymer anticalants can be broken down over time given sufficient exposure to sunlight, heat, or oxidant. It is possible that because of the high altitude and long winters at Beal Mountain, the lack of exposure to sunlight and the low temperature of the leach pad water are not conducive to promoting the degradation of the antiscalants and that increasing antiscalant concentrations can lead to increasing saturation levels of gypsum and other substances in the water.

If the gypsum saturation levels continue to rise, the increasing calcium and sulfate concentrations may lead to lower RO recoveries down the road. However, if only 16 MG of water needs to be removed from the leach pad every year, decreased RO recoveries may not be a big issue. To discharge 16 MG over 124 days would require approximately 90 gpm of effluent. With an influent capacity of 305 gpm at the Beal Mountain treatment facility, that would only require a recovery of 30%. To discharge 20 MG would require 112 gpm treated water or 37% recovery, and to discharge 25 MG would require 140 gpm treated water or 46% recovery. Although operating the RO treatment facility at such low recoveries would not be efficient, it would still likely meet the required discharge water balance without harming the RO membranes with scaling as long as recharge per year is kept to approximately 25 MG or less.

Besides using historical trending data, such as shown in Figure 2, a better way to predict how the recycling of the antiscalant would impact calcium sulfate scaling in the future may be to devise a way to analyze and quantify the concentration of the antiscalant in the heap leach pad and work with the antiscalant manufacturer to calculate the impact of its increase in concentration on calcium sulfate solubility and hence gypsum percent saturation in the heap leach pad.

Additional Treatment Technologies

Because the chemical modeling work shows that the Beal Mountain RO water treatment facility can likely be operated under existing conditions until the heap leach volume reaches approximately 7 MG, no additional treatment technologies are proposed.

However, as identified above, one potential data gap is the fact that selenium removal efficiencies may decrease due to higher influent TDS to a point where the treated water will not meet the selenium discharge standard of 0.005 mg/L at a lower leach pad volume than 7 MG. If that is the case, or if the U.S. Forest Service desires to examine additional treatment technologies that will allow the leach pad to be treated to much lower volumes than 7 MG, then one possible treatment technology to examine is biological selenium removal of the RO reject before returning the reject stream to the leach pad. The biological treatment will not only permanently remove selenium (as solid elemental selenium in the sludge) from the system, it will also remove ammonia, nitrite, and nitrate.

Another potential issue that has been identified and stated above is the fact that the gypsum saturation level may continue to rise in the heap leach due to buildup of antiscalant. It is not likely that the decreasing RO recoveries associated with this phenomenon will have a major impact on the water balance of the Beal Mountain heap leach pad now that less recharge is expected per year. If it does become an issue that needs to be addressed, then a potential additional treatment technology would be to use hydrated lime and/or oxidant treatment of the RO reject stream to remove or destroy the antiscalant. As the antiscalant is destroyed, the primarily calcium and sulfate dissolved solids in the RO reject stream can be precipitated using a solids recycling clarifier so that not only is antiscalant removed and prevented from going into the leach pad, but gypsum can be removed from the system as precipitated sludge.

Summary

Water quality modeling using historical data from Beal Mountain utilizing the chemical modeling program PHREEQC was conducted to predict potential rises in major ion and trace metal concentrations from continued operation of the RO water treatment facility at Beal Mountain such that the RO reject is recycled back to the heap leach pad. It was found that under the assumptions used in the modeling, the volume in the heap leach could be treated down to approximately 7.5 MG without going over any discharge limits, except for ammonia, and that selenium would be the limiting contaminant of concern under such a scenario. The water quality modeling also indicated minimal decreasing RO recoveries due to increasing calcium and sulfate concentrations. Another reason why decreasing RO recoveries are not likely to be a concern is that less water per year will need to be removed in the future now that the heap leach pad cap has been repaired and less recharge water is expected per year.

Two unknowns were identified that may cause the actual results from future RO water treatment operations at Beal Mountain to differ significantly from the chemical modeling predictions. One of these unknowns is how the projected increasing TDS from reducing the volume of the leach pad will reduce the contaminant rejection efficiencies of the RO membranes. If there are significant reductions in RO rejection efficiencies as a result of the increasing TDS levels, then reducing the leach pad volume to near 7.5 MG may not be feasible. The second unknown is whether and how much the gypsum saturation level will continue to increase in the leach pad as a result of increasing antiscalant concentrations from recycling RO reject back to the leach pad. If the gypsum saturation continues to rise, the RO recoveries will decrease, which alone may not negatively impact the water balance at Beal Mountain. However, if recharge levels become much higher than 25 MG in the future, then decreases in RO recoveries may negatively impact the ability to dewater the leach pad at sufficient rates. The reason why increasing gypsum saturation levels may negatively impact the RO recoveries is because there is an upper limit to the gypsum saturation level at which antiscalants can protect the RO membranes. The conservative value cited in many RO text books is that with the use of antiscalants, the gypsum saturation in the RO *reject stream* may be able to go up to ~240% saturation without significant scaling and harming of the membranes (Wilf, 2007). So if the gypsum saturation levels in the leach pad (i.e. - RO influent stream) continues to rise, the RO recovery that is possible without going over ~240% gypsum saturation may become lower than the current ~60% recovery.

Reference

Bartels, C. Franks, R. Rybar, S. Schierach, M. Wilf, M. (2005), "The Effect of Feed Ionic Strength on Salt Passage Through Reverse Osmosis Membranes." *Desalination*, ***184***, 185-195.

Wilf, M. *The Guidebook to Membrane Desalination Technology, Balaban Desalination Publications*, L'Aquila, Italy, 2007.