December 31, 2019 *Via e-Mail* (bmiller2@ameren.com)

Ameren Services
1901 Chouteau Avenue
PO Box 66149, MC 6
St. Louis, MO 63166-6149

RE: Ashpond Metals Treatability Study Results

XDD Project No. 19005.00, 19005.01, 19010.00, and 19011.0

XDD ENVIRONMENTAL, LLC (XDD) appreciates the opportunity to provide Ameren Services (Ameren) with the results of the data evaluation, bench-scale treatability testing, and remedial technology evaluation to address elevated levels of arsenic (As), molybdenum (Mo), lithium (Li), boron (B), and other site metals in ashponds leachate / groundwater from the Rush Island Energy Center (RIEC), the Meramec Energy Center (MEC), the Labadie Energy Center (LEC), and the Sioux Energy Center (SEC). The bench-scale testing was performed in accordance with the scope of work described in XDD's *Proposal for Metals Treatability Study* dated February 12, 2019, *Proposal for Metals Treatability at the Labadie Energy Center* dated April 23, 2019, and *Proposal for Metals Treatability at the Sioux Energy Center* dated April 23, 2019, with modifications as noted in this report. The report herein includes preliminary results of the treatability testing for all sites with a final pilot study design approach for RIEC.

If you have any questions regarding the information presented in this report, please do not hesitate to call me at 314.609.3065.

Sincerely,

DEREK INGRAM

XDD Environmental

cc:

Michael Marley
Laurel Crawford
Bridget Cavanagh

ASHPOND METALS TREATABILITY STUDY RESULTS

Ameren Services

Prepared For:

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December 31, 2019

EXECUTIVE SUMMARY

XDD Environmental (XDD) was retained by Ameren Services (Ameren) to perform metals treatability studies for the remediation of arsenic, molybdenum, lithium, boron, and other metals of concern (MOC) from ashpond leachate / groundwater. Phase 1 of the three phases of treatability studies included a review of geological conditions and existing metals in leachate from four sites [Rush Island Energy Center (RIEC), Meramec Energy Center (MEC), Labadie Energy Center (LEC), and Sioux Energy Center (SEC)]. In addition, the Phase 1 involved literature research on possible treatment trains and chemical conditions favorable for the MOC remediation. The results from the Phase 1 study identified several possible in situ treatment technologies for further evaluation, including: pH adjustment, iron precipitation / coprecipitation, zero valent iron (ZVI), metals reducing geochemical conditions, and biological stimulation as possible approaches to be tested in the Phase 2 studies.

The Phase 2 studies evaluated the Phase 1 identified treatment approaches effectiveness for MOC remediation using site groundwaters and soils, mimicking an in situ treatment application. The primary objective of the Phase 2 testing was to determine which treatment approaches / changes to geochemical conditions would promote adsorption, precipitation, or coprecipitation of the MOC, without adversely affecting the dissolved and total MOC concentrations in groundwater or other metals present at the site. The tests were carried out for periods of one to eight weeks (depending on the technology under evaluation). Of the remedial approaches tested in Phase 2, microscale ZVI and pH reduction (to pH 6) were the only methods that treated arsenic and molybdenum (the two metals of greatest regulatory concern at RIEC) to the required criteria. The other remedial approaches tested had limited to no impact on the MOC in groundwater.

The results from the Phase 2 testing were to be used to refine Phase 3 testing and to develop the pilot test design for the RIEC site. However, prior to the Phase 3 testing, boron was changed from a secondary to a primary MOC. Microscale ZVI was the only technology that had been shown to remove boron from groundwater in the Phase 2 testing; additional research identified an ion-specific resin (resin) that could treat boron to the required criteria using an ex situ remedial approach. The addition of boron as a primary MOC, along with concerns with clogging of the aquifer from precipitation of site metals, and the complexity of in situ treatment of boron, resulted in a transition from an in situ to an ex situ treatment system conceptual treatment approach for all sites MOC. The primary concern /difference in the transition from in situ to ex situ treatment is the decreased treatment time; the available in situ treatment time based on site hydraulics is weeks to a month or more; ex situ treatment requires a few minutes to hours of reaction time to permit a practical and cost-effective remedial approach.

Accordingly, for the Phase 3 treatability studies, pH adjustment, microscale ZVI, and ferric chloride addition (added due to additional literature research on the decreased available reaction timeframes for ex situ treatment) were tested for the treatment of arsenic and molybdenum in the RIEC groundwater, with polishing of the treated groundwater using resin for boron removal. The results of the Phase 3 testing identified pH adjustment, ferric chloride aided precipitation, sand filtration, and resin polishing as the most effective and reliable ex situ treatment option for RIEC groundwater.

Going forward, the results of the Phase 3 treatability testing for the RIEC groundwater will be used to guide the finalization of the treatability testing of the other sites ashpond leachate / groundwaters. Each of the individual sites unique water geochemical conditions, MOC, and hydraulics will require evaluation to ensure a reliable treatment approach design for each site.

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1.0 INTRODUCTION

XDD Environmental (XDD) was retained by Ameren Services (Ameren) to perform metals treatability studies on ashpond leachate / groundwater from four sites: Rush Island Energy Center (RIEC), Meramec Energy Center (MEC), Labadie Energy Center (LEC), and Sioux Energy Center (SEC). The primary objective of the studies was to evaluate potential remedial technologies for metals of concern (MOC) identified as part of the requirements of United States Environmental Protection Agency (USEPA) 40 CFR Part 257 “Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals From Electric Utilities; Final Rule” (the CCR Rule). The CCR Rule requires owners or operators of existing CCR units to produce an Annual Groundwater Monitoring and Corrective Action Report (Annual Report) each year (§§ 257.90(e)). XDD was provided, through a third party, data from the annual reports, samples from compliance wells with previously identified elevated MOC concentrations, and applicable statistically determined action levels (target goals for MOC treatment) for each site.

The treatability studies were developed and completed using a conservative approach of testing groundwaters from the areas of highest MOC concentrations, with the understanding that proposed engineered caps for each site should result in reduced MOC groundwater concentrations over time. Though the MOC and regulatory concerns are similar at each site, site-specific groundwater geochemistry’s and varying MOC concentrations required XDD to approach treatment for each site separately. This approach ensures certainty in the MOC treatment effectiveness based on the differing site conditions and MOC concentrations for each site. It also provides for information needed in developing a treatment train specific to each site to address the differing geochemical conditions.

Initially, the primary MOC at the sites (though not all present at all sites) were arsenic, molybdenum, and lithium. Other potential MOC carried through the studies for each site (though again not all present at all sites) included boron, lead, cobalt, and selenium. A key component of the study was to determine if a potential MOC treatment approach would affect other metals in site groundwater and soil in either a positive (reduced concentration) or negative (increased concentration) manner. Baseline MOC / metals concentrations for all four sites (five locations; two sample sets being studied at MEC due to the presence of localized lithium) are presented in **Table 1**. The initial conceptual remedial approach was to treat the metals in situ, taking advantage of the slow moving groundwaters at the sites (allowing weeks of treatment time for MOC removal to occur), and for the potential for the most cost-effective treatment.

Around June 2019, during the performance of the treatability studies, per direction from Ameren, boron was transitioned from a potential MOC to a primary MOC, to account for an anticipated revision in the CCR Rule compliance. With this transition, any remedial option would be required to include boron treatment to below the applicable action. The complexity of in situ treatment of boron and its limited treatability options became a primary driver to change the conceptual treatment approach to ex situ treatment for the sites groundwaters.

This report focuses on the initial literature research conducted for all sites, initial treatability testing of the leachate / groundwater for all sites (for in situ treatment), then a refocus of the studies to consider ex situ treatment of the MOC (with boron added as a MOC), and finally the refinement of the treatment effectiveness and development of a MOC remedial approach for pilot testing at RIEC. The results from the additional treatability studies performed for RIEC will be used to guide refinement of the treatability studies and pilot test design for the other three sites (MEC, LEC, and SEC).

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

The treatability studies for each site consisted of two phases; with a final / third phase conducted on RIEC only, at this time, each of the three phases of testing are described below:

- Phase 1 – Site Review and Data Evaluation for Preparation of the Treatability Study Design (**Appendix A**)
    - Compare site-specific data to each site's MOC target goals and develop a conceptual MOC remedial approach based on a summary of the site-specific geochemical and hydrological conditions.
    - Evaluate existing literature to identify potential remedial options for the MOC to be tested for each site.
- Phase 2 – Bench-Scale Treatability Study for In Situ Remediation of MOCs
    - Based on the literature review results from Phase 1, bench-scale reactors were developed, using site soil and groundwater, to evaluate promising in situ treatment technologies or treatment trains. Treatment options identified in the Phase 1 review included (**Table 2**):
        - pH adjustment

        - Addition of calcium polysulfide (CaSx)
        - Addition of dissolved iron
        - Addition of microscale zero valent iron (ZVI)
        - Addition of particle size ZVI
        - Biodegradation / biostimulation in conjunction with ZVI.
    - The focus of Phase 2 testing was to identify specific MOC removal methods from site groundwater over the course of a one month treatment period without adversely affecting other MOCs in the groundwater (e.g., mobilizing MOCs present on site soils). The one month treatment period was selected based on the groundwater flow rates from the proposed in situ treatment application area to the regulatory point of compliance; actual site-specific treatment periods will have some variance greater than this selected period.
- Phase 3 –Treatment Train Development for Ex Situ Remediation of the MOCs at RIEC
    - Per above, boron was added as a primary MOC during the Phase 2 testing timeframe. The limitation to the availability and the complexity of in situ remedial options for boron removal, along with concern for long-term aquifer clogging from MOC precipitation / coprecipitation, caused a change in the conceptual remedial approach for the sites from an in situ to an ex situ treatment train process. The primary consequence of the change was the available time for treatment of metals in an above-surface treatment train. For in situ remediation, a one month MOC treatment period was readily available for the sites; however, for practical and cost-effective ex situ MOC remediation, the treatment period would need to be reduced to minutes to a few hours, dependent upon groundwater extraction rates and storage limitations of the ex situ treatment processes.
    - Additional literature research suggested that the most reliable approach for removal of boron from groundwater was boron selective ion-exchange resins (resin)
    - Based on the RIEC Phase 2 treatability study results, ZVI and pH adjustment were identified as potential effective in situ remedial options for the initial MOCs at RIEC. One of the ZVI products tested in Phase 2 was effective on boron, though pH adjustment had no effect. Accordingly, the following column tests were conducted in the Phase 3 testing:
        - Initial groundwater pH adjustment, followed by passing groundwater through a column filled with a ZVI/sand mixture for treatment of arsenic

        and molybdenum, with evaluation of the treatment effectiveness of that system for boron

        - pH adjustment of groundwater to approximately pH 6, followed by passing the groundwater through a sand column for treatment of arsenic and molybdenum only
        - Addition of a column filled with resin after the ZVI/sand column and the pH followed by sand column tests, for additional treatment of boron

    - Based on the change to an ex situ remedial approach, requiring fast treatment periods (faster reaction kinetics), additional literature research identified the addition of ferric chloride to the groundwater as a potential approach for rapid arsenic removal through coagulation / flocculation / precipitation. The following additional tests were conducted to further evaluate ex situ treatment of arsenic and molybdenum:
        - Initial groundwater pH adjustment, followed by the addition of ferric chloride, followed by settling of the developed precipitants and filtration to remove the suspended precipitants from the groundwater
        - A resin filled column after the above filtration step for treatment of boron

Details on each of these three phases of treatment are provided in the following sections of this report.

2.0 PHASE 1 LITERATURE REVIEW

An extensive literature review was conducted for in situ treatment and general chemical behavior of the MOC prior to the selection of remedial options for consideration for the sites. The results of the literature review are presented in **Appendix A**. The literature review was necessary since the MOC precipitate, co-precipitate, or adsorb under varying geochemical conditions; however, these preferred MOC treatment geochemical conditions may result in increased mobility of other metals / MOC at the sites. The literature review identified the geochemical conditions that were either favorable for the MOC to be removed from the groundwater or would not negatively affect other MOC present. From this research, potential treatment trains were identified for remediating site MOC and for Phase 2 treatability testing.

3.0 PHASE 2 – TREATABILITY TESTING

3.1 Phase 2 Experimental Procedures

Based on the initial literature review, five mechanisms were identified as possible treatment approaches for the in situ removal of arsenic, molybdenum, and lithium from the sites groundwaters. The selection of arsenic, molybdenum, and lithium as the MOC was based on detections above the provided statistically-derived action levels for at least one of the four sites evaluated (**Table 1**). Boron was initially not on the list of primary MOC but as a metal being analyzed for since it does not have a current regulatory required action level. Boron was added as a primary MOC in the Phase 3 testing, per the request of Ameren and as a statistically-derived action level for each site was provided.

Below is a summary of each of the Phase 2 potential in situ approaches tested. A breakdown of the experimental setup for the approaches tested are presented in **Table 2**.

1. pH adjustment (7-day test)
    - For the pH adjustment, a range of pH of 6 to 10 was evaluated for RIEC to determine how the MOC concentrations would change as the pH decreased (at RIEC the initial pH in groundwater from monitoring well MW-2 was 11). Reduction and maintaining a pH of 6 resulted in arsenic and molybdenum removal after a week of treatment, without adversely affecting the concentrations of the other MOC present; therefore, this approach was maintained for testing of the other sites groundwaters.
2. Addition of calcium polysulfide (CaSx) (7-day test)
    - CaSx has been proven to reduce certain dissolved metal concentrations through forcing of reduced groundwater chemistry and subsequent metal sulfide formation. The dosage of CaSx used in these tests was based on a 1:2 mass of metals to mass of CaSx, with a 100 percent (%) safety factor (**Table 2**).
3. Addition of ferrous iron (4-week test)
    - The RIEC site groundwater samples have low concentrations of dissolved iron; dissolved iron is beneficial for the coprecipitation of certain MOC and as a sorbent for MOC. Dissolved iron (ferrous sulfate at 50 mg/L) was added to the site groundwater and soil. The test was conducted under both aerobic and anaerobic groundwater chemistries to determine if coprecipitation or sorption of the MOC can be induced.

4. Addition of ZVI (4-week test)
    - ZVI can also introduce dissolved iron, under anaerobic conditions, into groundwater for coprecipitation and possible adsorption of the MOC.
    - Two ZVI products were evaluated as potential remedial options: a microscale (7 micron) product, which is typically injected into the subsurface, and granular ZVI, which is commonly used in permeable reactive barriers (PRBs) (SR.25 particle size). Given the MOC concentrations present in site groundwater, ZVI dosages were established for the RIEC and MEC (MW-5 and MW-6) sites, based on manufacturer recommendations. While preliminary results from this approach suggested ZVI as a promising method for MOC removal, the required ZVI dosage was determined to be impractical for full-scale implementation. The ZVI dosage for the LEC and SEC site treatability tests were reduced to more practical dosage levels (see **Table 2**).
5. Biostimulation with ZVI addition (8-week test)
    - Test conditions, described in Test 4 above, were duplicated with the addition of food and nutrients, which are typically lacking in site groundwater and soils, to promote biotransformation of metals from a soluble to an insoluble form. Since biological processes are often slower than chemical processes, the biostimulated reactors were maintained for twice as long a treatment period as the ZVI only reactors (8 weeks vs. 4 weeks).

3.2 Phase 2 – Treatability Testing - Results

The results of the metals in groundwater analyses for the Phase 2 testing are presented in **Table 3** (RIEC), **Table 4** (MEC, MW-5), **Table 5** (MEC, MW-6), **Table 6** (LEC), and **Table 7** (SEC) for the in situ treatment approaches tested. The Phase 2 testing results suggest:

- A pH adjustment to 6 resulted in the reduction of arsenic and molybdenum to near action levels at all sites (Test 1).
- There was some benefit to using the granular size ZVI and a pH adjustment (reduction to 6) for the removal of arsenic and molybdenum (Test 4). Granular ZVI achieved action levels for arsenic and molybdenum for all sites, with the exception of molybdenum at SEC.
- There was minimal reduction in total metals concentrations for the tests conducted at a pH greater than 8 (Test 1).

- There was minimal reduction in MOCs as a result of treatment with CaSx, dissolved ferrous iron, or biostimulation (Tests 2, 3, and 5, respectively).
- Microscale ZVI was the only product tested that reduced boron to action levels for all sites, except for SEC.

Upon completion of the Phase 2 testing, per the request of Ameren, boron was added as a primary MOC with an action level of 4 mg/L. Of the approaches tested, microscale ZVI was the only approach that had a positive impact in reducing boron levels in groundwater. The literature research, supported by the phase 2 test results, suggests boron is most efficiently and reliably treated via ex situ filtration through a ion-selective resin. Given the addition of boron as a primary MOC and with concerns of long-term clogging of the site aquifers from metals precipitation, it was collectively decided to change the conceptual remedial approaches from an in situ to an ex situ treatment process. At this point in the testing (entering Phase 3), it was suggested by XDD and presented to Ameren, to focus on developing an ex situ remedial approach for RIEC to expedite the design and testing of a pilot scale system. The proposed Phase 3 treatability work and developed pilot test approach for RIEC would then be used to guide future Phase 3 testing and pilot test designs for the other sites (MEC, LEC, and SEC). An additional advantage of an ex situ remedial approach is the flexibility and ease of adjustment of an ex situ treatment system, given the variability in the groundwater geochemistry's and hydraulics across the four sites under evaluation. In addition, changes in site groundwater conditions are expected over time as both the consequences of the engineered cap placement and the potential ex situ treatment implementations stabilize, with respect to groundwater MOC concentrations.

4.0 PHASE 3 – TREATABILITY TESTING - RIEC

4.1 Phase 3 Experimental Procedures

The Phase 3 treatability testing focused on refining the ex situ remedial approach for RIEC and to finalize the RIEC pilot test design. The initial results from the Phase 2 testing for the in situ treatment of the MOC at RIEC, conducted in batch reactors with site groundwater and soil, supported that pH adjustment and the addition of ZVI were the most promising remedial options for treatment of arsenic and molybdenum (the primary MOC at RIEC) to action levels. The phase 3 testing consisted of a treatment train that was scaled, for the bench testing, using an ex situ conceptual pilot test design sized to fit within single or double Conex box (portable storage unit) treatment units, that could be positioned above ground at any of the sites.

The major design issue, refined in the Phase 3 testing, was the transition from the Phase 2 test results developed for an in situ treatment approach, to a reliable ex situ treatment train. For ex situ treatment to be practical and cost-effective the time of reaction (kinetics) to create precipitants needs to be on the order of minutes to a few hours. For the in situ approaches tested in Phase 2, a month-long contact time was available between amendments addition and for precipitation of metals to occur (based on the site groundwater velocity and distance from the remedial implementation area to the compliance sampling locations). For the in situ reaction timeframe, batch reactors were ideal. The required reaction timeframes for the Phase 3 testing made it necessary to use columns in the test procedures and to scale the reactor sizes and groundwater flow rates to match the conceptual field pilot and full-scale Conex box remedial systems sizing.

The Phase 3 treatability tests were also scaled for site hydraulics, assuming a 200-ft long cross-sectional treatment length, perpendicular to impacted groundwater flow, at the RIEC. Site-specific groundwater modeling was performed to determine the full-scale groundwater capture / flow rates required to permit an approximate 6 to 12-month pilot test duration to demonstrate the effectiveness of the treatment train. The pilot test treatment results need to be reflected both within the ex situ treatment process sampling points but also in existing compliance monitoring wells located within and downgradient of the treatment system hydraulic capture zone. For the RIEC site, the projected pilot test groundwater flow rate was estimated at 8 gallons per minute (gpm) (2 gpm per well) which is approximately four times the projected full-scale required groundwater flow rate.

It was also initially estimated that the ex situ treatment vessels (either filters or settling tanks) within the proposed Conex box system would have to be on the order of 750 to 1,000 gallons maximum capacity to fit in the unit, and that the Phase 3 testing would need to have reaction timeframes (kinetics) that would match the available vessel sizing. To scale the pilot test treatment train conceptual design to the Phase 3 treatability study design, the treatability study columns were made 3-inch (in) long and 1.5-in in diameter, with a groundwater flow rate of 0.7 milliliters per minute (mL/min).

Based on the results of the literature research and the Phase 2 testing, the initial Phase 3 tests were conducted with pH adjustment to pH 6 for the RIEC groundwater. The pH adjusted groundwater was then passed through a sand filter (with a residence time of 40 minutes) for arsenic and molybdenum removal. The pH adjusted groundwater was also tested by adding dissolved iron either via a ZVI/sand filter or by the addition of ferric chloride. Ferric chloride was incorporated into the Phase 3 testing due to the potential faster reactions times to create metal precipitates, per the discussion in Section 1 of this report. The ferric chloride was added to the groundwater to a concentration of 40 mg/L, the ferric chloride treated groundwater was passed into a settling vessel with a residence time of 1.25 hours, the metals were allowed to precipitate and settle, and the treated groundwater was passed through either a bag or a sand filter.

Since pH adjustment and iron addition had proved ineffective at boron removal in the Phase 2 testing, a resin filter was added to the effluent of the pH and iron addition ex situ treatment processes tested to evaluate the resins effectiveness for boron removal given the RIEC groundwater geochemistry. The resin was added post pH and ferric chloride addition as the resin is relatively expensive and focusing its use on the boron only is considered an overall more cost-effective approach for the groundwater treatment.

4.2 Phase 3 – Treatability Testing – RIEC – Results

Ferric Chloride ($FeCl_3$) Addition

The ex situ treatment method that proved most successful and reliable in the Phase 3 testing for pilot and full-scale implementation at the RIEC site is the pH adjusted, $FeCl_3$ aided flocculation / removal of arsenic and molybdenum. Preliminary testing with the ZVI and pH adjustment, discussed below, helped guide the design of the $FeCl_3$ treatment train. Understanding that the resin can be successful at removing boron at the concentrations present at the RIEC, Phase 3 testing focused on arsenic and molybdenum removal and developing a removal approach that worked effectively in the available ex situ treatment timeframes.

A preliminary Phase 3 test was performed to evaluate varying dosages of $FeCl_3$ and pH adjustment specific to the treatment of the arsenic in the RIEC groundwater. A kinetics / rate of treatment / reaction test was conducted where $FeCl_3$ was added to the groundwater and allowed to react, flocculate / precipitate and settle out of the groundwater for periods of 1 hour, 3 hours, and 6 hours, prior to flowing the groundwater through a sand filter column (**Table 8**). Since arsenic(V) is the form of arsenic that coprecipitates more readily with iron, hydrogen peroxide was tested as an oxidizer to transform any arsenic(III) in the groundwater to arsenic(V), prior to removal with the $FeCl_3$ addition. The results from the preliminary $FeCl_3$ tests suggested that:

- Both arsenic and molybdenum can be reduced to concentrations at or below action levels, using $FeCl_3$ addition.
- An initial pH of 6 (prior to the addition of $FeCl_3$) caused faster settling of the precipitants than an initial pH of 4 (also, pH 6 was determined to be a more favorable pH for RIEC groundwater treatment, based on the Phase 2 test results).
- Higher $FeCl_3$ dosage (40 mg/L vs. 20 mg/L) provided greater removal of arsenic and molybdenum. Though the difference in $FeCl_3$ dosage performance for the RIEC groundwater was not significant, based on the concentrations detected in the groundwater and the applicable action levels for the MOC at the RIEC site. The dosage evaluation results were however considered beneficial for refinement of Phase 3 testing for the other sites.

- The additional of hydrogen peroxide did not improve the arsenic removal efficiency. However, a check on the arsenic form in groundwater at RIEC showed the arsenic to be predominantly arsenic(V), so the pre-oxidation step was not needed for RIEC.

The reaction time determined for the $FeCl_3$ coagulation and flocculation / precipitation and associated removal of arsenic and molybdenum from groundwater in the preliminary testing was adequate for the conceptual ex situ treatment approach.

Following the preliminary testing it was considered beneficial to run further testing to confirm the preliminary test results, and to optimize the pilot test design. Based on additional literature research, aeration of the groundwater prior to $FeCl_3$ addition was added as a treatment step. Additional treatability tests were conducted using pH adjustment of the RIEC groundwater to approximately 6, followed by addition of 40 mg/L of $FeCl_3$, followed by settling and filtration of precipitants using either sand or bag filters. The treated groundwater was then passed through the resin filter for boron removal. Results of these additional tests are presented in **Table 9**. Key observations and conclusions from the additional $FeCl_3$ testing are:

- Aeration of the groundwater prior to the addition of $FeCl_3$ accelerates the formation of precipitants.
- Influent pH should be close to pH of 6 at RIEC for optimal precipitant settling times.
- Higher $FeCl_3$ concentrations added to the groundwater appear to provide larger precipitant particles that settle faster. However, the higher dosage of $FeCl_3$ will also increase the sludge volume that will require additional disposal and may increase maintenance needs.
- 100-micron bag filters are insufficient to remove the arsenic particles in the groundwater (and reduce total arsenic concentrations to below action levels). Though 10-micron filters work effectively to meet action levels, the 10-micron filter is likely to cause operational issues in a pilot and full-scale system and is therefore not a preferred treatment option. Also, bag filters are unlikely to remove iron in the treated groundwater to below 2 mg/L, which may negatively impact the resin filter longevity.
- The sand filter was effective as a polishing step to reduce total arsenic and molybdenum concentrations to below action levels, while also decreasing total iron concentrations to approximately 0.3 mg/L. Sand filtration is therefore recommended for the pilot scale system.
- The resin filter is needed to remove boron from the groundwater to action levels. The resin operates optimally between a pH of 4 and 10. The $FeCl_3$ addition reduces the

groundwater pH to approximately 4 so pH adjustment back to pH 6 is recommended prior to resin treatment.

- Though total lead is reported in groundwater at RIEC below action levels, the $FeCl_3$ addition reduced the total lead concentration from 0.0057 mg/L to 0.0026 mg/L or lower, suggesting that $FeCl_3$ is a potential option at other sites for treatment of total lead levels which exceed action levels.

pH Adjustment followed by Resin Column Treatment

The Phase 2 pH adjustment only bench testing had proven effective for arsenic and molybdenum removal (though not boron) over a week-long treatment period in the presence of site soils. The Phase 3 tests included an evaluation of pH adjustment followed by the resin as an alternative RIEC treatment train. Since the resin is specially designed for boron removal, the manufacturer could not provide insight into its effectiveness, performance or sustainability for arsenic or molybdenum treatment, so it was assumed that pre-treatment to remove arsenic and molybdenum was still needed.

The columns tests were conducted by decreasing the pH of the RIEC groundwater to pH 5 then passing the pH adjusted groundwater through a sand filter sized to provide a hydraulic residence time of 40 minutes. The filtered groundwater was then passed through a resin column. Groundwater exiting the resin column were collected for analysis of MOC (**Table 10**). The analysis results showed that MOC action levels were achieved after Days 1 and 3 of treatment for all MOCs; however, breakthrough of arsenic occurred by Day 7.

Groundwater samples collected between the sand filter and the resin columns showed that the pH adjustment by itself did not effectively treat the arsenic or molybdenum in the groundwater, over the short treatment period available in the scaled ex situ treatment train. Consequently, it was determined that the resin was responsible for the removal of arsenic, molybdenum, and boron in the RIEC groundwater. A further review of the data and the procedures used in this test suggests that for pH adjustment to be successful for removing arsenic and molybdenum from the RIEC groundwater, the groundwater needs to be maintained at a reduced pH for longer than 40 minutes (the residence time in the tested columns). Hence, pH adjustment alone would not be a viable ex situ treatment approach as an ex situ treatment system design.

Further, while the resin was successful at temporarily removing arsenic, molybdenum, and boron, it was not designed for arsenic and molybdenum treatment, and the arsenic concentration reduction could not be sustained below REIC action levels for up to a week. This indicates that a large resin vessel and / or frequent regeneration of the resin would be needed for resin to be considered as a stand-alone treatment approach. Also, since the resin was not designed to remove arsenic and molybdenum, it is unknown if the metals will desorb during the resin regeneration, in which case, the resin could be ineffective for further arsenic and molybdenum removal. The adsorption capacity of the resin for arsenic and molybdenum should only be considered as a safety factor in the final pilot test design, if the pretreatment for arsenic and molybdenum failed, but not as a stand-alone remedial option.

ZVI Column Testing

Since the microscale ZVI was identified in the Phase 2 tests as a possible approach for removing boron, arsenic, and molybdenum from the RIEC site groundwater, test columns were constructed using a mixture of the microscale ZVI and commercial sand (to allow the required flow through the column / ZVI, without clogging due to the ZVI microscale particle size). The columns were prepared using a 5:1 ratio of sand to microscale ZVI, and a 2:1 ratio of sand to microscale ZVI. The columns were operated for 7 days, with treated groundwater samples collected from the column effluent after 1, 3, and 7 days of treatment time (simulating groundwater treatment over a one week period through a pilot or full-scale 1,000-gallon capacity column / filter).

Table 11 presents the results of the ZVI column testing. The results show partial treatment of arsenic and molybdenum, though not to action levels. Both the 5:1 and 2:1 sand to ZVI dosed columns showed some treatment occurred the first day, but treatment effectiveness decreased by Days 3 and 7. Results for both the columns showed that concentrations did not decrease to action levels for arsenic, and results for only one column sample showed that molybdenum concentrations decreased to action levels (Day 1 of the 5:1 dose column). Boron concentrations did not change passing through the ZVI columns.

From the Phase 3 test results, it was determined that the ZVI treatment effectiveness (at the design sand to ZVI dosages) and the associated treatment longevity was questionable, and likely not reliable as a sustainable remedial option. To ensure the ZVI was being adequately evaluated, XDD had additional discussions with the ZVI vendor on the system design and effectiveness. It was determined that the recommendations by the vendor on how to use ZVI in an ex situ process was impractical for the site given the conceptual pilot test design constraints (action levels, MOC, flow rates, vessel sizing, etc.).

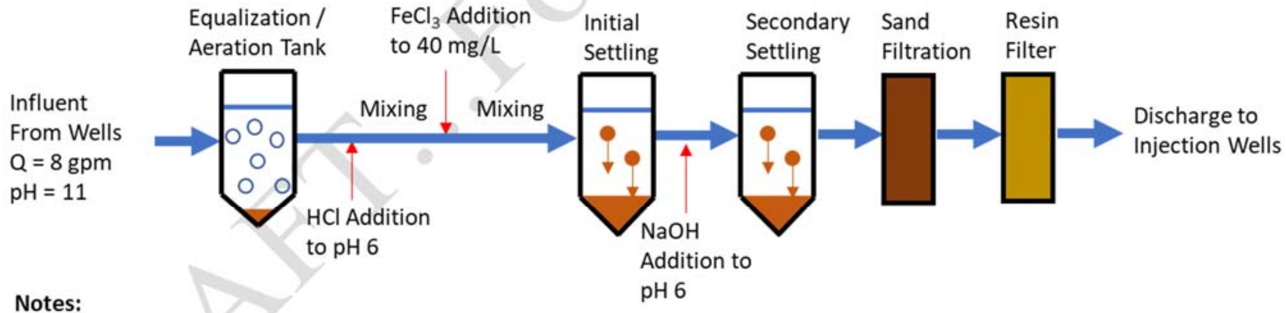
5.0 CONCLUSIONS AND RECOMMENDATIONS FROM TREATABILITY TESTING

Several potential treatment technologies were evaluated for the MOC at the sites. While ZVI and pH adjustment were the most promising remedial approaches from the Phase 2 testing for in situ treatment of the initially identified primary MOC, the subsequent addition of boron as a primary

MOC resulted in the requirement to transition to an ex situ remedial approach. Added benefits of the transition to an ex situ remedial approach are concerns with potential aquifer clogging from in situ MOC precipitation and the benefits of the flexibility in ex situ system design for varying site groundwater geochemistry's. The difference in available and practical treatment times (reaction kinetics) for in situ treatment versus ex situ treatment systems resulted in the elimination of the ZVI and pH adjustment alone technologies as viable ex situ remedial options and the evaluation of additional technologies for the MOC treatment.

Based on the results of the Phase 1 through Phase 3 treatability testing, the proposed treatment train identified for the RIEC pilot test is presented below in **Figure 1**. Modifications and optimizations to the treatment train will be evaluated during the pilot scale startup. The Phase 3 remedial approach refinement testing demonstrated that pH adjustment, followed by $FeCl_3$ aided coagulation/flocculation for arsenic and molybdenum treatment of the RIEC groundwater was effective and reliable. Boron removal requires the addition of an ion-specific resin following the $FeCl_3$ treatment. To expedite the arsenic and molybdenum removal, aeration of the groundwater prior to pH adjustment and the addition of 40 mg/L of $FeCl_3$ is required. The $FeCl_3$ reduces the groundwater pH to approximately 4 so pH adjustment back to pH 6 is recommended prior to resin treatment for boron removal.

Figure 1: Conceptual Treatment Train for Pilot Scale System at RIEC



Notes:

Q = flow
gpm = gallons per minute
mg/L = milligrams per liter
HCl = hydrochloric acid
NaOH = sodium hydroxide
$FeCl_3$ = ferric chloride

Going forward, MEC, LEC, and SEC have similar MOC to RIEC (primarily molybdenum and boron) but with a few distinct deviations from the RIEC groundwater quality. The main points of difference that need to be considered in subsequent Phase 3 testing for the individual sites are:

- At MEC (monitoring well MW-6), lithium has been detected above action levels. The literature review performed during Phase 1 (**Appendix A**) suggests ZVI is a viable remediation approach for lithium; it is suspected that $FeCl_3$ may also be effective at lithium removal.

- The boron concentration at SEC is above the manufacturer's maximum concentration recommendation for the resin (10 mg/L maximum vs. 22 to 25 mg/L measured at SEC). A recirculation method or resin vessels in series may be needed to reduce the boron concentration in SEC groundwater to meet action levels in the resin treated groundwater.
- SEC also has significantly higher molybdenum concentrations (3.05 mg/L) than RIEC (0.16 mg/L) so testing is needed to ensure $FeCl_3$ can be effective at removing molybdenum to action levels at these higher groundwater concentrations.
- Higher remediation system flow rates are likely to be encountered at some of the sites (in particular LEC) so refinement of the system hydraulics and available treatment timeframes need to be evaluated.
- The high pH at RIEC resulted in the need for an initial pH adjustment. This may not be necessary at the other locations, but confirmation tests should be performed.
- $FeCl_3$ flocculation / precipitation is facilitated with increased groundwater alkalinity. Additional alkalinity may be needed to be added to the treatment systems at the other sites to increase the rates of formation and settling of the precipitants.
- General groundwater geochemistry's are also likely to have subtle differences for the other sites. Testing is needed to provide confidence in the effectiveness of the treatment train at the other sites / locations.

The information gathered in the Phase 3 RIEC treatability testing will be used to guide the design of treatability testing and remedial approaches for the other three sites.

APPENDIX A: PHASE 1 LITERATURE REVIEW

Primary Metals of Concern

Arsenic

- Detected at 0.22 milligrams per liter (mg/L) (RIEC) and 0.02 mg/L (MEC, monitoring well MW-5). Arsenic was not detected at LEC, SEC, or at monitoring well MW-6 at MEC.
- Action levels are 0.030 mg/L (RIEC), 0.01 mg/L (MEC and SEC), and 0.0426 mg/L (LEC).
- Potential treatment methods include precipitation/coprecipitation, pH adjustment, adsorption, and ZVI/ZVI with carbon:
    - Speciation – trivalent arsenite [As (III)] is more soluble and mobile than pentavalent arsenate [As(V)].
    - Redox – arsenic is more readily mobilized under reducing conditions.
    - pH – mobility is lowest at pH 3 to 7, increases under very acidic or alkaline pH conditions.
    - Competing ions – phosphate and sulfate can limit arsenic adsorption and increase mobility.
    - Adsorption – iron oxides sorb arsenic and can greatly limit arsenic mobility.
    - Precipitation – formation of insoluble calcium arsenates can reduce leaching and mobility.
- Application of ferrous sulfate to soils has shown promise in reducing arsenic concentrations in groundwater at utility substation sites (EPRI, 2010).
    - Data review has shown that both RIEC and MEC lack iron – this indicates ZVI treatment may be promising.
- pH adjustment in trench application case study: The pH was raised from 1.93 to 7.9, leading to a reduction in groundwater arsenic concentrations from 35,000 micrograms per liter (µg/L) to <4 µg/L (EPRI, 2006).
- Summary of favorable conditions for arsenic removal:
    - pH range of 3 to 7, oxidizing conditions
    - Addition of Iron and calcium complexes
    - Low phosphate and sulfate concentrations

Molybdenum

- Detected at 0.16 mg/L (RIEC), 0.11 mg/L (MEC, monitoring well MW-5), 0.15 mg/L (MEC, monitoring well MW-6), 0.155 mg/L (LEC), and 3.05 mg/L (SEC).
- Action Level is 0.1 mg/L for all sites.
- Potential treatment methods include precipitation/coprecipitation, pH adjustment, adsorption, and ZVI/ZVI with carbon

- Molybdenum adsorption is highly pH-dependent. Peak adsorption for most sorbents (except maghemite nanoparticles) occurs at pH < 5 and limited adsorption occurs at pH > 8. In alkaline conditions, molybdenum behaves conservatively, and its dissolved concentration is controlled by precipitation, not adsorption, reactions (EPRI, 2011).
- Permeable Reactive Barrier (PRB)/ZVI/pH adjustment case study: Molybdenum was sequestered under reducing/oxidizing conditions with pH 7.3 to 10; effective for 15 months (reducing conditions sustained for 5 to 9 months) (Bellantoni, 2014).
- Summary of potential treatment options for molybdenum removal:
    - Maintaining a neutral or slightly alkaline pH with ZVI addition.

<u>Lithium</u>

- Detected at 0.12 mg/L (MEC, monitoring well MW-6), and either non-detect or below action levels at the other sites.
- Action Levels are 0.0647 mg/L (RIEC), 0.04 mg/L (MEC and SEC), and 0.055 mg/L (LEC).
- Potential treatment is limited to precipitation using ZVI PRBs.
- “Additional research is needed to evaluate, and possibly develop, in situ groundwater treatment technologies for lithium, specifically reagents for in situ injection or media for a permeable reactive barrier. Zeolites such as clinoptilolite and clays such as bentonite and kaolinite have been shown to exhibit lithium-sorbing characteristics in a laboratory setting, making these candidates for future in situ injection and PRB application studies” (EPRI, 2018).
- Summary of potential treatment options for lithium removal:
    - ZVI

<u>Boron</u>

- Detected at 3.85 mg/L (RIEC), 5.2 mg/L (MEC, monitoring well MW-5), 7.9 mg/L (MEC, monitoring well MW-6), 7.9 mg/L (LEC), 23.5 mg/L (SEC).
- Action Level is 4 mg/L for all sites.
- “Additional research is needed on the mechanisms of boron attenuation, both precipitation and adsorption, for a wider range of soil and mineral types, and in hydrogeologic environments typical of CCP management sites. While the literature suggests nonlinear sorption and some dependence on general soil type and pH, these relationships are not well understood. The same is true for competing ion effects, such as sulfate and fluoride. In addition, there are few field studies documenting boron attenuation at utility sites” (EPRI, 2005).

- "There is a need to measure boron sorption in the alkaline pH range associated with ash leachate, and to make these measurements with a wider range of soil and mineral types. Moreover, there are relatively few field-scale studies available on the fate and transport of boron derived from coal ash in groundwater. Studies based on site-specific sorption, hydrogeologic, and leaching data may yield a better understanding of the long-term impacts of boron from coal-combustion residues (EPRI, 2005)."
- Case study: pH adjustment to > 9.1 and the addition of proprietary ionizing agents resulted in 99% removal (sorption of boron complexes) (Kreinberg, 2017).
- Summary of potential treatment options for boron removal:
  - ZVI or boron specific ion-exchange resin (ex situ)

Metals of Concern Potentially Released as a Result of Treatment:

Cobalt

- Not detected in baseline samples collected at any of the sites.
- Action Level is 0.006 mg/L for all sites.
- Potential treatment methods include ZVI PRB and carbon substrate injections
  - Ontario ZVI case study: sulfate-reducing conditions (anaerobic, ORP <-250 mV), cobalt remediation achieved (reduction of ~260 parts per billion [ppb] to 40 ppb) (Pare, 2014, RPIC).

Lead

- Either reported below action levels or not detected in baseline samples collected at all sites.
- Action Level is 0.015 mg/L for all sites.
- Potential treatment methods include metal cation precipitation as sulfides, adsorption to iron corrosion products, pH adjustment using Acid-B Extra™ reagent (10%) (EPRI, 2006).
  - Success Mine PRB case study: Lead was reduced from 0.658 mg/L upgradient of the PRB to <0.002 mg/L downgradient of the PRB. The pH was buffered from 4.9 to 6.9 throughout the thickness of the barrier wall. PRB is anaerobic and creates conditions optimal for sulfate-reducing bacteria. Expected to provide treatment for 30 years (EPRI, 2006).
  - Case study at Gilt Edge Mine, SD: leachate pH was raised from 1.93 to 7.9, resulting in the following reductions in metals concentrations: arsenic from 35,000 µg/L to <4 µg/L, antimony from 500 µg/L to 10 µg/L, and lead from 390 µg/L to <10 µg/L (EPRI, 2006).

Selenium

- Not detected in baseline samples from any of the sites.
- Action Level is 0.05 mg/L for all sites.
- Potential treatment methods include reductive precipitation with oxidized iron minerals, adsorption to iron oxides, ZVI, and ZVI/carbon – many positive case studies (EPRI, 2006)
- Oxyanions (e.g., arsenic, chromium, selenium, molybdenum, vanadium, and sulfate) adsorb most strongly at low pH levels and cations (e.g., lead, cadmium, and nickel) adsorb most strongly at high pH levels.
- Like arsenic, selenium is generally present in predominantly two oxyanion forms in natural waters: Se (IV) as selenite ion SeO_3^{-2}, and Se (VI) as selenate ion SeO_4^{-2}. Selenite tends to dominate in impoundment settings when the source coal is bituminous or a mixture of bituminous and subbituminous, while selenate tends to predominate in landfill settings and when the source coal is subbituminous/lignite (EPRI, 2006). Selenate is generally soluble and mobile and is readily taken up by organisms and plants. Selenite is less soluble and mobile than selenate; therefore, reductive precipitation/coprecipitation of selenium could serve as a viable remediation approach. However, re-oxidation is a potential problem. Phytoremediation has also been reported and adsorption has been used.

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Tables

Table 1
Baseline Metal Concentrations and Action Levels
Ameren Services, Missouri

	Rush Island			Meramec MW-5			Meramec MW-6		
	Action Levels	Baseline/Baseline Dup		Action Levels	Baseline/Baseline Dup		Action Levels	Baseline/Baseline Dup	
	Total Metals (mg/L)								
Arsenic	0.03	0.22	0.22	0.01	0.020	0.020	0.01	0.005 U	0.005 U
Molybdenum	0.1	0.16	0.16	0.1	0.11	0.11	0.1	0.15	0.15
Boron	4	4.0	3.7	4	5.2	5.2	4	7.8	8.0
Lead	0.015	0.007	0.007	0.015	0.005 U	0.005 U	0.015	0.005 U	0.005 U
Cobalt	0.006	0.01 U	0.01 U	0.006	0.01 U	0.01 U	0.006	0.01 U	0.01 U
Selenium	0.05	0.01 U	0.01 U	0.05	0.01 U	0.01 U	0.05	0.01 U	0.01 U
Lithium	0.0647	0.06 U	0.06 U	0.04	0.06 U	0.06 U	0.04	0.12	0.12

	Labadie			Sioux		
	Action Levels	Baseline/Baseline Dup		Action Levels	Baseline/Baseline Dup	
	Total Metals (mg/L)					
Arsenic	0.0426	0.025 U	0.025 U	0.01	0.025 U	0.025 U
Molybdenum	0.1	0.15 J	0.16 J	0.1	3.20 J	2.90 J
Boron	4	7.7	8.1	4	25.0	22.0
Lead	0.015	0.025 U	0.025 U	0.015	0.025 U	0.025 U
Cobalt	0.006	0.05 U	0.05 U	0.006	0.05 U	0.05 U
Selenium	0.05	0.05 U	0.05 U	0.05	0.05 U	0.05 U
Lithium	0.055	0.019 J	0.016 J	0.04	0.029 J	0.020 J

Notes:

mg/L = milligrams per liter

U = not detected above the indicated reporting limit concentration

J = estimated value

🟩	Concentrations are at or below action level
⬜	Concentrations are between action level and reporting limit

Table 2

Summary of In Situ Test Conditions for Metal Treatability Study

Ameren Services, Missouri

Test Conditions				Rush Island			Meramec MW-5			Meramec MW-6		
Test condition	Soil (g)	Addition	Duration (week)	Amount	pH	Aerobic or Anaerobic	Amount	pH	Aerobic or Anaerobic	Amount	pH	Aerobic or Anaerobic
pH adjusted	48	HCl 36%	1	Varied	10, 9, 8, 7, 6	Aerobic	Varied	10, 8, 6	Aerobic	Varied	10, 8, 6	Aerobic
CaSx- No pH change	48	CaSx	1	2.1 mg		Aerobic	3.1 mg		Aerobic	5.5 mg		Aerobic
CaSx- pH adjusted	48	CaSx	1	2.1 mg	8	Aerobic	NA			NA		
Fe- anaerobic	48	Fe(II) sulfate	4	12 mg		Anaerobic	12 mg		Anaerobic	12 mg		Anaerobic
Fe -anaerobic- pH adjusted	48	Fe(II) sulfate	4	12 mg	8	Anaerobic	NA			NA		
Fe - aerobic	48	Fe(II) sulfate	4	12 mg		Aerobic	12 mg		Aerobic	12 mg		Aerobic
Fe - aerobic- pH adjusted	48	Fe(II) sulfate	4	12 mg	8	Aerobic	NA			NA		
ZVI (SR.2S)	48	SR.2S	4	96 mg		Anaerobic	96 mg		Anaerobic	96 mg		Anaerobic
ZVI (SR.2S)- pH adjusted	48	SR.2S + HCl	4	96 mg	8	Anaerobic	NA			NA		
ZVI (SR.2S)-Food	48	SR.2S + Food	8	96 mg		Anaerobic	96 mg		Anaerobic	96 mg		Anaerobic
ZVI (SR.2S)-Food- pH adjusted	48	SR.2S + Food + HCl	8	96 mg	8	Anaerobic	NA			NA		
ZVI (7 micron)	48	7 micron	4	96 mg		Anaerobic	96 mg		Anaerobic	96 mg		Anaerobic
ZVI (7 micron)- pH adjusted	48	7 micron + HCl	4	96 mg	8	Anaerobic	NA			NA		
ZVI (7 micron)- Food	48	7 micron + Food	8	96 mg		Anaerobic	96 mg		Anaerobic	96 mg		Anaerobic
ZVI (7 micron)- Food- pH adjusted	48	7 micron + Food + HCl	8	96 mg	8	Anaerobic	NA			NA		

Test Conditions				Labadie			Sioux		
Test condition	Soil (g)	Addition	Duration (week)	Amount	pH	Aerobic or Anaerobic	Amount	pH	Aerobic or Anaerobic
pH adjusted	48	HCl 36%	1	Varied	6	Aerobic	Varied	6	Aerobic
CaSx- No pH change	48	CaSx	1	0.09 mg		Aerobic	0.09 mg		Aerobic
CaSx- pH adjusted	48	CaSx	1	0.09 mg	7	Aerobic	NA		
Fe- anaerobic	48	Fe(II) sulfate	4	13.8 mg		Anaerobic	13.8 mg		Anaerobic
Fe -anaerobic- pH adjusted	48	Fe(II) sulfate	4	13.8 mg	7	Anaerobic	NA		
Fe - aerobic	48	Fe(II) sulfate	4	13.8 mg		Aerobic	13.8 mg		Aerobic
Fe - aerobic- pH adjusted	48	Fe(II) sulfate	4	13.8 mg	7	Aerobic	NA		
ZVI (SR.2S)	48	SR.2S	4	11 mg		Anaerobic	11mg		Anaerobic
ZVI (SR.2S)- pH adjusted	48	SR.2S + HCl	4	11 mg	7	Anaerobic	NA		
ZVI (SR.2S)-Food	48	SR.2S + Food	8	11 mg		Anaerobic	11mg		Anaerobic
ZVI (SR.2S)-Food- pH adjusted	48	SR.2S + Food + HCl	8	11 mg	7	Anaerobic	NA		
ZVI (7 micron)	48	7 micron	4	11 mg		Anaerobic	11mg		Anaerobic
ZVI (7 micron)- pH adjusted	48	7 micron + HCl	4	11 mg	7	Anaerobic	NA		
ZVI (7 micron)- Food	48	7 micron + Food	8	11 mg		Anaerobic	11mg		Anaerobic
ZVI (7 micron)- Food- pH adjusted	48	7 micron + Food + HCl	8	11 mg	7	Anaerobic	NA		

Notes:

SR.2S = particle size ZVI

ZVI = zero valent iron

7 micron = microscale ZVI

Food = lactate, EOL, cornsweet, and nutrients

NA = test condition not run

HCl = hydrochloric acid

CaSx = calcium polysulfide

Fe = iron (dissolved)

Table 3

Summary of Rush Island In Situ Total Metals Removal Performance

Rush Island Energy Center, Missouri

	Arsenic	Molybdenum	Boron	Lead	Cobalt	Selenium	Lithium
	mg/L						
Action Levels	0.03	0.1	4	0.015	0.006	0.05	0.065
Average of All Controls[1]	0.18	0.12	3.10	0.13	0.03 J*	0.03 J*	0.13
pH 10	0.17	0.12	3.05	0.08	0.02	0.02	0.07
pH 9	0.12	0.12	2.80	0.08	0.02	0.02	0.09
pH 8	0.10	0.13	3.15	0.05	0.01 J*	0.01 J*	0.06
pH 7	0.07	0.11	3.05	0.06	0.02	0.01	0.08
pH 6	0.02 J*	0.08	3.80	0.03 U	0.06 U	0.06 U	0.06 U
CaSx	0.23	0.12	3.60	0.08	0.07 U	0.07 U	0.07
CaSx pH7	0.05	0.14	3.75	0.03 U	0.06 U	0.06 U	0.04 J*
Dissolved Iron (Anaerobic)	0.20	0.13	3.20	0.11	0.05 U	0.05 U	0.11
Dissolved Iron pH 8 (Anaerobic)	0.11	0.14	3.20	0.08	0.05 U	0.05 U	0.06
Dissolved Iron (Aerobic)	0.19	0.13	3.05	0.13	0.05 U	0.05 U	0.10
Dissolved Iron pH 8 (Aerobic)	0.06	0.14	3.45	0.04 J*	0.05 U	0.05 U	0.13
ZVI Injectable	0.03 U	0.05 U	0.30	0.03 U	0.05 U	0.05 U	0.08 U
ZVI Injectable pH 8	0.03 U	0.05 U	0.13 J*	0.03 U	0.05 U	0.05 U	0.09 U
ZVI PRB	0.02 J*	0.39	3.60	0.03 U	0.05 U	0.05 U	0.04 U
ZVI PRB pH 8	0.03 U	0.04 J*	2.55	0.03 U	0.05 U	0.05 U	0.02 J
ZVI Injectable + Bio	0.025 U	0.05 U	0.32 J	0.025 U	0.05 U	0.05 U	0.06 U
ZVI Injectable pH 8 + Bio	0.025 U	0.05 U	0.07 J	0.025 U	0.05 U	0.05 U	NS
ZVI PRB + Bio	0.03 U	0.32 J	4.45 J	0.03 U	0.05 U	0.05 U	0.02 J
ZVI PRB pH 8 + Bio	0.03 U	0.05 U	2.20 J	0.03 U	0.05 U	0.05 U	0.04 J

Notes:

U = not detected above the indicated concentration

PRB = permeable reactive barrier

Injectable = iron particles at micro-scale; potentially applied through injection

Dissolved iron = 50 mg/L Iron(II) sulfate

NS = not sampled

CaSx = calcium polysulfide

🟩 At or below action level

🟦 Approaching action level

🟧 Above action level and increase relative to control

⬜ Non-detect but detection limit greater than action level

NA = no action level

mg/L = milligrams per liter

J* = half the detection limit was used for non-detect when duplicates had a detection and a non-detect.

pH adjustment testing was conducted over a 7-day test period. The native pH in monitoring well MW-2 was pH 11.

1) Average of All Controls = average of all controls used in the Phase 2 testing for Rush Island Energy Center

Table 4

Summary of Meramec MW-5 In Situ Total Metals Removal Performance

Meramec Energy Center, Missouri

	Arsenic	Molybdenum	Boron	Lead	Cobalt	Selenium	Lithium
	mg/L						
Action Levels	0.01	0.1	4	0.015	0.006	0.05	0.040
Average of All Controls[1]	0.034 J*	0.174	5.5	0.028 J*	0.062 U	0.062 U	0.028 J
pH 10	0.031	0.18	5.55	0.013	0.01 U	0.01 U	0.0285 J
pH 8	0.03	0.16	5.30	0.02	0.01 U	0.01 U	0.04 J
pH 6	0.029	0.11	5.6	0.027	0.01	0.01 U	0.049 J
CaSx	0.05 U	0.17	5.3	0.05 U	0.1 U	0.1 U	0.026 J
Dissolved Iron (Anaerobic)	0.039	0.18 J	4.8	0.035	0.05 U	0.05 U	0.029 J
Dissolved Iron (Aerobic)	0.031	0.17 J	4.6	0.03	0.05 U	0.05 U	0.03
ZVI Injectable	0.025 U	0.05 U	0.33	0.025 U	0.05 U	0.05 U	0.06 U
ZVI PRB	0.025 U	0.08	3.7	0.025 U	0.05 U	0.05 U	0.035 J
ZVI Injectable + Bio	0.05 U	0.1 U	0.31	0.05 U	0.1 U	0.1 U	NS
ZVI PRB + Bio	0.05 U	0.1 U	4.8 J	0.05 U	0.1 U	0.1 U	0.032 J

Notes:

U = not detected above the indicated concentration

PRB = permeable reactive barrier

Injectable = iron particles at micro-scale; potentially applied through injection

Dissolved iron = 50 mg/L Iron(II) sulfate

NS = not sampled

CaSx = calcium polysulfide

J* = half the detection limit was used for non-detect when duplicates had a detection and a non-detect.

pH adjustment testing was conducted over a 7-day test period. The native pH in monitoring well MW-6 was approximately pH 7.5.

1) Average of All Controls = average of all controls used in the Phase 2 testing for Merimec Energy Center MW-5

🟩 At or below action level

🟦 Approaching action level

🟧 Above action level and increase relative to control

▨ Non-detect but detection limit greater than action level

NA = no action level

mg/L = milligrams per liter

Table 5
Summary of Meramec MW-6 In Situ Total Metals Removal Performance
Meramec Energy Center, Missouri

	Arsenic	Molybdenum	Boron	Lead	Cobalt	Selenium	Lithium
	mg/L						
Action Levels	0.01	0.1	4	0.015	0.006	0.05	0.040
Average of All Controls[1]	0.0259 J*	0.22 J	10.24 J	0.027 J*	0.062 U	0.062 U	0.128
pH 10	0.0285	0.215	10.5	0.0135	0.01 U	0.01 U	0.12
pH 8	0.013	0.18	11	0.016	0.01 U	0.01 U	0.15
pH 6	0.03	0.14	10	0.027	0.01	0.01 U	0.16
CaSx	0.05 U	0.19	10	0.05 U	0.1 U	0.1 U	0.12
Dissolved Iron (Anaerobic)	0.032	0.26 J	8.5	0.041	0.05 U	0.05 U	0.13
Dissolved Iron (Aerobic)	0.027	0.22 J	8.6	0.033	0.05 U	0.05 U	0.13
ZVI Injectable	0.025 U	0.05 U	0.69	0.025 U	0.05 U	0.05 U	0.5 U
ZVI PRB	0.025 U	0.05	6.5	0.025 U	0.05 U	0.05 U	0.11
ZVI Injectable + Bio	0.05 U	0.1 U	0.72	0.05 U	0.1 U	0.1 U	NS
ZVI PRB + Bio	0.05 U	0.1 U	8.5 J	0.05 U	0.1 U	0.1 U	0.1

Notes:

U = not detected above the indicated concentration

PRB = permeable reactive barrier

Injectable = iron particles at micro-scale; potentially applied through injection

Dissolved iron = 50 mg/L Iron(II) sulfate

CaSx = calcium polysulfide

mg/L = milligrams per liter

half the detection limit was used for non-detect when duplicates had a detection and a non-detect.

pH adjustment testing was conducted over a 7-day test period. The native pH in monitoring well MW-6 was approximately pH 7.6.

1) Average of All Controls = average of all controls used in the Phase 2 testing for Merimec Energy Center MW-6

🟩	At or below action level
🟦	Approaching action level
🟧	Above action level and increase relative to control
▨	Non-detect but detection limit greater than action level

NA = no action level

Table 6
Summary of Labadie In Situ Total Metals Removal Performance
Labadie Energy Center, Missouri

	Arsenic	Molybdenum	Boron	Lead	Cobalt	Selenium	Lithium
	mg/L						
Action Levels	0.0426	0.1	4	0.015	0.006	0.05	0.055
Average of All Controls[1]	0.042 U	0.162 J	9.133 J	0.042 U	0.083 U	0.083 U	0.022 J*
pH 6	0.025 U	0.13 J	7.6	0.025 U	0.05 U	0.05 U	0.018 J
CaSx	0.025 U	0.16 J	7.5	0.025 U	0.05 U	0.05 U	0.016 J
CaSx pH7	0.025 U	0.13 J	7.6	0.025 U	0.05 U	0.05 U	0.017 J
Dissolved Iron (Anaerobic)	0.05 U	0.17	9.5	0.05 U	0.1 U	0.1 U	0.06 U
Dissolved Iron (Aerobic)	0.05 U	0.17	9.6	0.05 U	0.1 U	0.1 U	0.023 J
Dissolved Iron pH 7 (Anaerobic)	0.05 U	0.15	9.5	0.05 U	0.1 U	0.1 U	0.06 U
Dissolved Iron pH 7 (Aerobic)	0.05 U	0.16	9.7	0.05 U	0.1 U	0.1 U	0.06 U
ZVI Injectable	0.05 U	0.1 U	6.5	0.05 U	0.1 U	0.1 U	0.06 U
ZVI Injectable pH 7	0.05 U	0.1 U	6.3	0.05 U	0.1 U	0.1 U	0.06 U
ZVI PRB	0.05 U	0.1	9.3	0.05 U	0.1 U	0.1 U	0.06 U
ZVI PRB pH 7	0.05 U	0.1 U	8.9	0.05 U	0.1 U	0.1 U	0.022 J
ZVI Injectable + Bio	0.05 U	0.1 U	10 J	0.05 U	0.1 U	0.1 U	0.016 J
ZVI Injectable pH 7 + Bio	0.05 U	0.1 U	8.9 J	0.05 U	0.1 U	0.1 U	0.019 J
ZVI PRB + Bio	0.05 U	0.1 U	9.9 J	0.05 U	0.1 U	0.1 U	0.063 J
ZVI PRB pH 7 + Bio	0.05 U	0.1 U	9.2 J	0.05 U	0.1 U	0.1 U	0.038 U

Notes:

U = not detected above the indicated concentration

PRB = permeable reactive barrier

Injectable = iron particles at micro-scale; potentially applied through injection

Dissolved iron = 50 mg/L Iron(II) sulfate

CaSx = calcium polysulfide

mg/L = milligrams per liter

J* = half the detection limit was used for non-detect when duplicates had a detection and a non-detect.

pH adjustment testing was conducted over a 7-day test period. The native pH at Labadie was approximately pH 8.3.

1) Average of All Controls = average of all controls used in the Phase 2 testing for Labadie Energy Center

🟩	At or below action level
🟦	Approaching action level
🟧	Above action level and increase relative to control
⬜	Non-detect but detection limit greater than action level

NA = no action level

Table 7

Summary of Sioux In Situ Total Metals Removal Performance

Sioux Energy Center, Missouri

	Arsenic	Molybdenum	Boron	Lead	Cobalt	Selenium	Lithium
	mg/L						
Action Levels	0.01	0.1	4	0.015	0.006	0.05	0.040
Average of All Controls[1]	0.033 J*	2.867 J	26.7 J	0.065 J*	0.052 J*	0.083 U	0.049
pH 6	0.025 U	1.7 J	23	0.025 U	0.05 U	0.05 U	0.028 J
CaSx	0.025 U	2.7 J	21	0.025 U	0.05 U	0.05 U	0.025 J
Dissolved Iron (Anaerobic)	0.05 U	2.7	28	0.05 U	0.1 U	0.1 U	0.028 J
Dissolved Iron (Aerobic)	0.05 U	2.6	27	0.069	0.1 U	0.1 U	0.085
ZVI Injectable	0.05 U	0.1 U	23	0.05 U	0.1 U	0.1 U	0.06 U
ZVI PRB	0.05 U	0.81	26	0.05 U	0.1 U	0.1 U	0.024 J
ZVI Injectable + Bio	0.05 U	0.5 J	19 J	0.05 U	0.1 U	0.1 U	0.029 J
ZVI PRB + Bio	0.05 U	0.1 U	27 J	0.05 U	0.1 U	0.1 U	0.021 J

Notes:

U = not detected above the indicated concentration

PRB = permeable reactive barrier

Injectable = iron particles at micro-scale; potentially applied through injection

Dissolved iron = 50 mg/L Iron(II) sulfate

CaSx = calcium polysulfide

mg/L = milligrams per liter

J* = half the detection limit was used for non-detect when duplicates had a detection and a non-detect.

pH adjustment testing was conducted over a 7-day test period. The native pH at Sioux was approximately pH 7.8.

1) Average of All Controls = average of all controls used in the Phase 2 testing for Sioux Energy Center

🟩 At or below action level

🟦 Approaching action level

🟧 Above action level and increase relative to control

▨ Non-detect but detection limit greater than action level

NA = no action level

Table 8
Summary of Preliminary Ferric Chloride Treatability Testing - Rush Island
Rush Island Energy Center, Missouri

	Arsenic			Molybdenum		
	1 hour[1]	3 hour[2]	6 hour[3]	1 hour[1]	3 hour[2]	6 hour[3]
	mg/L					
Action Level	0.03			0.1		
Total Metals						
Baseline	0.224			0.146		
20 mg/L $FeCl_3$, pH 6[4]	0.0072	0.0109	0.0126	0.0205	0.0241	0.0283
40 mg/L $FeCl_3$, pH 6[4]	0.0049	0.0059	0.0062	0.01 U	0.01 U	0.01 U
40 mg/L $FeCl_3$, pH 4[5]	0.0056	0.0085	0.0105	0.01 U	0.01 U	0.01 U
40 mg/L $FeCl_3$, 3% H_2O_2, pH 6[4,6]	0.0269	NM	NM	0.188	NM	NM

Notes:

U = not detected above the indicated concentration

mg/L = milligrams per liter

NM = not measured

$FeCl_3$ = ferric chloride

🟩 At or below action level

🟦 Approaching action level

🟧 Above action level and increase relative to baseline

⬜ Non-detect but detection limit greater than action level

1) 1 hour sample started collecting 1.5 hours after $FeCl_3$ added (flow through column started 0.5 hours after $FeCl_3$). Ended collection 3 hours after $FeCl_3$ added.

2) 3 hour sample started collecting 3.5 hours after $FeCl_3$ added. Ended collection 5 hours after $FeCl_3$ added.

3) 6 hour sample started collecting 5.5 hours after $FeCl_3$ added. Ended collection 7 hours after $FeCl_3$ added.

4) pH of 6 was the goal but after adding the $FeCl_3$, the 20 mg/L test was a pH of 4.65 and the 40 mg/L was a pH of 3.66. Did not measure the final pH of the H_2O_2 test.

5) pH of 4 was the goal but after adding the $FeCl_3$, the 0 mg/L test was a pH of 3.45.

6) this was the only sample that had a brownish tent to it in the effluent. The flocks had formed faster and seemed to settle out better than those without the H_2O_2. Bubbles noted in effluent of column.

Table 9
Summary of Ferric Chloride Continuous Flow Test - Rush Island
Rush Island Energy Center, Missouri

Sand Filter									
	Action Level	Influent	Intermediate			Effluent Sand Filter			
			19 hr	2 day	8 day*	Ave first 19 hr	19 hr	2 day	7 day
Total mg/L									
Arsenic	0.03	0.212	NM	NM	0.0288	0.0013	0.001	0.001 U	0.0107
Molybdenum	0.1	0.156	NM	NM	0.0267	0.01 U	0.01 U	0.01 U	0.0151
Lead	0.015	0.0057	NM	NM	0.0016	0.0026	0.0023	0.001 U	0.001 U
Lithium	0.0647	0.005 U	NM	NM	NM	0.005 U	0.005 U	0.005 U	NM
Iron	NA	0.0769	NM	NM	1.15	NM	NM	NM	0.299
Boron	4	4**	NM	NM	NM	NM	NM	NM	NM
Dissolved mg/L									
Arsenic	0.03	0.198	0.0019	0.0032	0.0219	0.001 U	0.001 U	0.001 U	0.0094
Molybdenum	0.1	0.144	0.01 U	0.01 U	0.0224	0.01 U	0.01 U	0.01 U	0.0136
Lead	0.015	0.0052	0.0022	0.0035	0.0014	0.0029	0.0027	0.001 U	0.001 U
Lithium	0.0647	0.005 U	0.005 U	0.005 U	NM	0.005 U	0.005 U	0.005 U	NM
Iron	NA	0.0552	NM	NM	0.831	NM	NM	NM	0.204
Boron	4	NM	NM	NM	NM	NM	NM	NM	NM

Filters - Mimic Resin Filtration Followed By Resin						
	Action Level	Influent	Effluent 100 micron filter - 3 Days	Effluent 10 micron filter - 3 Days	filter pH to 7.5 adjusted - 3 Days	Post Resin
Total mg/L						
Arsenic	0.03	0.212	0.0363	0.0023	NM	0.0016
Molybdenum	0.1	0.156	0.0257	0.01 U	NM	0.01 U
Lead	0.015	0.0057	NM	NM	NM	NM
Lithium	0.0647	0.005 U	NM	NM	NM	NM
Iron	NA	0.0769	4.41	2.69	NA	5.11
Boron	4	4**	NM	4**	NA	0.02 U
Dissolved mg/L						
Arsenic	0.03	0.198	0.0032	0.0016	0.001 U	0.0012
Molybdenum	0.1	0.144	0.01 U	0.01 U	0.01 U	0.01 U
Lead	0.015	0.0052	NM	NM	NM	NM
Lithium	0.0647	0.005 U	NM	NM	NM	NM
Iron	NA	0.0552	1.92	2.33	0.951	0.503
Boron	4	NM	NM	NM	NM	0.02 U

Notes:

U = not detected above the indicated concentration

mg/L = milligrams per liter

$FeCl_3$ = ferric chloride at 40 mg/L

NM = not measured

NA = not applicable. Not a metal of concern

hr = hour

Ave = average of the flow collected in the first 19 hours

Intermediate = collected after $FeCl_3$ has been added and mixed, and the flocculants are being settled

Rush Island water was adjusted to a pH of 5.8-6.0 prior to adding the $FeCl_3$ and had a final pH of 4.0-4.3.

Effluent water was adjusted to a pH of 6-8 prior to passing through the resin.

* = the total intermediate sample was passed through a 5 micron filter to simulate a bag filter.

** = results are internal XDD measurements using colorimetric Hach testing

🟩	At or below action level
🟦	Approaching action level
🟧	Above action level and increase relative to baseline
⬜	Non-detect but detection limit greater than action level

Table 10
Summary of pH Adjustment and Resin Column Testing - Rush Island
Rush Island Energy Center, Missouri

	Arsenic	Boron	Molybdenum
	mg/L		
Action Level	0.03	4	0.1
Total Metals			
Baseline	0.224	3.72	0.146
Day 1	0.0261	0.02 U	0.01 U
Day 3	0.0042	0.02 U	0.01 U
Day 7 - pH only	0.198	3.64	0.153
Day 7	0.0568	0.02 U	0.01 U
Dissolved Metals			
Baseline	0.211	3.39	0.14
Day 1	0.0242	0.02 U	0.01 U
Day 3	0.0032	0.02 U	0.01 U
Day 7 - pH only	0.189	3.27	0.142
Day 7	0.0525	0.02 U	0.01 U

Notes:

U = not detected above the indicated concentration

mg/L = milligrams per liter

pH was adjusted to 5

pH only = sample collected after pH adjustment and flowing through sand, but before the ion-specific resin

🟩 At or below action level
🟦 Approaching action level
🟧 Above action level and increase relative to baseline
▨ Non-detect but detection limit greater than action level

Table 11

Summary of Zero Valent Iron Column Metals Removal - Rush Island

Rush Island Energy Center, Missouri

	Column Construction: 5 Parts Sand per 1 Part ZVI				Column Construction: 2 Parts Sand per 1 Part ZVI			
	Arsenic	**Boron**	**Iron**	**Molybdenum**	**Arsenic**	**Boron**	**Iron**	**Molybdenum**
	mg/L							
Action Level	0.03	4	--	0.1	0.03	4	--	0.1
Total Metals								
Baseline	0.195	3.84	0.0721	0.143	0.211	3.51	0.0817	0.148
Day 1	0.034	3.48	0.357	0.0954	0.0419	3.47	0.503	0.145
Day 3	0.114	3.86	0.0959	0.15	0.082	3.4	0.166	0.134
Day 7	0.113	3.9	0.15	0.151	0.089	3.51	0.11	0.143
Dissolved Metals								
Baseline	0.18	3.71	0.0614	0.139	0.212	3.47	0.0489	0.143
Day 1	0.025 U	3.117	0.047	0.0792	0.0439	3.42	0.04 U	0.143
Day 3	0.104	3.59	0.0569	0.134	0.0836	3.36	0.0702	0.133
Day 7	0.101	3.61	0.114	0.135	0.0898	3.34	0.0805	0.138

Notes:

U = not detected above the indicated concentration

ZVI = zero valent iron - micro-scale size

mg/L = milligrams per liter

🟩 At or below action level

🟦 Approaching action level

🟧 Above action level and increase relative to baseline

⬜ Non-detect but detection limit greater than action level