



To: Barbara Miller
(Ameren Missouri)

Date: January 6, 2022

From: XDD (DRAFT)

cc: Michael Marley (XDD)

RE: Sioux Treatability Memo
Sioux Energy Center
8501 MO-94, West Alton, MO

1.0 INTRODUCTION

XDD Environmental (XDD) was retained by Ameren Missouri (Ameren) to perform a metals treatability study for the remediation of metals of concern (MOC) from ash pond groundwater at the Sioux Energy Center (SEC) in West Alton, MO. Groundwater is currently monitored as required by the United States Environmental Protection Agency (USEPA) in 40 CFR Part 257 "Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities; Final Rule" (the CCR Rule), the facility's NPDES permit (No MO-000043), and the facilities UIC permit (UI-0000043). Groundwater is analyzed for metals via EPA Methods 200.7 and 200.8, alkalinity via SM Method 2320B, total dissolved solids via SM Method 2450C, ferric and ferrous iron via SM Method 3500, anions via EPA Method 300, and phosphorous via EPA Method 365.4. Based on statistical analysis, elevated levels of molybdenum exceed the site-specific groundwater protection standard (GWPS) established under the CCR Rule at SEC.

While metals cannot be destroyed, they can be susceptible to treatment and undergo changes in form to become either (a) less soluble; or (b) more sorbent and bind to particle surfaces. Both methods involve the physical removal of metals from the dissolved state (a very mobile state) to either a solid state or an adsorbed state. The three primary approaches for metals removal from groundwater are:

- Precipitation: Transformation of a dissolved species to a solid form, which can then settle out of suspension.
- Co-precipitation with other minerals: Transformation of a dissolved species to a solid form that combines with another material (such as iron), which can then settle out of suspension.
- Adsorption: Introduction or production of a solid that will absorb the MOC from the groundwater.

Where multiple metals are present, there is a potential that one metal can inadvertently affect

other metal(s) either positively (reduced dissolved concentration) or negatively (increased dissolved concentration). Therefore, a treatment chain consisting of a sequence of multiple technologies is often needed to address all metals of concern at a site. The focus of this study is on MOC which have regulatory action levels exceeded at SEC ash pond.

Due to the fluctuation of groundwater flow directions at SEC and the slow groundwater velocity, the treatment objective for SEC is to create hydraulic controls where groundwater is extracted along the border of the ash pond to capture and contain the groundwater MOC plume. The water will then be treated above ground and reinjected between the extraction wells to create a hydraulic control that will minimize the extraction rate, maintain natural hydraulic flow, and prevent further migration of MOC from the ash pond groundwater.

Since the treated water will be injected into the extracted aquifer for hydraulic control, the treated water also will be required to meet groundwater permit levels for compounds such as sulfate and boron, as well as molybdenum, which currently exceed permit discharge levels. The primary MOC at SEC is molybdenum.

This memo will address the treatability work performed for SEC groundwater to remove molybdenum along with an evaluation of sulfate and boron removal to meet the discharge permit levels. The treatability lab testing for SEC was done in parallel with the treatability studies performed for two other Ameren sites; Labadie Energy Center (LEC) and Rush Island Energy Center (RIEC). All three sites have overlap on treatment objectives, MOC, and similar water chemistry; therefore, promising results at one site were used to guide treatment at the other two sites.

Preliminary evaluations focused on in-situ treatment options; however, due to concerns of precipitation clogging pore space thereby affecting subsurface flow conditions, along with the lack of available in-situ options for removing or stabilizing boron, the focus transitioned to ex-situ treatment options. This memo will focus on the ex-situ treatment options only. The findings presented will focus on SEC but will include relevant results obtained from treatability tests from LEC and RIEC.

2.0 TREATABILITY OBJECTIVE

The focus of the treatability study is to remove the site MOC so that the water will meet the groundwater permit discharge levels. This will allow safe injection of the treated groundwater back into the aquifer from which it was extracted. For SEC, the proposed treatment system must address molybdenum, sulfate, and boron. The target discharge permit levels for these compounds are:

- molybdenum = 100 micrograms per liter ($\mu\text{g/L}$)
- sulfate = 250,000 $\mu\text{g/L}$
- boron = 2,000 $\mu\text{g/L}$

This memo will summarize the tests performed to address each compound, conditions under which each method was tested, how successful each remedial option was shown to be, and recommendations for full scale implementation.

2.1 Molybdenum

Groundwater samples collected from SEC for the treatability test showed molybdenum concentrations to be over 10 times greater than the target discharge limit. Preliminary treatability work performed on groundwater from RIEC determined that processes shown to treat arsenic were also successful at removing molybdenum. The methods developed for arsenic and molybdenum removal at RIEC were tested on SEC and found to be affected at treating molybdenum at SEC.

Tests were performed using RIEC water for precipitation of molybdenum at a pH of 5, filtering the water through zero valent iron (ZVI) columns, pH adjustment followed by ferric chloride (FeCl_3) precipitation, and pH adjustment followed by FeCl_3 and oxidative (hydrogen peroxide) precipitation. Results are discussed below. Confirmation testing of RIEC best treatment option was performed on SEC water. It was determined that the pH adjustment using hydrochloric acid (HCl) followed by FeCl_3 could transform the dissolved molybdenum to solid iron-molybdenum but that the solid particles formed would not settle within a reasonable timeframe for treatment. Additional tests were performed on SEC water to aid in the precipitation process and is discussed below in Section 2.1.4.

2.1.1 pH adjustment

The pH adjustment process involved adjusting the pH of RIEC water to 5 using HCl followed by flow through a sand filter than a SIR-150 boron resin filter (see Section 2.2 for more information on SIR-150). Since the resin is specially designed for boron removal and it is not desirable to have the resin capacity exacerbated with high concentrations of other groundwater constituents, samples were collected prior to the resin to determine the effects of the pH adjustment on molybdenum treatment (**Table 1, Test M-1**).

Groundwater samples collected between the sand filter and the resin columns showed that the pH adjustment followed by sand filtration did not effectively remove the molybdenum in the groundwater to the discharge permit levels (**Table 1, Test M-1**). A further review of the data and the procedures used in this test suggests that, for pH adjustment to be successful for removing molybdenum from RIEC groundwater, the groundwater needs to be maintained at a reduced pH for longer than 40 minutes (the residence time in the sand filter tested columns). Hence, pH adjustment alone would not be a viable ex-situ remedial approach.

2.1.2 ZVI Columns

Iron can precipitate molybdenum as a low-solubility iron-molybdenum. To test the feasibility of using a ZVI column to remove molybdenum ex-situ, test columns were constructed using a mixture of the microscale ZVI and commercial sand. Microscale ZVI was tested due to its highly reactive surface and increased potential to remove molybdenum. The sand was added to allow the required flow through the ZVI column without clogging due to the microscale ZVI particle size. The columns were prepared using a 5:1 and 2:1 ratios of sand to microscale ZVI. The columns were operated for 7 days, with effluent groundwater samples collected from the column after 1, 3, and 7 days of flow.

The Day 7 results are shown on **Table 1 Test M-2** (5:1 sand to ZVI ratio) and **M-3** (2:1 sand to ZVI ratio). The results show partial removal of molybdenum, though not to action levels. Boron concentrations did not change passing through the ZVI columns though research suggested there may be a reduction. It was concluded that the ZVI removal effectiveness (at the design sand to ZVI dosages) was questionable, and likely not reliable as a sustainable remedial option.

2.1.3 Ferric Chloride Co-Precipitation

The ex-situ remediation method that proved most successful and reliable for molybdenum treatment of groundwater is pH adjusted followed by FeCl₃ aided flocculation. Preliminary testing with the ZVI and pH adjustment, discussed above, helped guide the design of the FeCl₃ treatment train.

FeCl₃ testing was performed to determine reaction time needed (**Table 1 Tests M-4 to M-12**), optimal pH ranges (**Table 1 Tests M-7 to M-12**), optimal FeCl₃ dosage (**Table 1 tests M-4 to M-9**), and if oxidation through hydrogen peroxide addition could increase performance (**Table test M-13**) for RIEC water. A summary of the finding are:

- Molybdenum can be reduced to concentrations at or below action levels, using FeCl₃ addition.
- An initial pH of 6 (prior to the addition of FeCl₃) caused faster settling of the precipitants than an initial pH of 4.
- Higher FeCl₃ dosage (40 mg/L vs. 20 mg/L) provided greater removal of arsenic and molybdenum.
- The additional of hydrogen peroxide hindered molybdenum removal efficiency.

The reaction time determined for the FeCl₃ coagulation and flocculation/precipitation and associated removal of molybdenum from groundwater in the preliminary testing using RIEC groundwater was adequate for the conceptual ex-situ remedial approach (an hour or less).

Confirmation testing using SEC water showed that:

- 40 mg/L of FeCl₃ was insufficient to reach discharge limits for molybdenum (**Table 1 Test M-14**)
 - For SEC, 80 mg/L FeCl₃ is required to meet molybdenum discharge limits (**Table 1 Test M-15**).
- The dissolved concentrations of molybdenum were significantly lower than the total molybdenum concentrations using the pH 6 adjustment followed by FeCl₃ addition method established for RIEC (**Table 1 Tests M-14 and M-15**)
- Visually observations noted little to no settling of the pin flocs formed in SEC water after an hour.

The results of SEC confirmation testing suggested that, while the chemistry needed to remove dissolved molybdenum from the groundwater was similar between RIEC and SEC, the higher concentration of molybdenum found at SEC require a higher dose of FeCl₃ (80 mg/L as compared to 40 mg/L for RIEC) and a flocculant aid is needed to remove the total molybdenum from the suspended solid phase.

2.1.4 Coagulant Aid Testing

All coagulant aid testing was done after the water had been adjusted to a pH of 6 followed by FeCl₃ addition of 40 or 80 mg/L (except the test of the alternative coagulant). There are several approaches to increase the formation of larger flocs that can help in settling of total metals and water clarity:

- Increase alkalinity
- Shifting to another coagulant (alum instead of FeCl₃)
- Bulking agent
- Polymers

The addition of calcium hydroxide was tested to see if increasing the alkalinity of the water would increase the size of the flocculants (**Table 1 Tests M-16 to M-19**). While the 2:3 molar ratio of FeCl₃ to calcium hydroxide (**Table 1 Tests M-16 and M-17**) greatly increased the formation of flocculants, the calcium hydroxide increased the pH above the target range which resulted in the settling of the iron without the molybdenum. Testing was done adding calcium hydroxide at lower dosages which would not increase the pH much above the target range (target is a final pH of 4 after the FeCl₃ is added) (**Table 1 Tests M-18 and M-19**) but this was insufficient alkalinity to form flocs that would settle and the pH increases from 4 to pH of 5 or 6 decreased the removal of dissolved molybdenum compared to the conditions with no calcium hydroxide added.

Alum is another coagulant that may remove molybdenum from water as a lower soluble aluminum-molybdenum compound. Alum was added at 120 mg/L but had little to no effect on the molybdenum removal and no significant increase in floc formation (**Table 1 Test M-20**).

Bulking agents are often added to water to act as a nucleus on which smaller flocs can bind to and settle out. One bulking agent that is often used in water treatment systems is bentonite. Bentonite was tested as a powder form (**Table 1 Test M-21**) and as a liquid slurry form (**Table 1 Test M-22**) to look at alternative methods of application. The bentonite slurry test where 80 mg/L FeCl₃ was tested showed significant reduction in total molybdenum and had significant floc formation resulting in increased density of flocks for settling and improved water clarity. The one concern with bentonite is the difficulty in handling and maintenance of a clay in a flow through semi-automated system and dispersion of the bentonite in a water mixture.

Polymer coagulant aids are often used when flocs are too small to settle on their own. They act as a charge surface to draw solids to them and increase the density of the solids resulting in an increase rate of flocculation. Two polymers were tested; a cationic and an anionic inorganic polymer (**Table 1 Tests M-23 to M-26**). While both polymer formed large flocs that aided in water clarity and were capable of removing molybdenum, the cationic polymer resulted in the lowest molybdenum concentrations at an FeCl₃ concentration of 80 mg/L (**Table 1 Test M-26**).

Based on the coagulant aid test results and considering the ease of implementation, the cationic inorganic polymer is the recommended approach for increasing the settling of the solids from the flocculation tank (**Table 1 Tests Final 1 and Final 3**).

2.2 Boron

Resins and reverse osmosis are the primary methods used to remove boron from water sources. There is a low efficiency of treated water to wastewater using reverse osmosis, so the boron treatment has focused on resins. Three commercially available boron-removal resins were identified and tested; SIR-150, IRA-743, and PWA-10.

As discussed in Section 2.1.1, a pH of 5 adjusted water followed by a column test of the SIR-150 was tested over 7 days using RIEC water. After 7 days of passing through the column, boron concentrations were still below the detection limit of 10 ug/L (**Table 1 Test B-1**). As shown in the sample collected between pH adjustment to 5 and the resin column (**Table 1 Test M-1**), molybdenum was not treated sufficiently by the pH adjustment showing that molybdenum removed to discharge levels in **Table 1 Test B-1** is from attachment to the resin.

While the resin beds in this treatability test were designed for a 15 minute residence time, when scaling the lab test to field application flow rates, the mass of resin was much larger than would be used in a site application. In addition, these tests were performed on RIEC water where molybdenum is much lower compared to SEC water. For RIEC test, breakthrough of arsenic after 7

days suggests that, given field-sized vessels, the resin utilization would be too high without pre-treatment for molybdenum prior to resin filtration. With the high concentration of molybdenum at SEC, SEC water is likely to put a higher demand on the resin resulting in quicker breakthroughs and increased frequency of regeneration.

Subsequent testing used the procedure discussed in Section 2.1.3 prior to filtration through the resin beds. The process involved RIEC water adjusted to a pH of 6 with HCl followed by FeCl₃ (40 mg/L), settling, and sand filtration. The water was then passed through one of three columns containing SIR-150 (**Table 1 Test B-2**), IRA-743 (**Table 1 Test B-3**), or PWA-10 (**Table 1 Test B-4**). While all resins were capable of removing the boron and polishing the arsenic and molybdenum, SIR-150 showed the highest performance for sulfate removal. Additional temporal testing was performed on the SIR-150 and PWA-10 resins for sulfate removal along with surfactant coated zeolite (**Table 1 Tests B,S-1 to B,S-24**). These tests are discussed further in Section 2.3.2.

Confirmation testing of the treatment process discussed in Section 2.1.4 followed by filtration through the SIR-150 resin using SEC water was performed with results shown in **Table 1 Tests Final 2** and **Final 4** with both results showing successful treatment of molybdenum, sulfate, and boron.

2.3 Sulfate

2.3.1 Sorption and Precipitation

Sulfate can be precipitated out at high concentrations (thousands of milligrams per liter (mg/L) concentration ranges) but is difficult to reduce at lower concentrations (hundreds of mg/L concentration ranges). The primary approaches used for the lower level concentration of sulfate are reverse osmosis and resin removal. As mentioned for boron, there is a low efficiency of treated water to wastewater using reverse osmosis. The cost, maintenance, and waste stream of resins are such that it would be preferable to not rely on a second resin bed for sulfate removal which would result in a second resin waste stream. Other options discussed in literature were:

- sorption using
 - zeolite (**Table 1 Tests S-1, S-5, S-22**);
 - surfactant coated zeolite (**Table 1 Tests S-2, S-6, S-11, S-12, S-19 to S-21**);
 - sodium chloride coated zeolite (**Table 1 Tests S-3, S-7, S-9, S-10**).
- precipitation using
 - limestone (**Table 1 Tests S-4, S-8**);
 - cement (**Table 1 Tests S-13 to S-15**);
 - calcium hydroxide (**Table 1 Tests S-16 to S-18**);

- chitosan (**Table 1 Tests S-23 to S-25**);
- sodium aluminate (**Table 1 Test S-26**);
- calcium aluminate (**Table 1 Test S-27**);
- calcium aluminate cement (**Table 1 Test S-28**).

Since the success of these processes are sensitive to water quality and water chemistry (alkalinity, pH, total dissolved solids, etc.), several dosages, treatment train applications, product formulations, and pH ranges were tested to identify if there was a method for success.

Of the methods and conditions tested, none were shown to greatly reduce the sulfate concentration relative to the baseline value.

2.3.2 Resin

Based on the results of RIEC pilot study which was conducted in parallel with the sulfate portion of the lab treatability testing, approximately 20% of the influent sulfate can be removed through the FeCl_3 coagulation/flocculation process and is removed after the sand filtration. This reduction brings the sulfate concentrations at RIEC below the discharge permit levels. In addition, the pilot study showed an average of 58% reduction in sulfate between the influent and post resin treatment (**Table 1 Tests P1 to P20**).

Based on the lack of success of the options in Section 2.3.1 and the ability of the current proposed treatment train to treat RIEC sulfate concentrations to below discharge permit levels (250,000 $\mu\text{g/L}$), the best option would be to use the treatment train developed for molybdenum to decrease the sulfate concentrations and then polish the water with the boron resin.

As mentioned in Section 2.2, there were three resins identified that could remove boron and preliminary results suggested that sulfate coated zeolite could reduce sulfate. Temporal testing was performed to evaluate the longevity of two of the resins (SIR-150 and PWA-10) and the surfactant coated zeolite. Columns were constructed that were scaled to the proposed full scale vessel sizes for the lab defined flow rate and were run for 6 days. While the residence time and vessel sizing was scaled appropriately, due to water volume restraints, the surface area of vessel media to flow is an underestimate of the full scale system. Regardless, the design allowed for a comparison of the performance of the two resins and the surfactant coated zeolite. Based on the results, the SIR-150 resin (**Table 1 Tests B,S-19 to B,S-24**) outperformed the PWA-10 resin (**Table 1 Tests B,S-1 to B,S-6 and B,S-13 to B,S-18**) with lower magnitudes of breakthrough. The surfactant coated zeolite (**Table 1 Tests B,S-7 to B,S-12**) was shown to be ineffective at treatment under the design residence times.

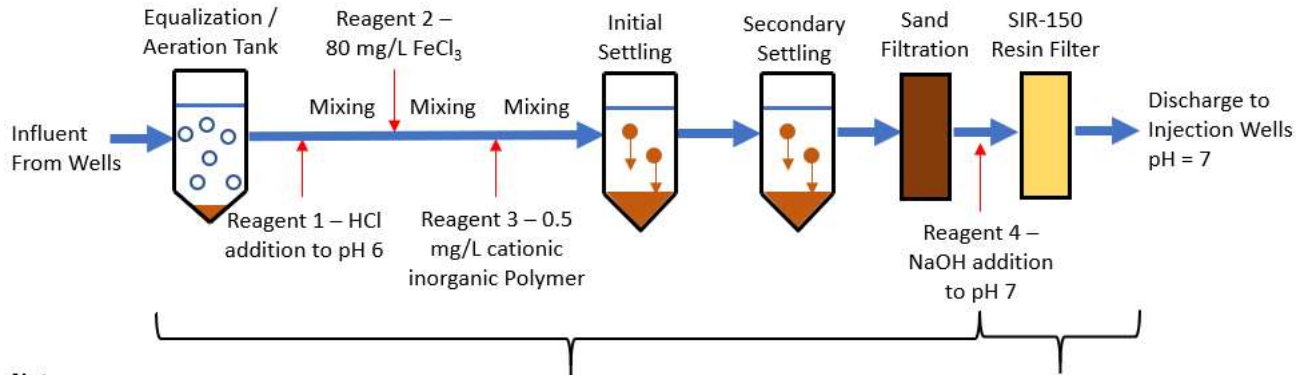
2.4 Final Design

As mentioned above, final confirmation tests were performed of SEC water to 1) confirm the treatment train process works for molybdenum, sulfate, and boron and 2) identify if cationic or anionic polymers are more successful (**Table 1 Tests Final 1 to 4**). The final treatment train process is to aerate, adjust the pH to 6 with HCl, add FeCl₃ at 80 mg/L, add the cationic inorganic polymer at 0.5 mg/L, settling, sand filter, and finally SIR-150 resin filtration. Key observations and conclusions from the treatability testing, pilot study, and additional FeCl₃ testing are:

- Aeration of the groundwater prior to the addition of FeCl₃ accelerates the formation of precipitants.
- The initial adjustment pH should be close to pH of 6 at SEC for optimal molybdenum removal.
- Higher FeCl₃ concentrations provided greater removal of dissolved molybdenum.
- SEC water requires a coagulant aid to increase the density of the iron-molybdenum flocks. The cationic inorganic polymer had higher removal of molybdenum than the anionic inorganic polymer.
- The sand filter was effective as a polishing step to reduce total molybdenum concentrations to below action levels, while also decreasing total iron concentrations.
- The resin filter is needed to remove boron from the groundwater to action levels. The SIR-150 resin performed best of those tested. The SIR-150 resin operates optimally between a pH of 4 and 10.
- While removing boron from the groundwater, the resin also acts as a polishing tool for removal of residual molybdenum and additional reduction of sulfate.

The final proposed treatment design is shown in **Figure 1** below:

Figure 1: Proposed Treatment Process



Notes:

HCl = hydrochloric acid
 FeCl₃ = ferric chloride
 NaOH = sodium hydroxide
 mg/L = milligrams per liter

Molybdenum Removal,
 Sulfate Reduction

Boron Removal, Polish
 Removal of Molybdenum
 and Sulfate

Table 1
Summary of Sioux Energy Center Treatability Testing
Sioux Energy Center, Missouri

Test Condition Reference		Molybdenum	Sulfate	Boron
		Permit Limits	100	250,000
	High Concentration Area Water	3,470	725,000	32,200
	Low Concentration Area Water	65	71,000	756
	Blended Water	1,767	398,000	16,478
Focus on Molybdenum Removal - RIEC				
M-1	Adjust water to pH of 5 - Day 7	142	NM	3,270
M-2	Zero Valent Iron Column - 5 parts sand, 1 Part ZVI - Day 7	151	NM	3,900
M-3	Zero Valent Iron Column - 2 parts sand, 1 Part ZVI - Day 7	143	NM	3,510
M-4	Adjust water to pH 6, FeCl ₃ (20 mg/L) - 1 hour reaction	20.5	NM	NM
M-5	Adjust water to pH 6, FeCl ₃ (20 mg/L) - 3 hour reaction	24.1	NM	NM
M-6	Adjust water to pH 6, FeCl ₃ (20 mg/L) - 6 hour reaction	28.3	NM	NM
M-7	Adjust water to pH 6, FeCl ₃ (40 mg/L) - 1 hour reaction	<10	NM	NM
M-8	Adjust water to pH 6, FeCl ₃ (40 mg/L) - 3 hour reaction	<10	NM	NM
M-9	Adjust water to pH 6, FeCl ₃ (40 mg/L) - 6 hour reaction	<10	NM	NM
M-10	Adjust water to pH 4, FeCl ₃ (40 mg/L) - 1 hour reaction	<10	NM	NM
M-11	Adjust water to pH 4, FeCl ₃ (40 mg/L) - 3 hour reaction	<10	NM	NM
M-12	Adjust water to pH 4, FeCl ₃ (40 mg/L) - 6 hour reaction	<10	NM	NM
M-13	Adjust water to pH 6, FeCl ₃ (40 mg/L) and 3% H ₂ O ₂ - 1 hour reaction	188	NM	NM
Focus on Molybdenum Removal - SEC				
M-14	Adjusting water to pH of 6, FeCl ₃ (40 mg/L)	440 total 240 dissolved	NM	NM
M-15	Adjusting water to pH of 6, FeCl ₃ (80 mg/L), Sand Filter	1,170 total 38 Dissolved	NM	31500
Focus on Molybdenum Removal and Settling Conditions - SEC				
M-16	Adjust water to pH 6, FeCl ₃ (80 mg/L), 2:3 molar ratio FeCl ₃ to Ca(OH) ₂ , Sand Filter	1,890	NM	NM
M-17	Adjust water to pH 6, FeCl ₃ (40 mg/L), 2:3 molar ratio FeCl ₃ to Ca(OH) ₂ , Sand Filter	2,560	NM	NM
M-18	Adjust water to pH 6, FeCl ₃ (40 mg/L), Ca(OH) ₂ to pH of 6, Sand Filter	2,490	NM	NM
M-19	Adjust water to pH 6, FeCl ₃ (40 mg/L), Ca(OH) ₂ to pH of 5, Sand Filter	1,430	NM	NM
M-20	Adjust water to pH 6, Alum (120 mg/L), Sand Filter	2,880	NM	NM
M-21	Adjust water to pH 6, FeCl ₃ (40 mg/L), Bentonite Powder, Sand Filter	340	NM	NM
M-22	Adjust water to pH 6, FeCl ₃ (80 mg/L), Bentonite Slurry, Sand Filter	170	NM	NM
M-23	Adjust water to pH 6, FeCl ₃ (40 mg/L), Anionic Polymer, Sand Filter	200	NM	NM
M-24	Adjust water to pH 6, FeCl ₃ (40 mg/L), Cationic Polymer, Sand Filter	170	NM	NM
M-25	Adjust water to pH 6, FeCl ₃ (80 mg/L), Anionic Polymer, Sand Filter	120	NM	NM
M-26	Adjust water to pH 6, FeCl ₃ (80 mg/L), Cationic Polymer, Sand Filter	27	NM	NM
Focus on Boron Removal - RIEC				
B-1	Adjust water to pH of 5, SIR 150 Resin Column - Day 7	<20	NM	<10
B-2	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, SIR-150 Boron Resin	<10	600	<10
B-3	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, IRA-743 Boron Resin	<10	17,000	<10
B-4	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Resin	<10	4,400	<10
B-5	Adjusting water to pH of 6, FeCl ₃ (40 mg/L), Sand Filter, SIR 150 Resin Column - System Operated 7 Days	<10	NM	<20

Table 1
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Sioux Energy Center, Missouri

Test Condition Reference		Molybdenum	Sulfate	Boron
		100	250,000	2,000
	Permit Limits	100	250,000	2,000
	High Concentration Area Water	3,470	725,000	32,200
	Low Concentration Area Water	65	71,000	756
	Blended Water	1,767	398,000	16,478
Focus on Sulfate Removal - SEC				
S-1	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Zeolite Filter	180	380,000	14,000
S-2	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Surfactant Coated Zeolite Filter	160	360,000	15,000
S-3	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, NaCl treated Zeolite Filter	200	370,000	14,000
S-4	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Limestone Filter	200	380,000	14,000
S-5	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, adjust to pH 10, Zeolite Filter	220	390,000	14,000
S-6	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, adjust to pH 10, Surfactant Coated Zeolite Filter	220	390,000	15,000
S-7	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, adjust to pH 10, NaCl treated Zeolite Filter	200	360,000	13,000
S-8	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, adjust to pH 10, Limestone Filter	220	390,000	14,000
S-9	Adjust water to pH6, NaCl Treated Zeolite Filter	NM	430,000	1,500
S-10	NaCl Treated Zeolite Filter Only	NM	420,000	1,600
S-11	Adjust water to pH 6, Surfactant Coated Zeolite Filter	NM	270,000	540
S-12	Surfactant Coated Zeolite Filter Only	NM	230,000	370
S-13	Adjust water to pH 6, FeCl ₃ (80 mg/L - Bentonite to help settling), Sand Filter, 1:1 cement:sulfate molar ration (20 min mixing)	NM	460,000	NM
S-14	Adjust water to pH 6, FeCl ₃ (80 mg/L - Bentonite to help settling), Sand Filter, 1.5:1 cement:sulfate molar ration (20 min mixing)	NM	470,000	NM
S-15	Adjust water to pH 6, FeCl ₃ (80 mg/L - Bentonite to help settling), Sand Filter, 2:1 cement:sulfate molar ration (20 min mixing)	NM	490,000	NM
S-16	Adjust water to pH 6, FeCl ₃ (80 mg/L - Bentonite to help settling), Sand Filter, 1:1 Ca(OH) ₂ :sulfate molar ration (60 min mixing)	NM	430,000	NM
S-17	Adjust water to pH 6, FeCl ₃ (80 mg/L - Bentonite to help settling), Sand Filter, 3:1 Ca(OH) ₂ :sulfate molar ration (60 min mixing)	NM	420,000	NM
S-18	Adjust water to pH 6, FeCl ₃ (80 mg/L - Bentonite to help settling), Sand Filter, 5:1 Ca(OH) ₂ :sulfate molar ration (60 min mixing)	NM	420,000	NM
Focus on Sulfate Removal - RIEC				
S-19	DS-200 Zeolite Only	1,000	300,000	8,300
S-20	OC-300 Zeolite Only	1,100	360,000	9,100
S-21	HS-200 Zeolite Only	890	330,000	8,400
S-22	Clinoptilolite Zeolite Only	1,100	230,000	8,400
S-23	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Chitosan High MW (50 mg/L), adjust pH to 3.5, Mix for 1 hour	NM	230,000	8,300
S-24	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Chitosan Medium MW (50 mg/L), adjust pH to 3.5, Mix for 1 hour	NM	230,000	9,100
S-25	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Chitosan Low MW (50 mg/L), adjust pH to 3.5, Mix for 1 hour	NM	230,000	9,400
S-26	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Sodium Aluminate at 2:1 molar ration with sulfate, adjust pH to 11.3, Mix for 1 hour	NM	230,000	8,100
S-27	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Calcium Aluminate at 2:1 molar ration with sulfate, adjust pH to 11.3, Mix for 1 hour	NM	230,000	8,200
S-28	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Calcium Aluminate Cement at 2:1 molar ration with sulfate, adjust pH to 11.3, Mix for 1 hour	NM	230,000	8,100

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Test Condition Reference		Molybdenum	Sulfate	Boron
		Permit Limits	100	250,000
	High Concentration Area Water	3,470	725,000	32,200
	Low Concentration Area Water	65	71,000	756
	Blended Water	1,767	398,000	16,478
Focus on Sulfate and Boron Resin Removal - RIEC				
B,S-1	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - RIEC - 1 Day	14	210,000	<10
B,S-2	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - RIEC - 2 Day	20	210,000	<10
B,S-3	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - RIEC - 3 Day	<10	220,000	180
B,S-4	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - RIEC - 4 Day	<10	220,000	3,400
B,S-5	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - RIEC - 5 Day	<10	220,000	7,300
B,S-6	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - RIEC - 6 Day	<10	220,000	9,100
B,S-7	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Surfactant Coated Zeolite - RIEC - 1 Day	200	220,000	8,600
B,S-8	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Surfactant Coated Zeolite - RIEC - 2 Day	200	220,000	9,100
B,S-9	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Surfactant Coated Zeolite - RIEC - 3 Day	220	220,000	9,900
B,S-10	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Surfactant Coated Zeolite - RIEC - 4 Day	220	220,000	9,400
B,S-11	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Surfactant Coated Zeolite - RIEC - 5 Day	240	220,000	9,300
B,S-12	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, Surfactant Coated Zeolite - RIEC - 6 Day	240	220,000	9,500
Focus on Sulfate and Boron Resin Removal - SEC				
B,S-13	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - SEC - 1 Day	<10	360,000	<10
B,S-14	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - SEC - 2 Day	<10	380,000	750
B,S-15	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - SEC - 3 Day	<10	370,000	8,600
B,S-16	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - SEC - 4 Day	<10	370,000	16,000
B,S-17	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - SEC - 5 Day	<10	380,000	19,000
B,S-18	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, PWA-10 Boron Resin - SEC - 6 Day	<10	360,000	17,000
B,S-19	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, SIR-150 Boron Resin - SEC - 1 Day	<10	330,000	<20
B,S-20	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, SIR-150 Boron Resin - SEC - 2 Day	<10	370,000	30
B,S-21	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, SIR-150 Boron Resin - SEC - 3 Day	<10	370,000	4,300
B,S-22	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, SIR-150 Boron Resin - SEC - 4 Day	<10	380,000	13,000
B,S-23	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, SIR-150 Boron Resin - SEC - 5 Day	<10	360,000	17,000
B,S-24	Adjust water to pH 6, FeCl ₃ (40 mg/L), Sand Filter, SIR-150 Boron Resin - SEC - 6 Day	<10	360,000	18,000
Focus on Final Design; Settling and Treatment - SEC				
Final 1	Adjust water to pH 6, FeCl ₃ (80 mg/L), Anion Polymer (2.5 mg/L), Sand Filter	360	400,000	17,000
Final 2	Resin	<100	7.2	<100
Final 3	Adjust water to pH 6, FeCl ₃ (80 mg/L), Cation Polymer (0.5 mg/L), Sand Filter	22	400,000	16,000
Final 4	Resin	<10	12.0	<100

Table 1
Summary of Sioux Energy Center Treatability Testing
Sioux Energy Center, Missouri

Test Condition Reference		Molybdenum	Sulfate	Boron
	Permit Limits	100	250,000	2,000
	High Concentration Area Water	3,470	725,000	32,200
	Low Concentration Area Water	65	71,000	756
	Blended Water	1,767	398,000	16,478
Pilot Study Results - RIEC				
P-1	2/10/21 RIEC Pilot Influent	1,070	263,000	7,510
P-2	2/10/21 RIEC Pilot Post Resin Filter	14	8,000	<250
P-3	2/12/21 RIEC Pilot Influent	852	261,000	8,110
P-4	2/12/21 RIEC Pilot Post Sand Filter	349	253,000	2,230
P-5	2/12/21 RIEC Pilot Post Resin Filter	0.7	7,000	20
P-6	2/15/21 RIEC Pilot Influent	871	280,000	1,620
P-7	2/15/21 RIEC Pilot Post Sand Filter	93	228,000	7,530
P-8	2/15/21 RIEC Pilot Post Resin Filter	<5	63,000	<10
P-9	2/25/21 RIEC Pilot Influent	880	265,000	7,940
P-10	2/25/21 RIEC Pilot Post Sand Filter	134	237,000	NM
P-11	2/25/21 RIEC Pilot Post Resin Filter	10	208,000	<10
P-12	3/3/21 RIEC Pilot Influent	1,030	255,000	8,550
P-13	3/3/21 RIEC Pilot Post Resin Filter	6	212,000	<10
P-14	4/9/21 RIEC Pilot Influent	1,060	278,000	9,940
P-15	4/9/21 RIEC Pilot Post Resin Filter	33	128,000	62
P-16	5/7/21 RIEC Pilot Influent	946	228,000	8,710
P-17	5/7/21 RIEC Pilot Post Resin Filter	248	100,000	2,330
P-18	5/11/21 RIEC Pilot Influent	1,020	235,000	9,480
P-19	5/11/21 RIEC Pilot Post Sand Filter	4	186,000	6,910
P-20	5/11/21 RIEC Pilot Post Resin Filter	8	136,000	NM

Notes and Abbreviations:

RIEC = Rush Island Energy Center

SEC = Sioux Energy Center

NM = not measured

< = concentration is less than value

Red values exceed discharge permit limits

H₂O₂ = hydrogen peroxide

mg/L = milligrams per liter

ug/L = micrograms per liter

Ca(OH)₂ = calcium hydroxide

ZVI = zero valent iron

NaCl = sodium chloride

FeCl₃ = ferric chloride