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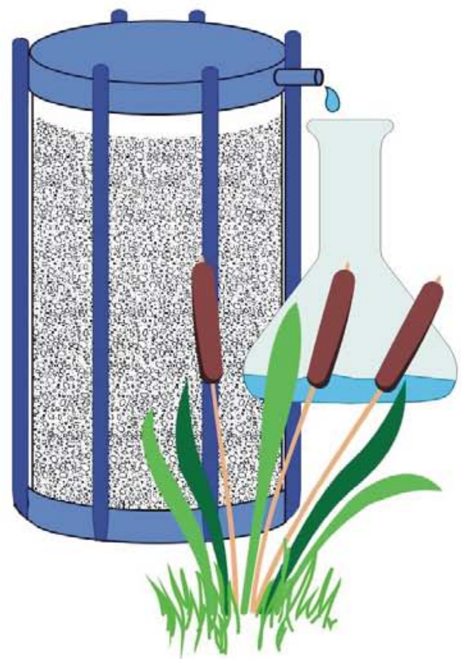
Environmental Sciences Laboratory

Alternatives for Mending a Permeable Reactive Barrier at a Former Uranium Milling Site: Monticello, Utah

April 2005



Prepared for
U.S. Environmental Protection Agency
Region 8, Denver, Colorado
Under Interagency Agreement DW89953767018
By U.S. Department of Energy
Grand Junction, Colorado

Work Performed by S.M. Stoller Corporation Under DOE Contract No. DE–AC01–02GJ79491 for the U.S. Department of Energy Office of Legacy Management, Grand Junction, Colorado
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Signature Page

Alternatives for Mending a Permeable Reactive Barrier at a Former Uranium Milling Site: Monticello, Utah

April 2005

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*The Environmental Sciences Laboratory is operated by S.M. Stoller Corporation for the U.S. Department of Energy Office of Legacy Management, Grand Junction, Colorado

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Executive Summary

In 1999, the U. S. Department of Energy installed an in-situ permeable reactive barrier (PRB) containing zero-valent iron (ZVI) downgradient of the former uranium milling site near Monticello, Utah. Soil-bentonite slurry walls are used to direct ground water to the PRB. The slurry walls extend south and north of the PRB and were designed to extend from the PRB to the valley walls; thus, directing the entire alluvial ground water system to the PRB. Unfortunately, some contaminated ground water is flowing around the south slurry wall. This project investigated methods that might be used to *mend* the gap on the south end of the slurry wall. Although not required as part of the Record of Decision, DOE is considering these alternatives that might be capable of supplementing the existing ground water remedial actions at the site.

An engineering cost evaluation was completed for seven mending alternative technologies: (1) ground water extraction and treatment at the PRB, (2) placing ZVI in borings, (3) placing ZVI in borings using removable canisters, (4) jet grouting ZVI , (5) ferric iron injections, (6) ferrous iron injections, and (7) dithionite injections. The net present values of the seven alternatives range from $71,877 to $137,000. The costs are somewhat similar and we conclude that selecting an alternative should focus on factors such as land use and likelihood of success rather than cost.

All of the technologies evaluated, except ferrous iron injection, had been bench-scale tested prior to this investigation. To fill the data gap, this project conducted batch and column tests of ferrous iron injection. Batch tests confirmed that ferrous iron minerals are capable of sorbing uranium from ground water. Ferrous hydroxide minerals were effective in sorbing uranium with distribution ratios up to 19,528 mL/g.

Three column tests were conducted with ferrous iron. In one column test, ferrous iron minerals precipitated from dissolved ferrous sulfate contacting hydrated lime, but did not precipitate upon contact with calcite. In another column test, ferrous iron minerals precipitated from dissolved ferrous sulfate contacting a commercial bentonite clay that we pretreated with sodium hydroxide. The goal of the pretreatment was to saturate adsorption sites with hydroxyl ions. In a third test, ferrous iron was emplaced in a column containing alluvial sediment collected from the Monticello site that had been pretreated with hydroxyl ions. The column treated with ferrous iron was able to sorb uranium and molybdenum from a solution with ionic composition similar to ground water at the Monticello site. A potential issue with ferrous iron injection is that it is highly soluble and may travel long distances before precipitating.

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1.0 Introduction

A permeable reactive barrier (PRB) is a zone of chemically-reactive material placed in the flow path of contaminated ground water such that contaminants are stabilized or degraded as ground water moves through the zone. An in-situ PRB containing zero-valent iron (ZVI) was installed downgradient of the Monticello site in 1999; it is a funnel and gate system with a three zone PRB. The furthest upgradient zone (the “pretreatment” zone) has 13 percent ZVI by volume mixed with pea gravel. Just downgradient from the “pretreatment zone” is a zone of 100 percent ZVI followed by the third zone containing 100 percent gravel and an air sparging unit.

Contaminated ground water flows through alluvium in the mid-portion of an erosional valley. The alluvium is underlain by low-permeability bedrock composed of siltstone and shale. The PRB is keyed into the bedrock to prevent ground water from underflowing the reactive material. Soil-bentonite slurry walls are used to direct ground water to the PRB and are also keyed into the bedrock. The slurry walls extend south and north of the PRB, and were designed to extend from the PRB to the valley walls; thus, directing the entire alluvial ground water system to the PRB. Unfortunately, despite the effort to key the slurry wall into the low permeability bedrock at the valley wall, some contaminated ground water is flowing around the south slurry wall. This project investigated methods that might be used to mend the gap on the south end of the slurry wall. Information from the investigation would be applicable to other PRB sites.

Seven alternatives were proposed for consideration in mending the PRB:

1. Ground water extraction and treatment at the PRB
2. Place ZVI in borings
3. Place ZVI in borings using removable canisters
4. Jet grouting of ZVI
5. Ferric iron injections
6. Ferrous iron (Fe^{2+}) injections
7. Dithionite injections

The use of ZVI for treating uranium (U) is well documented and requires no additional bench-scale testing (Naftz et al. 2002). Jet grouting and bore hole fill methods of emplacement have been implemented at other sites and information is sufficient to establish a reasonable conceptual-scale cost estimate for these emplacements (Rumar and Mitchell 1995). Injection of ferric iron has been tested at bench scale and design parameters can be estimated without additional bench-scale testing (Morrison et al. 1996). Dithionite injection has been used at field scale to stabilize chromium contamination in ground water (Vermeul et al. 2002). Limited bench and field scale experience indicates that ferrous iron (Fe^{2+}) will immobilize chromium, but no comparable data are available for U. Therefore, the bench-scale efforts in this study focus on evaluating Fe^{2+} to stabilize U.

2.0 Costs of Mending Alternatives

The following assumptions are made for all alternatives:

1. A ground water flux of 1 gpm is bypassing the slurry wall on the south; U concentration is 1 mg/L.
2. The mending remedy will need to function for 10 years. Thus, about 5.3 M gal of ground water need to be treated (~ 20 M liters). This corresponds to removal of about 20 M mg of U (equivalent to 20 kg or 44 lbs). Equivalent to 84 mol of U.
3. Depth to bedrock is 35 ft, 2 ft of saturation overlies bedrock, and the width of the bypass zone is 40 ft (DOE 2004)
4. Dissolved oxygen (DO) concentration of the ground water to be treated is 2.5 mg/L based on analyses from well PW-17.

Alternatives for mending the PRB are summarized in Table 1. The cost basis for the estimates is provided in the following sections. No monitoring wells are included in the cost analysis; it is assumed that the monitoring needs are the same for all alternatives. Costs include only direct subcontractor costs and labor for technical staff; additional costs for permitting, access, health and safety coverage, etc., are not included. Details of the cost estimates are provided in Appendix A.

Table 1. Summary of Mending Options

Alternative	Net Present Value	Alternative Description
1	$72,393	Ground water extraction and treatment at the PRB
2	$90,313	Place ZVI in borings
3	$77,678	Place ZVI in borings using removable canisters
4	$137,000	Jet grouting of ZVI
5	$96,764	Ferric iron injections
6	$71,877	Ferrous iron injections
7	$84,430	Dithionite injections

This type of analysis involves many assumptions and the actual costs may vary considerably if the assumptions are inaccurate. Other than Alternative 4 (jet grouting), net present values for the alternatives are similar. Thus, the choice of alternative should be based more on a skilled assessment of technical feasibility and likelihood for success, rather than implementation costs.

2.1 Alternative 1: Ground Water Extraction and Treatment at the PRB

This alternative is discussed in the Focused Feasibility Study (DOE 2004). Three extraction wells are placed in the bypass zone and extracted water is pumped into wells of the PRB. The net present value of this option is $72,393.

2.2 Alternative 2: Place ZVI in Borings

This alternative assumes that an array of 20 borings will be used. ZVI will be added to the borings through auger flights. Thickness of the ZVI is 10 ft. The net present value of this alternative is $90,313.

2.3 Alternative 3: Place ZVI in Borings Using Removable Canisters

The costs of removable cartridges are based on a simple system involving placement of slotted PVC casings filled with ZVI within an outer casing. No attempt is made to assure continuity of the PRB, as is the case for Alternative 2.

More elaborate design concepts are presented by MSE (1997). At the time of the MSE report, no sites were using replaceable media and to our knowledge this is still the case. The authors of MSE (1997) believe significant issues would have to be overcome prior to commercialization of removable canister PRBs including: (1) fabrication methods, (2) size/weight restrictions, and (3) leaking surface seals.

We assume $20K for design and fabrication of 10 canisters. We assume that the canisters will be changed out once during the 10 year period. Using these assumptions, the mass of ZVI and longevity are similar to the 20 borings used in Alternative 2. The net present value of this alternative is $77,678.

2.4 Alternative 4: Jet Grouting

Jet grouting involves a substantial amount of heavy equipment. Mobilization and demobilization costs for a jet grouting demonstration at Cape Canaveral Air Station in 1999 was $75K (Rust Environmental 1999). Mobilization costs for a jet-grouting demonstration at Travis Air Force Base in 2002 was similar (MACTEC 2002). It is assumed that smaller equipment can be located for the Monticello work because it is shallower in depth than these other projects; thus, mob/demob costs for Monticello are estimated at $20K.

Based on the Travis AFB project that injected on 5-ft centers, 8 injection points are required to span the 40 ft width at Monticello. It is assumed that ZVI would be grouted in “thin diaphragm” style rather than “columnar” style due to the relatively small amount of ZVI required. For “thin diaphragms”, grouting jets are opposed 180 degrees and the jetting pipe is not rotated as it grouts. This method leaves a thin slab of ZVI perpendicular to ground water flow. The net present value of this alternative is $137,000.

2.5 Alternative 5: Ferric Iron Injections

Morrison et al. (1996) presented data on sorption of U by amorphous ferric oxyhydroxide (AFO). The study reported that about 0.024 kg of U are sorbed to 1 kg of Fe (as AFO). To remove 20 kg of U during the PRB mending period, about 850 kg of Fe (~2,500 kg of $FeCl_3$; 5,500 lbs; 2.8 tons) are required. The cost of ferric chloride delivered in liquid form is about $500/ton ($2.50/lb) of $FeCl_3$. The net present value of this alternative is $96,764.

2.6 Alternative 6: Ferrous Iron Injections

Costing for this alternative assumes that Fe^{2+} will precipitate in the formation without the addition of hydroxide. The cost of dissolved ferrous sulfate delivered to Amarillo Texas was $0.67 per pound of Fe, based on a quote from Kemiron Co., January 2004. Costing for Monticello assumed a delivered price of $0.90 per lb of Fe.

We need to treat 20 M liters of ground water. Dissolved oxygen concentration in well PW-17 is about 2.5 mg/L; in 20 M liters of ground water, there is 1562 mol of DO (20 M L * 2.5 mg/L * 1/32,000 mol/mg). Each mol of DO oxidizes 4 mol of Fe so the ground water contains enough O_2 to oxidize 6248 mol (1562 *4) of Fe^{2+}. This is equivalent to 350 kg (770 lbs of Fe). The amount of Fe^{2+} required to reduce the DO is 350 kg (770 lbs).

To reduce the U we assume a simple reaction:

$$UO_2^{2+} + 2\ Fe^{2+}\ (solid) = UO_{2(solid)} + 2Fe^{3+}\ (solid)$$

Thus, 2 mols of Fe is required to reduce 1 mol of U. To reduce 84 mols of U requires 168 mols of Fe^{2+}. 168 mols of Fe^{2+} is equivalent to 9.4 kg (21 lbs) of Fe^{2+}. Thus, we need a total of 791 lbs (770 + 21) of Fe^{2+} to treat 20 M gal of ground water. The net present value of this alternative is $71,877.

2.7 Alternative 7: Dithionite Injections

Dithionite reacts with indigenous ferric iron to form Fe^{2+} which is then available to reduce U:

$$S_2O_4^{2-}\ (aq) + 2\ Fe^{3+}\ (s) + 2\ H_2O = 2\ SO_3^{2-} + 2\ Fe^{2+}\ (s) + 4\ H^+$$

Thus, 1 mol of dithionite ion produces 2 mol of Fe^{2+}. We require 791 mols of Fe^{2+} (see Section 6.0); thus, about 400 mol of $S_2O_4^{2-}$ are required. assuming 100 % efficiency. This is equivalent to 69 kg (152 lbs) of $Na_2S_2O_4$. Because the reduction process is inefficient, we will assume 300 lbs of $Na_2S_2O_4$ are required.

Sodium dithionite mixed with potassium carbonate is available at $22,700 for 4300 lbs of $Na_2S_2O_4$ and 10,000 lbs of K_2CO_3 (in a volume of 4250 gal); based on a January 2004 price quote from John Anderson delivered to Amarillo, Texas. Cost per lb of contained $Na_2S_2O_4$ solution is $5.28. This mixture was used by Pacific Northwest National Laboratory personnel for injections at the Hanford site and at other sites (Isaacs 2004). The purpose of the higher-cost potassium buffer is to ensure that pH remains high without causing significant deleterious impact to the clay minerals in the formation. Chemical in liquid form is delivered to the site in refrigerated trucks. The cost estimate assumes that dithionite is left in the ground and no extraction is needed. The estimate also assumes that there is sufficient reducible iron in the formation at Monticello to be chemically reduced by the injected dithionite.

Process monitoring costs are included, consisting of taking measurements during the injection and within a few days of the injection to help establish the effects of the installation.

Measurements include water levels, pH, oxidation reduction potential (ORP), conductivity, sulfate concentration, and iron concentration. The net present value of this alternative is $84,430.

3.0 Bench-Scale Testing of a Mending Methodology Using Injection of Ferrous Iron

One alternative for mending the Monticello PRB is to inject Fe^{2+} into the subsurface. The goal of this remediation technology is to emplace immobile ferrous hydroxide minerals that are capable of sorbing or chemically reducing U from the ground water. The objective of the bench-scale testing was to evaluate the feasibility of various methods that might be used to emplace ferrous hydroxide into the subsurface.

Testing was conducted in four steps. First, batch tests were conducted to evaluate whether Fe^{2+} minerals are capable of sorbing U. Second, column tests were used to evaluate whether Fe^{2+} minerals could be emplaced by injection of dissolved Fe^{2+} into sediment containing carbonate or hydroxide minerals. These tests were conducted with "ideal" solid materials such as calcium (Ca) carbonate and $Ca(OH)_2$. The rationale for using "ideal' solids is to determine if Fe^{2+} emplacement is possible under the best possible conditions before attempting emplacement in the more heterogeneous conditions of the subsurface environment. Third, column tests were conducted to evaluate if a pre-injection of sodium hydroxide into a clay-bearing formation could condition the formation so that an injection of dissolved Fe^{2+} would successfully emplace ferrous hydroxide. Lastly, core samples from the Monticello site were used in a column test to evaluate the emplacement methodology and the efficiency of U and Mo uptake by the treated soil.

3.1 Batch Tests of Uranium Uptake by Ferrous Iron

Batch tests were conducted to determine if minerals, precipitated from dissolved Fe^{2+} are capable of sorbing U from ground water. A 0.1 M ferrous sulfate solution was prepared and 0.5 mL of concentrated sulfuric acid was added to ensure complete dissolution. The pH value and oxidation reduction potential (ORP) of the ferrous sulfate solution were 2.21 and 312 mV, respectively. Sodium hydroxide (NaOH) was added to the ferrous sulfate solution. The pH value increased to 7.58 and the ORP decreased to –624 mV as NaOH was added. A dark green precipitate (probably ferrous hydroxide) formed. The precipitate was concentrated into a suspension containing about 112 mg Fe per mL by centrifuging and decanting. Aliquots of ferrous hydroxide suspension were combined with U carbonate solution (2 mg/L U, 350 mg/L $NaHCO_3$, bubbled with helium gas to deoxygenate) and agitated end-over-end for 2 hours.

Some of the mixtures, particularly those with small amounts of ferrous hydroxide, turned red orange indicating they had oxidized due to leakage of laboratory air. Results are shown in Table 2. The ferrous hydroxide precipitant was effective in sorbing U with distribution ratios (R_d) up to 19,528 mL/g. A reactive material with an R_d of about 1,000 mL/g is believed to suitable for some PRB applications. Therefore, column testing was initiated.

Table 2. Results of batch tests of uranium uptake by suspensions of ferrous hydroxide

Sample Number	Suspension Volume (mL)	Final pH	Final ORP (mV)	Final U (µg/L)	Sorbed U (µg U/ mg Fe)	R_d[a] (mL/g)
1	0	8.20	46	1858	na	na
2	0.25	7.00	56	717.6	1.62	1,407
3	0.5	6.72	58	126.6	1.24	6,073
4	1.0	6.20	56	20.9	0.66	19,528
5	1.5	5.51	58	31.4	0.43	8,613
6	2.0	4.80	59	118.4	0.31	1,627
7	2.5	5.81	<20	19.9	0.13	4,100

[a]R_d = Distribution ratio. Calculated as the concentration in solid phase [based on $Fe(OH)_2$] divided by concentration in dissolved phase.

3.2 Column Test 1: Ferrous Iron Emplacement into a Column Containing Calcium Carbonate and Lime

Column test 1 evaluated the feasibility of precipitating ferrous hydroxide minerals from dissolved ferrous sulfate contacting calcite ($CaCO_3$) or hydrated lime [$Ca(OH)_2$]. We hypothesized that ferrous hydroxide would precipitate because of an increase in the pH values from contact with $CaCO_3$ or $Ca(OH)_2$. Calcite is present in many subsurface sediments, including Monticello, and $Ca(OH)_2$ could be emplaced by injection.

3.2.1 Experimental Methods

A column (1.5-in. diameter, 18-in. long clear acrylic) was packed with 5 zones of different materials. From bottom to top, the materials are: (1) 4.0 in. of sand, mass 317.0 g, (2) 3.4 in. of sand mixed with 4.7 weight percent powdered calcite, total mass 281.9 g, (3) 4.0 in. of sand, mass 323.1 g, (4) 3.9 in. of sand mixed with 5 weight percent $Ca(OH)_2$, total mass 285.4 g, and (5) 2.5 in. of sand, mass 145.2 g. The sand is mostly quartz with some feldspar and was obtained from Unimin Corp. (product number 2075). Calcite and $Ca(OH)_2$ are powdered and were obtained from Aldrich Chemicals; product numbers 23-921-6 and 23-923-2, respectively. The filled column prior to conducting the test is shown in Figure 1.

The column and tubing was purged with nitrogen gas (N_2) to remove residual oxygen. A 0.1 M ferrous sulfate solution was passed through the column at 10 mL/min. About 0.5 mL of concentrated sulfuric acid was added to each liter of ferrous sulfate solution to ensure complete dissolution. The ferrous sulfate solution was continually purged with N_2 gas. Values of pH and ORP were measured with inline probes at the inlet and outlet of the column; these data were recorded every 30 seconds with a datalogger. Effluent samples were collected in glass test tubes on a fraction collector. The collection tubes contained nitric acid as a preservative. The samples were analyzed for Ca and Fe by atomic absorption spectroscopy [ESL Procedures AP(Fe-1) and AP(Ca-1); DOE 2005].

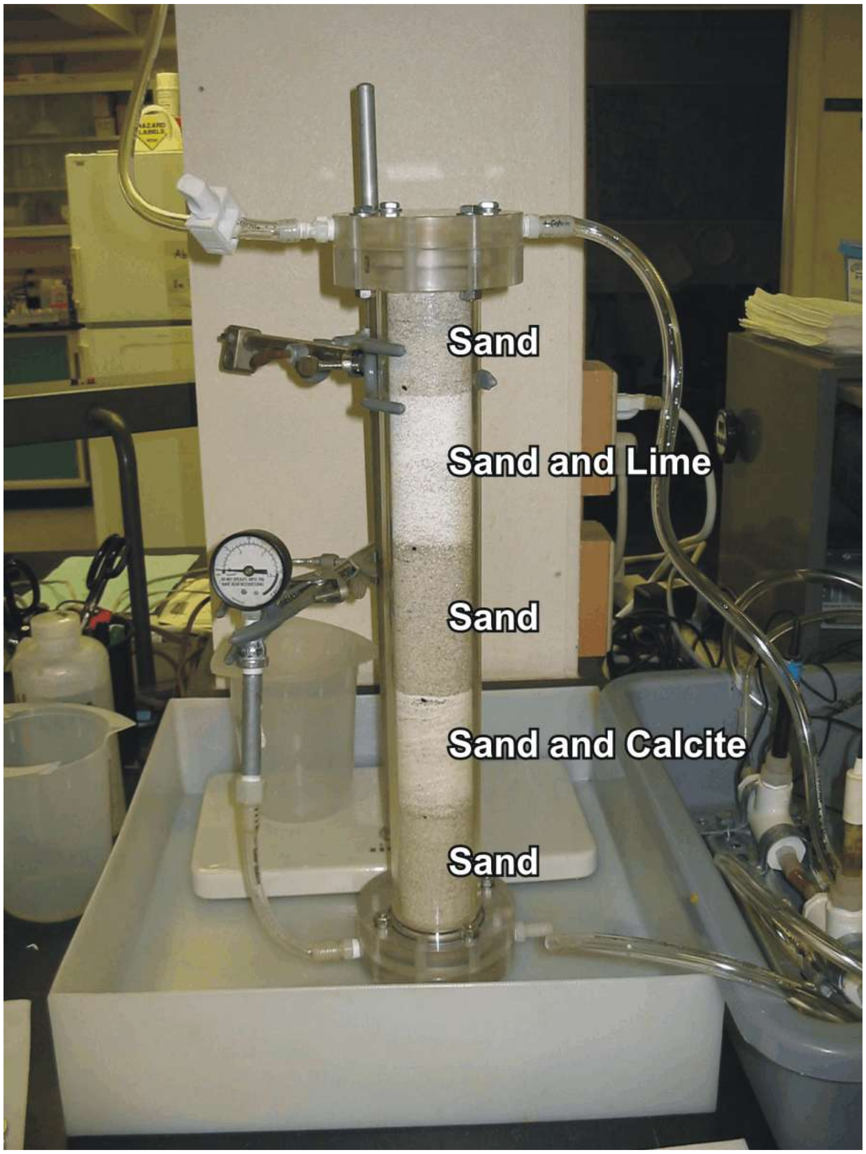

Figure 1. Column Test 1. Experimental apparatus filled with solid phases.

After the test was completed, the solid materials in the column were sampled. A composite sample was collected from each of the layers. The samples were digested in concentrated nitric acid in a microwave oven [ESL Procedure SE(MD-1); DOE 2005]. and analyzed for Ca and Fe by atomic absorption.

3.2.2 Results and Discussion

About 3.3 pore volumes (1.4 L) of ferrous sulfate solution was passed through the column. The acidic ferrous sulfate solution reacted with $CaCO_3$ and $Ca(OH)_2$ as it passed through the column. The influent values of pH and ORP were about 2.3 and 277 mV, respectively (Figure 2). Initial effluent values of pH were about 7.8 and the values decreased gradually to about 6.8 during the test. The effluent solution was strongly reducing as indicated by an ORP of about –400 mV (values may have been lower because -400 mV is the lowest value that could be read with the probes used in this test).

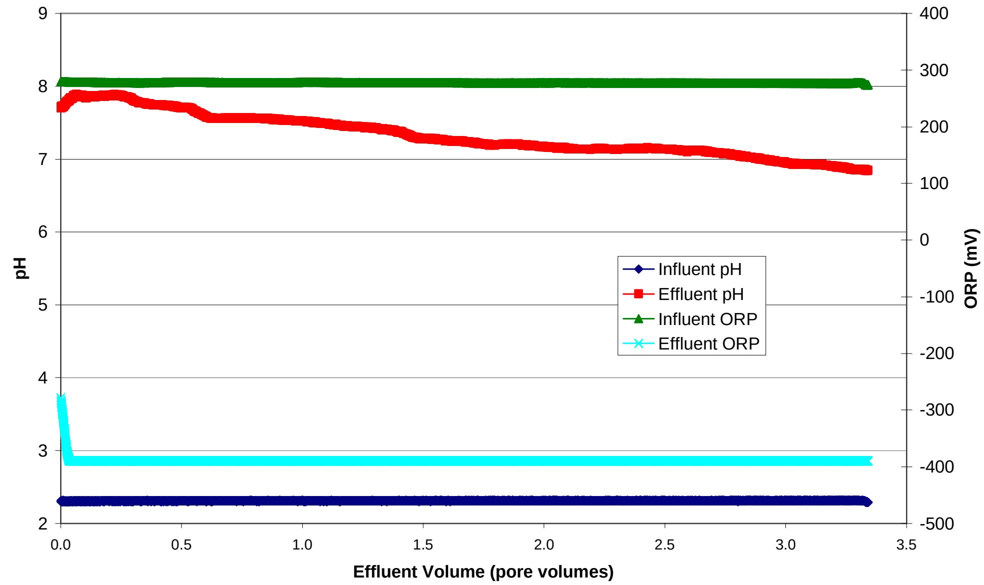

Figure 2. Column Test 1: Values of pH and ORP.

Calcium was dissolved and Fe was precipitated as the ferrous sulfate solution reacted with $CaCO_3$ and $Ca(OH)_2$. Effluent concentrations of Fe were less than the influent value (5,600 mg/L) until about 1.5 pore volumes of effluent (Figure 3). Subsequently, the concentrations of Fe were slightly higher than the influent values indicating that some Fe was being removed from the column. Green particles were observed at the column outlet indicating that some Fe was removed in particulate form. Nearly 1,000 mg of Fe had accumulated in the column prior to Fe being released (Figure 3). In a field application, this particulate Fe would probably be available for contaminant uptake.

Analysis of the column solid materials after the Fe^{2+} injection also indicates that Fe accumulated in the column. Dark green bands formed in the $Ca(OH)_2$ layer indicate the presence of ferrous hydroxide mineralization (Figure 4). The Fe concentration in the $Ca(OH)_2$/sand layer was 5,540 mg/kg compared to 1,290 mg/kg in the sand alone. The elevated pH caused by the $Ca(OH)_2$ caused the ferrous hydroxide to precipitate. Apparently, the pH increase in the $CaCO_3$/sand layer was insufficient to cause ferrous hydroxide precipitation as indicated by the lack of dark green color and low (1,430 mg/kg) Fe concentration (Figure 4).

These results suggest that a pH amendment, such as $Ca(OH)_2$, may be required to cause ferrous hydroxide precipitation in a field application. This result prompted the design of column test 2 (see next section) which used sodium hydroxide to condition clay minerals prior to application of dissolved Fe^{2+}.

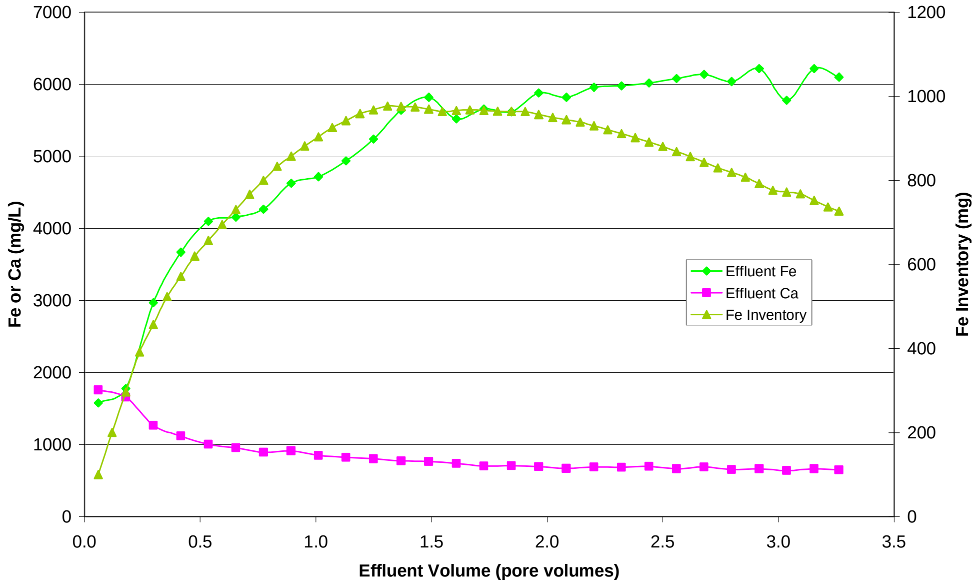

Figure 3. Column Test 1: Effluent concentrations of Fe and Ca, and inventory of Fe accumulated in the column. Influent concentrations of Fe and Ca are 5,600 and 0.0 mg/L, respectively.

3.3 Column Test 2: Ferrous Iron Emplacement into a Column Containing Bentonite Pretreated with Sodium Hydroxide

Column Test 2 evaluated the feasibility of precipitating ferrous hydroxide minerals from dissolved ferrous sulfate contacting bentonite clay that had been pretreated with sodium hydroxide. The goal of the pretreatment was to saturate adsorption sites with hydroxyl ions. Ferrous hydroxide precipitation is caused by interaction with the hydroxylated sites. In a field application, the subsurface would be saturated with hydroxide prior to injection of dissolved ferrous ions.

3.3.1 Experimental Methods

A column (1.5-in. diameter, 18-in. long, clear acrylic) was packed with 5 zones of different materials. From bottom to top, the materials are: (1) 2.5 in. of sand, mass 211.4 g, (2) 2.4 in. of sand mixed with 5.2 weight percent calcite, total mass 236.6 g, (3) 2.8 in. of sand, mass 212.6 g, (4) 5.0 in. of sand mixed with 9.2 weight percent bentonite, total mass 392.6 g, and (5) 4.8 in. of sand, mass 350.0 g. The sand is mostly quartz with some feldspar and was obtained from Unimin Corp. (product number 2075). The calcite is powdered and was obtained from Aldrich Chemicals; product number 23-921-6. The bentonite is “crumbles # 8” from Colloid Environmental Technologies, Co. (Arlington Heights, Illinois).

The column and tubing was purged with N_2 to remove residual oxygen. Three solutions were passed through the column: (in chronologic order) (1) 1.0 N NaOH, (2) deionized water, and (3) 0.1 M ferrous sulfate. About 0.5 mL of concentrated sulfuric acid was added to each liter of ferrous sulfate solution to ensure complete dissolution. The ferrous sulfate solution was purged with N_2 to remove DO. Values of pH and ORP were measured with inline probes at the inlet and outlet of the column; these data were recorded every 30 seconds with a datalogger. Effluent samples were collected in glass test tubes on a fraction collector. The samples were analyzed for Ca and Fe by atomic absorption. Porosity of the column (420 mL) was determined by measuring the volume of water during filling.

After the test was completed, the solid materials in the column were sampled. A composite sample was collected from each layer. The samples were digested in concentrated nitric acid in a microwave oven and analyzed for Ca and Fe by atomic absorption spectroscopy.

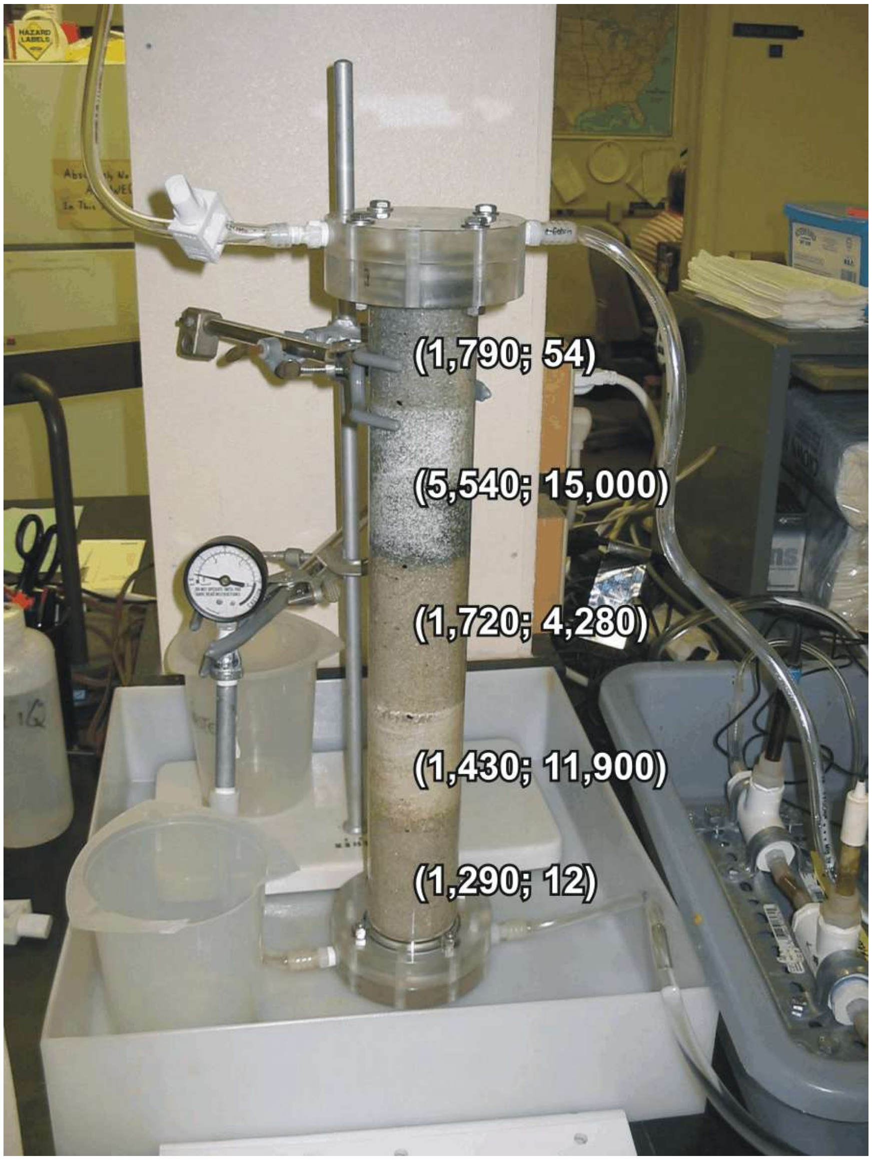

Figure 4. Column Test 1: Photo of column after reaction with ferrous sulfate solution. Numbers in parentheses are (Fe; Ca) solid-phase concentrations in mg/kg.

3.3.2 Results and Discussion

A 1.0 N NaOH solution was passed through the column from 0.0 to 4.0 pore volumes to condition the sediment at high pH. Effluent pH values reflect the high pH environment (Figure 5). Deionized water was then passed through from 3.8 to 4.2 pore volumes. The purpose of the deionized water was to flush the tubing to prevent ferrous hydroxide from precipitating in the tubing during the ferrous sulfate injection. The inlet pH value decreased slightly due to the deionized water. A 0.1 M ferrous sulfate solution was then passed through from 4.2 pore volumes until termination of the test at 6.5 pore volumes. The effluent pH and ORP values decreased to about 6 and –400 mV, respectively, due to the ferrous sulfate injection (Figure 5).

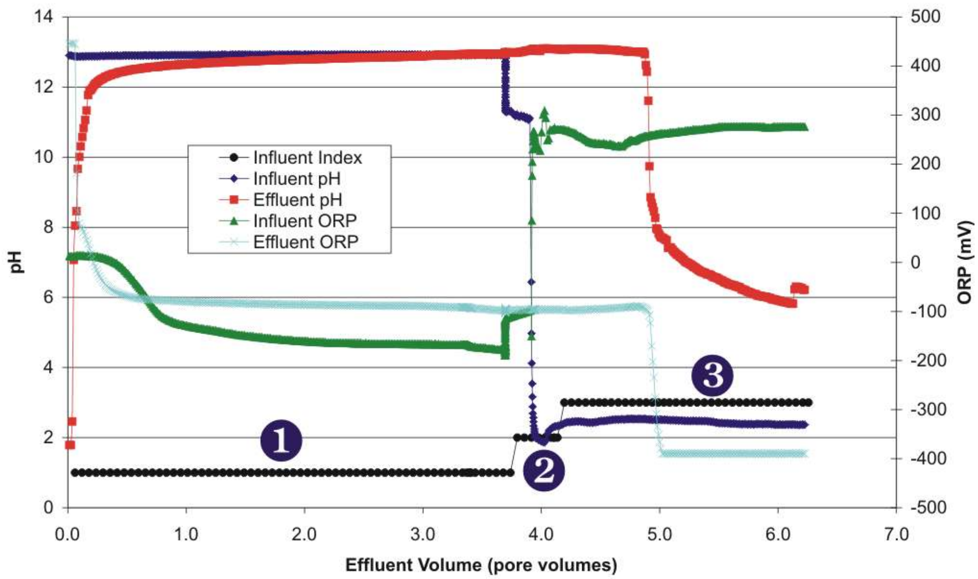

Figure 5. Column Test 2. Values of pH and ORP. The influent index indicates the composition of the influent solution for that period of the test column (1 = 1N NaOH, 2 = deionized water, 3 = ferrous sulfate solution).

The Fe inventory in the column increased by about 1000 mg because of the injection of Fe^{2+} (Figure 6). Dissolved Ca concentrations increased to about 500 mg/L, probably due to dissolution of calcite. These results indicate that the process of treating with NaOH followed by ferrous sulfate is capable of precipitating ferrous minerals in the sediment.

Following the column test, sediment samples from the column were analyzed for Fe. The highest Fe concentration of 3310 mg/kg was found in the bentonite/sand layer (Figure 7). This result suggests that Fe mineralization occurred in proximity to hydroxylated bentonite. The results prompted us to conduct a column test using sediment collected from the aquifer at Monticello.

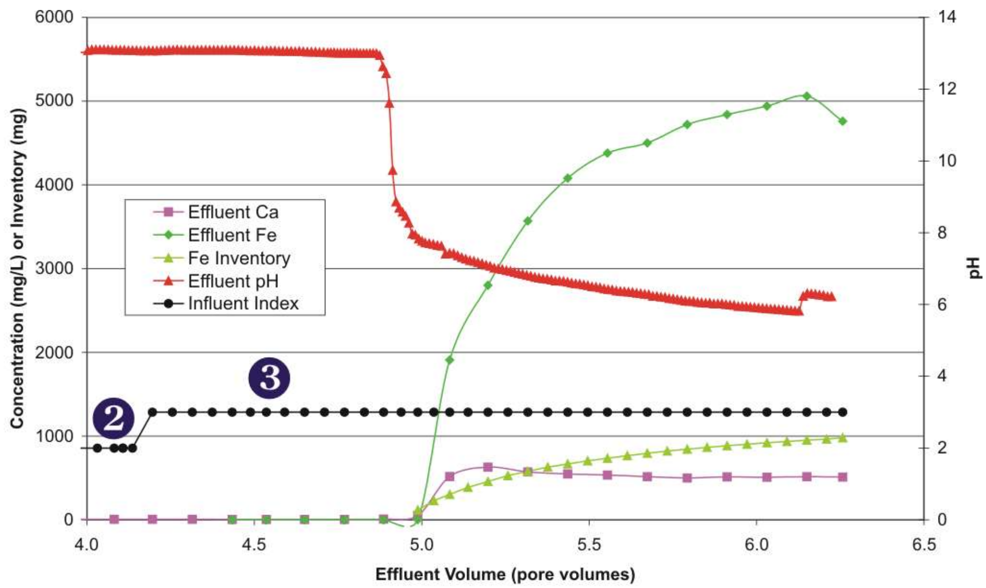

Figure 6. Column Test 2. Effluent concentrations of Ca and Fe, and Fe inventory for the ferrous sulfate injection period. Refer to Figure 5 for explanation of influent index.

3.4 Column Test 3: Ferrous Iron Emplacement into a Column Containing Monticello Alluvial Sediment

Column Test 3 evaluated the feasibility of precipitating ferrous hydroxide minerals from dissolved ferrous sulfate contacting Monticello alluvium that had been pretreated with sodium hydroxide. As before, the goal of the pretreatment was to create an alkaline environment by saturating adsorption sites with hydroxyl ions. Ferrous hydroxide precipitation is caused by contact with the hydroxylated sites. In a field application, the subsurface would be saturated with hydroxide prior to injection of dissolved ferrous ions.

3.4.1 Experimental Methods

A column (1.5-in. diameter, 18-in. long, clear acrylic) was packed with 1389 g of a sample of Monticello alluvium (Figure 8). A second column (control column) was packed with 1396 g of the same sample. The alluvium sample is a composite of core samples that were collected at 5 locations near the Monticello PRB. Two of the cores were collected about 20 ft from well PW-17 (south end of south funnel wall) and the other three locations were about 20 ft upgradient of the PRB near its center. The core material was air dried and sieved to less than 2 mm for use in the columns.

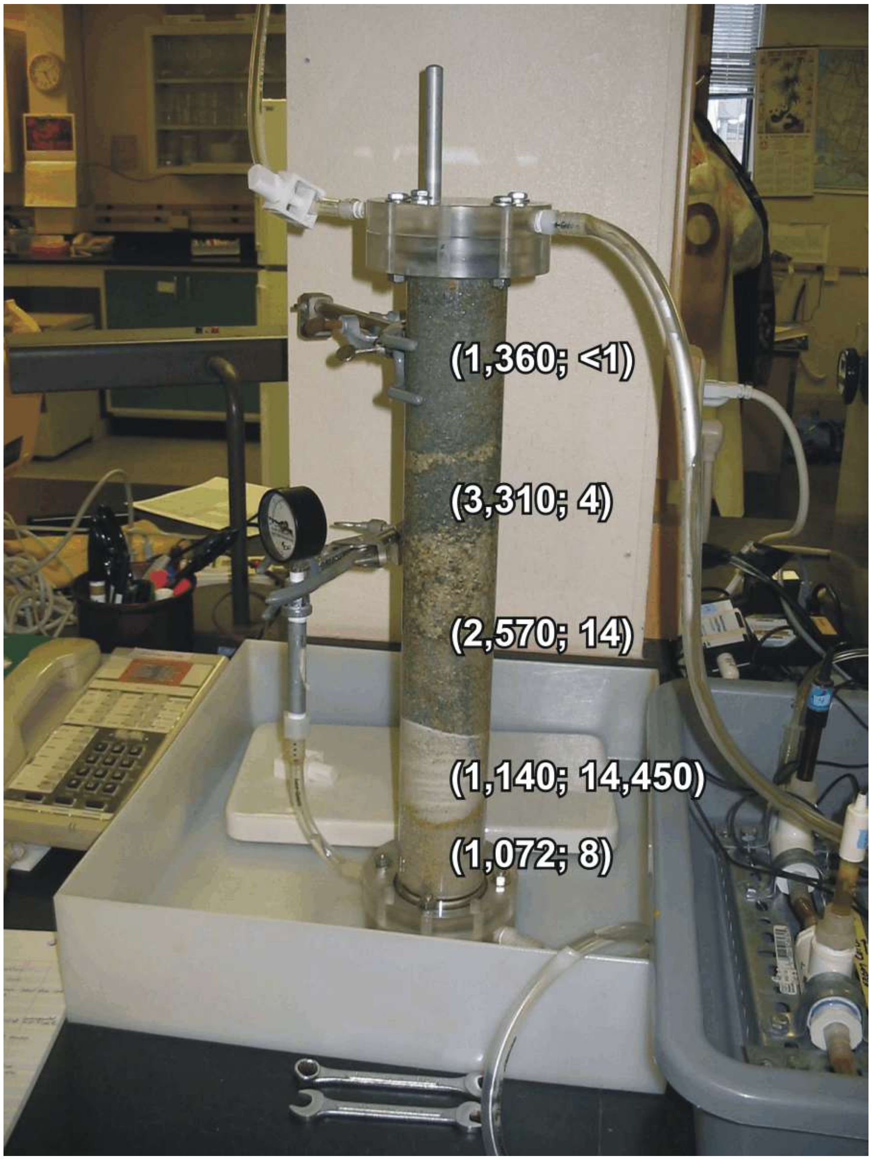

Figure 7. Column Test 2. Column appearance after Fe^{2+} injection. Numbers in parentheses are (Fe; Ca) solid-phase concentrations in mg/kg.

The experimental methods used for the test column and the control column were identical except for the solutions used. Four solutions were passed through the test column: (in chronologic order) (1) 1.0 N NaOH, (2) synthetic PW-17 ground water without U or Mo, (3) 0.1 M ferrous sulfate, and (4) synthetic PW-17 ground water with 1 mg/L each of U and Mo. The composition of synthetic PW-17 water is provided in Table 3. The only solution passed through the control column was synthetic PW-17 with 1 mg/L each of U and Mo. The columns and tubing were purged with N_2 to remove residual oxygen. About 0.5 mL of concentrated sulfuric acid was added to each liter of ferrous sulfate solution to ensure complete dissolution. The ferrous sulfate solution was continuously purged with N_2 to remove DO. Values of pH and ORP were measured with inline probes at the inlet and outlet of the column; these data were recorded every 30 seconds with a datalogger. Effluent samples were collected in glass test tubes on a fraction collector. The samples were analyzed for Fe by atomic absorption spectroscopy, for U by kinetic phosphorescence analysis [ESL Procedure AP(U-2); DOE 2005], and for Mo by the ternary complex method [ESL Procedure AP(Mo-3); DOE 2005]. Porosity of the columns (420 mL and 400 mL for test and control columns, respectively) was determined by measuring the volume of water during filling.

Table 3. Composition of ground water sample collected from well PW-17 on April 14, 2004, and synthetic PW-17 water used in column test 3 (mg/L)

Constituent or Parameter	PW-17	Synthetic PW-17
Sodium	140.00	141.53
Potassium	27.00	26.93
Calcium	300.00	298.66
Magnesium	64.00	29.88
Sulfate	730.00	748.41
Chloride	81.00	87.31
Nitrate	4.00	5.03
Inorganic Carbon	65.00[a]	72.86
Uranium[b]	0.99	1.00
Molybdenum[b]	0.087	1.00
pH	7.00	7.00[c]

[a]Calculated from alkalinity using geochemical program PHREEQC (Parkhurst and Appelo 1999).
[b]Two compositions of synthetic PW-17 water were used: one without U or Mo, and one that contained 1 mg/L each of U and Mo (see text).
[c]Varied slightly with time, continually adjusted with CO_2.

3.4.2 Results and Discussion

A 1.0 N NaOH solution was passed through the test column initially at a flow rate of 8.8 mL/min. Because of the large amount of fine-grained sediment, the inlet pressure increased and we reduced the flow rate in several steps to a minimum of about 3 mL/min. The NaOH flowed from 0.0 to 1.7 pore volumes to condition the sediment at high pH. Effluent pH values reflect the high pH environment (Figure 9). The effluent from the NaOH injection was dark brown indicating the removal of significant concentrations of humic material from the sediment (Figure 8). Synthetic PW-17 water without U or Mo was then passed through the column from 1.7 to 3.8 pore volumes. The purpose of the PW-17 water was to flush the tubing to prevent ferrous hydroxide from precipitating in the tubing during the ferrous sulfate injection. A 0.1 M ferrous sulfate solution was then passed through from 4.2 to 5.9 pore volumes, during which the effluent pH decreased to about 8 (Figure 9) and the ORP decreased to about –300 mV.

Approximately 4300 mg of Fe was emplaced in the test column during ferrous sulfate injection, but some of this was removed by the flow of synthetic PW-17 (Figure 9). The inventory of Fe appears to have stabilized near 3000 mg after about 15 pore volumes. The solid-phase Fe is likely some form of ferrous hydroxide mineral.

Figure 8. Column Test 3. Experimental apparatus. Tubes in fraction collector contain effluent from the NaOH injection; note the deep brown color due to humic material.

From 5.9 pore volumes through the termination of the test at 27.6 pore volumes, synthetic PW-17 water containing 1 mg/L each of U and Mo was injected into the test column at a rate of 2.3 mL/min. The same solution was passed through the control column at the same flow rate. In Figure 10, the effluent concentrations for the control column are plotted as if the injection of U-bearing water began at 5.9 pore volumes so that results from the two columns can be directly compared. Breakthrough of U occurs almost immediately for the control column indicating that the untreated Monticello alluvium has little sorption capacity. The Fe^{2+} treated column was able to maintain the effluent U concentration at a value less than 50 μg/L for about 6 pore volumes before the concentration began to increase steadily. Thus, the addition of Fe^{2+} increased the sorption capacity of the alluvium for U. The increased sorption was more prevalent for Mo than for U. Effluent concentrations of Mo remained less than the detection limit of 0.12 mg/L for about 12 pore volumes of Mo-spiked influent; whereas, effluent Mo concentrations for the control column increased soon after injection. Adsorption densitised are approximately 0.8 mg U and 1.6 mg Mo per g of Fe.

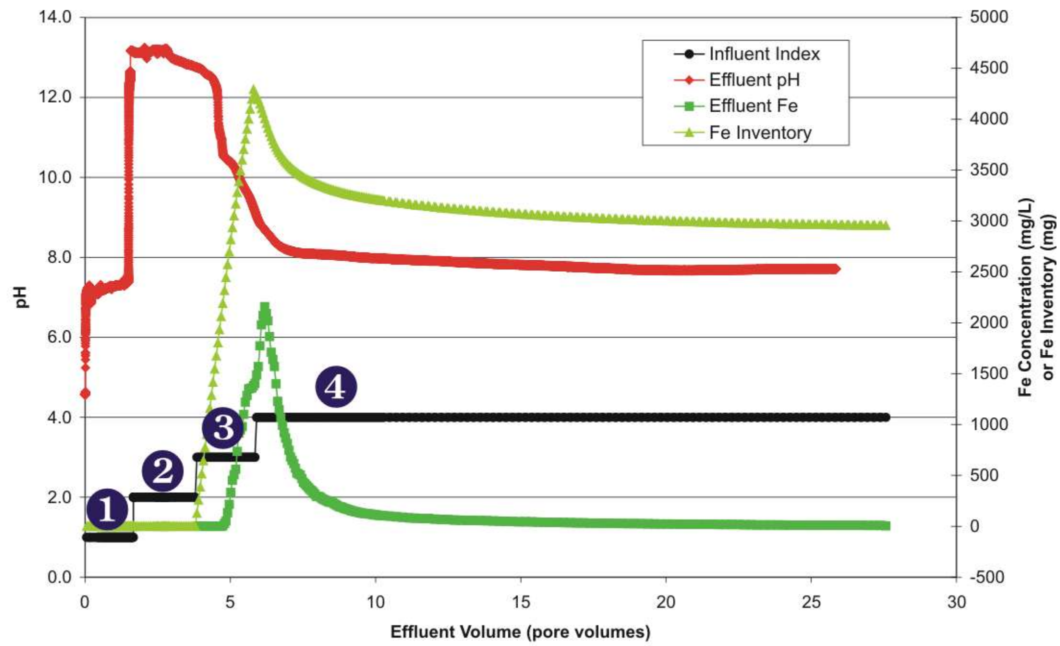

Figure 9. Column Test 3. Effluent Fe concentrations, pH values, and Fe inventory in test column. The influent index indicates the composition of the influent solution for that period of the test column (1 = 1N NaOH, 2 = synthetic PW-17 without U or Mo, 3 = ferric sulfate solution, and 4 = synthetic PW-17 with U and Mo).

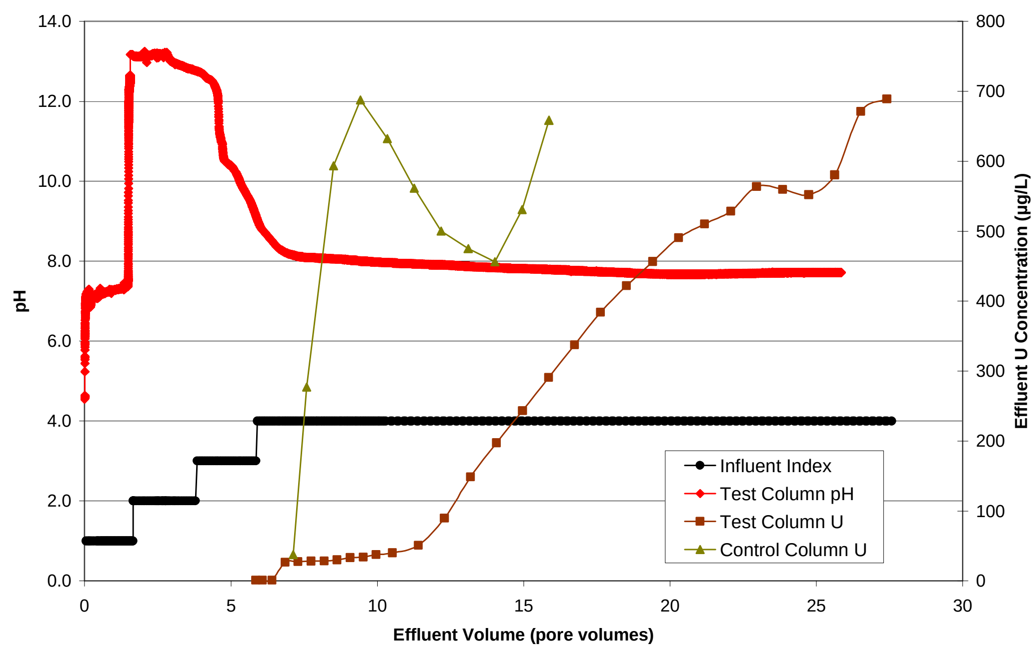

Figure 10. Column Test 3. Effluent concentrations of U in test column and control column. Refer to Figure 9 for explanation of influent index.

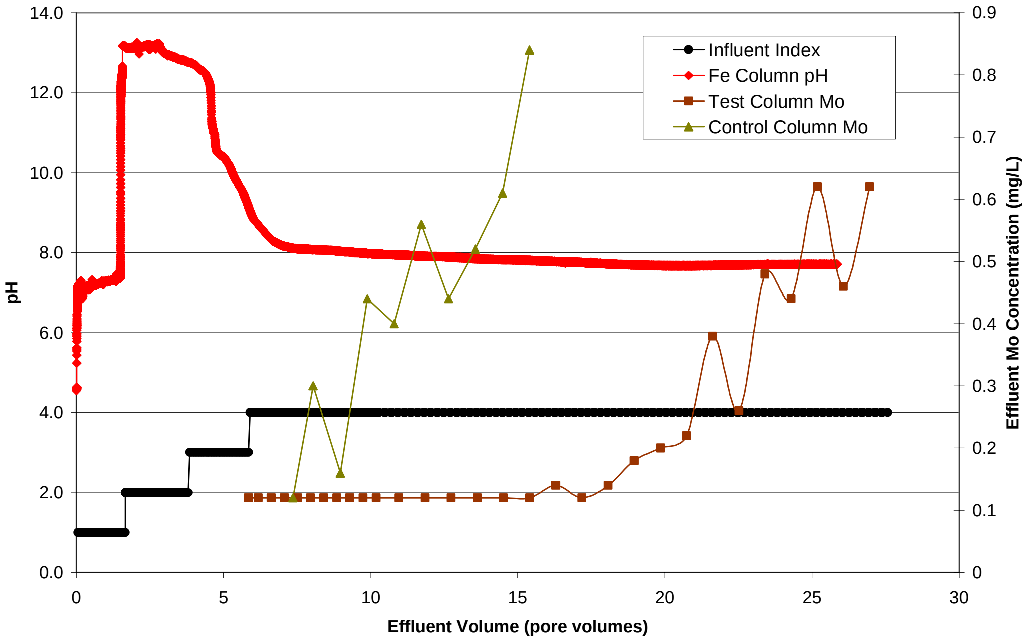

Figure 11. Column Test 3. Effluent concentrations of Mo in test column and control column. Refer to Figure 9 for explanation of influent index.

4.0 Conclusions

Estimates of net present value for implementation of seven PRB *mending* technologies suggest that all seven are reasonably similar. Thus, if a technology is used at Monticello, the selection should be based more on the following issues than implementation cost: (1) likelihood of successful operation of the technology, (2) disruption to land owner and other stakeholder issues, and (3) ability to alter or amend the technology if unanticipated issues arise.

All of the technologies evaluated, except Fe^{2+} injection, have been bench-scale tested. To fill this data gap, this project conducted batch and column tests of Fe^{2+} injection. The tests showed that solid phase Fe^{2+} can be emplaced into sediment that has been pretreated with hydroxyl ion. The addition of Fe^{2+} increased the sorption capacity of Monticello alluvium for both U and Mo. One possible drawback of the method is that the Fe^{2+} remains somewhat soluble and may transport long distances in the subsurface. Thus, controlling the location of the reactive zone may be problematic.

5.0 References

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Appendix A

Spreadsheet Calculations of Costs for the Seven Mending Alternatives

Mending Option 1									
Option 1: Ground water extraction and treatment at PRB									
Qty	**Description**	**Crew**	**Daily Output**	**Labor Hours**	**Unit**	**Bare Mat.**	**Bare Labor**	**Bare Equip.**	**Total**
1.00	Mobilization and demobilization of drill rig	A3E	2.50	6.400	Ea.	$ -			$ 2,000.00
120.00	Well, domestic water, drilled in normal soil, 4" to 6" dia	B23	120	.333	L.F.	$ -			$ 3,000.00
3.00	Wells, pumps, installed in wells to 50' D, 2" submersible, 1/2 h.p	Q1	3.22	4.969	Ea.	$ 828.00	$ 292.80	$ -	$ 1,120.80
120.00	Piping, not including excavation or backfill, class 160, 2" diameter	B20	685	.035	L.F.	$ 115.20	$ 85.20	$ -	$ 200.40
30.00	Well, domestic water, screen assembly, slotted PVC, 6" dia	B23A	126	.190	L.F.	$ 162.00	$ 117.30	$ 561.00	$ 840.30
440.00	Piping, not including excavation or backfill, class 160, 6" diameter	B20	315	.076	L.F.	$ 3,168.00	$ 682.00	$ -	$ 3,850.00
100.00	Piping, subdrainage, perforated PVC, 6" dia	B14	300	.160	L.F.	$ 141.00	$ 305.00	$ 73.00	$ 519.00
3.00	Valves, bronze, relief, 2" size, pressure, water, ASME, threaded	1 Plum	16	.500	Ea.	$ 91.50	$ 4.25	$ -	$ 95.75
3.00	Pipe, plastic ftngs, epoxy resin, fbgl reinf, gen svce, elb, 90<, 2"	Q1	33	.483	Ea.	$ 136.50	$ 36.90	$ -	$ 173.40
6.00	Pipe, plastic ftngs, epoxy resin, fbgl reinf, gen service, tee, 2"	Q1	20	.800	Ea.	$ 330.00	$ 123.00	$ -	$ 453.00
3.00	Fiberglass reinf epoxy, general service, couplings, 6"	Q1	10.10	1.584	Ea.	$ 114.00	$ 121.50	$ -	$ 235.50
350.00	Excavate trench, cont ftg, no sht/dewtrg, 1-4'D,3/8 CY tractor lder/backhoe	B11C	150	.107	C.Y.	$ -	$ 1,099.00	$ 511.00	$ 1,610.00
350.00	Excavate trench, backfill trench, FE loader, whl mtd, 1 CY bkt, min haul	B10R	400	.030	C.Y.	$ -	$ 325.50	$ 178.50	$ 504.00
350.00	Excavate trench, for tamping backfilled trenches, air tamp, add	A1	100	.080	C.Y.	$ -	$ 710.50	$ 203.00	$ 913.50
4.60	Non-metallic sheathed cable, 600V, copper w/ground, #10, 3 conductor	1 Elec	1.80	4.444	C.L.F.	$ 223.10	$ 533.60	$ -	$ 756.70
1.00	Grounding, rod, copper clad, 8' long, 1/2" dia	1 Elec	5.50	1.455	Ea.	$ 15.85	$ 38.00	$ -	$ 53.85
								Subtotal	**$ 16,326**
								40% OH&P	**$ 6,530**
								Total	**$ 22,857**

Option 1: Ground Water Extraction and Treatment at PRB

Alternative Components and Basis of Estimate	Quantity	
Capital Costs		
Construct PRB enhancement direct cost	*1*	lump sum in year 2005
Construct PRB enhancement contractor oversight	*20%*	of total construction cost
Decommission PRB & enhancement direct cost	*1*	lump sum in year 2015
Decommission PRB & enhancement contractor oversight	*20%*	of total decommissioning cost
Annual Costs		
O&M (electricity, pump change-out, maintenance)	*1*	per year for 10 yrs
Annual cost will occur for 10 years beginning 10/04.		

Item		Unit	Quantity	Cost/Unit	Cost per Item	Subtotal/Total
1	**Capital Costs**					
2	Construct PRB enhancement direct	lump sum	1	***$22,857***	$22,857	
3	Decommission enhancement direct	lump sum	1	***$4,692***	$4,692	
4						
5	Construct PRB enhancement indirect	lump sum	20%	$22,857	$4,571	
6	Decommission enhancement indirect	lump sum	20%	$4,692	$938	
7	Total direct capital costs					$27,549
8	Total indirect capital costs					$5,510
9	**Total capital costs**					**$33,058**
10	**Annual Costs**					
11	O & M (extraction system maintenance)	lump sum	1	***$4,000***	$4,000	
12						
13						
14	Total direct annual cost					$4,000
15	OH&P	lump sum	***40%***		$4,000	$1,600
16	**Total annual cost**					**$5,600**
17	**Net Present Value**					
18						
19	Total annual cost				$ 5,600	
20	* Present worth mulitplier				***7.024***	
21	Present value of annual cost					$39,334
22						
23	Total capital cost					$33,058
24						
25	**Net present value of alternative**					**$72,393**

Option 2 Mending									
Place ZVI in Borings									
Qty	**Description**	**Crew**	**Daily Output**	**Labor Hours**	**Unit**	**Bare Mat.**	**Bare Labor**	**Bare Equip.**	**Total**
1	Mobilization and demobilization of drill rig	A3E	2.50	6.400	Ea.	$ -			$ 2,000.00
700	Drilling 20 10-in borings to 35 ft.	B23	95	0.42	L.F.	$ -			$ 10,500.00
10	Pack wells, ZVI @ 10 L.F. each well				Ton	$ 7,363.13	$ 1,800.00	$ -	$ 9,163.13
500	Backfill wells with sand (25 ft each)	B23	95	0.42	L.F.	$ -	$ 5,000.00	$ 747.00	$ 5,747.00
								Subtotal	**$ 27,410**
								40% OH&P	**$ 10,964**
								Total	**$ 38,374**

			BOE
Assumed number of borings	20		Based on Focused FS
Average borehole depth	35	ft	Based on geologic cross sections
Volume of 1 boring, 10 in diam, 10 ft thick	5.45	cf	Geometry
Mass of 1 boring (180 lbs/cf)	981.75	lbs	Vol * density
Total mass of ZVI	9.82	tons	Mass of 1 boring * number of borings
Cost of ZVI	$750	$/ton	Recent communication with Peerless Metals, delivered cost -8 + 20 ZVI

Mob/Demob	$2,000.00	$	Tim - Based on recent drilling SOW
Drilling cost	$15.00	$/LF	Tim - Based on recent drilling SOW
Labor to pack wells	$1,800.00	$	Dan - From Focused FS
Backfill wells	$10.00	$/LF	Tim - Based on recent drilling SOW
Backfill Equip	$747	$	Dan - From Focused FS
OH&P	40	%	Mary Jones 6/30/04 for FY05

Option 2: Place ZVI in Borings

Alternative Components and Basis of Estimate	Quantity	
Capital Costs		
Construct PRB enhancement direct cost	*1*	lump sum in year 2005
Construct PRB enhancement contractor oversight	*20%*	of total construction cost
Decommission PRB & enhancement direct cost	*1*	lump sum in year 2015
Decommission PRB & enhancement contractor oversight	*20%*	of total decommissioning cost
Annual Costs		
O&M None	*0*	per year for 10 yrs

Item		Unit	Quantity	Cost/Unit	Cost per Item	Subtotal/Total
1	**Capital Costs**					
2	Construct PRB enhancement direct	lump sum	1	***$38,374***	$38,374	
3	Decommission enhancement direct	lump sum	1	***$36,887***	$36,887	
4						
5	Construct PRB enhancement indirect	lump sum	20%	$38,374	$7,675	
6	Decommission enhancement indirect	lump sum	20%	$36,887	$7,377	
7	Total direct capital costs					$75,261
8	Total indirect capital costs					$15,052
9	**Total capital costs**					**$90,313**
10	**Annual Costs**					
11	O & M (extraction system maintenance)	lump sum	0	***$0***	$0	
12						
13						
14	Total direct annual cost					$0
15	OH&P	lump sum	***40%***		$0	$0
16	**Total annual cost**					**$0**
17	**Net Present Value**					
18						
19	Total annual cost				$ -	
20	* Present worth mulitplier				***7.024***	
21	Present value of annual cost					$0
22						
23	Total capital cost					$90,313
24						
25	**Net present value of alternative**					**$90,313**

Option 3 Mending
Place ZVI in Borings in Removable Cannisters

Initial Construction

Qty	Description	Crew	Daily Output	Labor Hours	Unit	Bare Mat.	Bare Labor	Bare Equip.	Total
1	Mobilization and demobilization of drilling rig	A3E	2.50	6.400	Ea.	$ -			$ 2,000.00
350	Drilling of boreholes	B23	95	0.42	L.F.	$ -	$ 2,135.00	$ 7,175.00	$ 9,310.00
1	Design and fabricate cannisters				job				$20,000.00
5	ZVI				Ton	$ 3,681.56			$3,681.56
2	Mobilization or demobilization, truck-mounted crane over 75 ton. For ZVI changeout	A3E	2.50	6.400	Ea.	$ -	$ 431.20	$ 64.90	$ 496.10
								Subtotal	**$ 35,488**
								40% OH&P	**$ 14,195**
								Total	**$ 49,683**

INITIAL CONSTRUCTION			BOE
Assumed number of borings	10		Based on 50 % of the number of borings in Option 2
Average borehole depth	35	ft	Based on geologic cross sections
Volume of 1 boring, 10 in diam, 10 ft thick	5.45	cf	Geometry
Mass of 1 boring (180 lbs/cf)	981.75	lbs	Density * vol
Total mass of ZVI	4.91	tons	Number of borings * mass/boring
Cost of ZVI	$750	$/ton	Recent communication with Peerless Metals, delivered cost -8 + 20 mesh ZVI
Mob/Demob Drill Rig	$2,000.00	$	Based on recent drilling SOW
Drilling cost	$15.00	$/LF	Based on recent drilling SOW
Labor to pack wells	$1,800.00	$	From Focused FS
Backfill wells	$10.00	$/LF	Based on recent drilling SOW
Backfill Equip	$747	$	From Focused FS
OH&P	40	%	Mary Jones 6/30/04 for FY05
Cannister design and fabrication	$20,000.00	$	Stan WAG, Based somewhat on MSE report

Replacement (Year 2010)

Qty	Description	Crew	Daily Output	Labor Hours	Unit	Bare Mat.	Bare Labor	Bare Equip.	Total
2	Mobilization or demobilization, truck-mounted crane over 75 ton. For ZVI changeout	A3E	2.50	6.400	Ea.	$ -	$ 431.20	$ 64.90	$ 496.10
1	New cannisters				job				$3,000.00
5	ZVI				Ton	$ 3,681.56			$3,681.56
								Subtotal	**$ 7,178**
								40% OH&P	**$ 2,871**
								Total	**$ 10,049**

REPLACEMENT BOEs			
New cannisters	$3,000.00	$	Stan's WAG

Option 3: Place ZVI in Borings in Removable Cannisters

Alternative Components and Basis of Estimate	Quantity	
Capital Costs		
Construct PRB enhancement direct cost	*1*	lump sum in year 2005
Construct PRB enhancement contractor oversight	*20%*	of total construction cost
Decommission PRB & enhancement direct cost	*1*	lump sum in year 2015
Decommission PRB & enhancement contractor oversight	*20%*	of total decommissioning cost
Annual Costs		
O&M (ZVI change-out)	*0.1*	per year for 10 yrs
Annual cost will occur for 10 years beginning 2005.		

Item		Unit	Quantity	Cost/Unit	Cost per Item	Subtotal/Total
1	**Capital Costs**					
2	Construct PRB enhancement direct	lump sum	1	***$49,683***	$49,683	
3	Decommission enhancement direct	lump sum	1	***$5,000***	$5,000	
4	Replacement in Year 2010	lump sum	1	***$10,049***	$10,049	
5						
6	Construct PRB enhancement indirect	lump sum	20%	$49,683	$9,937	
7	Decommission enhancement indirect	lump sum	20%	$5,000	$1,000	
8	Replacement in Year 2010 indirect	lump sum	20%	$10,049	$2,010	
9	Total direct capital costs					$64,731
10	Total indirect capital costs					$12,946
11	**Total capital costs**					**$77,678**
12	**Annual Costs**					
13	O & M (none)	lump sum	1.0		$0	
14						
15						
16	Total direct annual cost					$0
17	OH&P	lump sum	***40%***		$0	$0
18	**Total annual cost**					**$0**
19	**Net Present Value**					
20						
21	Total annual cost				$ -	
22	* Present worth mulitplier				***7.024***	
23	Present value of annual cost					$0
24						
25	Total capital cost					$77,678
26						
27	**Net present value of alternative**					**$77,678**

Option 4 Mending									
Jet Grouting of ZVI									
Qty	Description	Crew	Daily Output	Labor Hours	Unit	Bare Mat.	Bare Labor	Bare Equip.	Total
1	Mobilization and demobilization jet grouting equipment				Ea.	$ -			$20,000.00
80	ZVI injections				L.F.	$ -			$ 28,000.00
8	ZVI cost				Ton	$ 7,200.00		$ -	$ 7,200.00
0	Backfill wells	B23	95	0.42	L.F.	$ -	$ -		$ -
								Subtotal	$ 55,200
								40% OH&P	$ 22,080
								Total	$ 77,280

			BOE
Assumed number of injections	8		Based on 2002 jet grouting project at Travis AFB
Average borehole depth	35	ft	Based on geologic cross section
Mass of ZVI injected into each boring	1	tons	Based on scaled down version of that used at Travis AFB
Total mass of ZVI	8.00	tons	
Cost of ZVI	$900	$/ton	Recent communication with Peerless Metals -30 + 70 mesh ZVI
Mob Demob	$20,000.00	$	Based on 2002 jet grouting project at Travis AFB
ZVI injections	$350.00	$/LF	Based on Travis AFB

Option 4: Jet Grouting

Alternative Components and Basis of Estimate	Quantity	
Capital Costs		
Construct PRB enhancement direct cost	*1*	lump sum in year 2005
Construct PRB enhancement contractor oversight	*20%*	of total construction cost
Decommission PRB & enhancement direct cost	*1*	lump sum in year 2015
Decommission PRB & enhancement contractor oversight	*20%*	of total decommissioning cost
Annual Costs		
O&M (none)	*0*	per year for 10 yrs

Item		Unit	Quantity	Cost/Unit	Cost per Item	Subtotal/Total
1	**Capital Costs**					
2	Construct PRB enhancement direct	lump sum	1	***$77,280***	$77,280	
3	Decommission PRB enhancement direct	lump sum	1	***$36,887***	$36,887	
4						
5						
6	Construct PRB enhancement indirect	lump sum	20%	$77,280	$15,456	
7	Decommission PRB indirect	lump sum	20%	$36,887	$7,377	
8	Decommission enhancement indirect	lump sum	20%	$0	$0	
9	Total direct capital costs					$114,167
10	Total indirect capital costs					$22,833
11	**Total capital costs**					**$137,000**
12	**Annual Costs**					
13	O & M (none)	lump sum	0	***$0***	$0	
14						
15						
16	Total direct annual cost					$0
17	OH&P	lump sum	***40%***		$0	$0
18	**Total annual cost**					**$0**
19	**Net Present Value**					
20						
21	Total annual cost				$ -	
22	* Present worth mulitplier				***7.024***	
23	Present value of annual cost					$0
24						
25	Total capital cost					$137,000
26						
27	**Net present value of alternative**					**$137,000**

Option 5 Mending									
Ferric Iron Injections									
Qty	**Description**	**Crew**	**Daily Output**	**Labor Hours**	**Unit**	**Bare Mat.**	**Bare Labor**	**Bare Equip.**	**Total**
1	Mobilization and demobilization, drill rig	A3E	2.50	6.400	Ea.	$ -			$2,000.00
140	Well, domestic water, drilled in normal soil, 8" to 10" dia	B23	95	0.42	L.F.	$ -			$ 3,500.00
1	Process monitoring								$ 2,000.00
5,500	Ferric iron (as $FeCl_3$) injection				lbs	$ 13,750.00	$ 10,000.00	$ 2,000.00	$ 23,750.00
0	Backfill wells	B23	95	0.42	L.F.	$ -	$ -	$ -	$ -

Subtotal	**$ 31,250**
40% OH&P	**$ 12,500**
Total	**$ 43,750**

BOE

Number of wells	4	ea	Based on 40 ft of coverage
Average borehole depth	35	ft	Based on geologic cross sections
Mass of ferric chloride required	5,500.00	lbs	Based on bench-scale testing
Cost of $FeCl_3$	$2.50	$/lb	Based vendor estimate
Mob/Demob	$2,000.00	$	Based on recent contracts
Drilling costs	$25.00	$/LF	Based on actual costs for LM

Assumes no extraction of sodium chloride water

Option 5: Ferric Iron Injections

Alternative Components and Basis of Estimate	Quantity	
Capital Costs		
Construct PRB enhancement direct cost	***1***	lump sum in year 2005
Construct PRB enhancement contractor oversight	***20%***	of total construction cost
Decommission PRB & enhancement direct cost	***1***	lump sum in year 2015
Decommission PRB & enhancement contractor oversight	***20%***	of total decommissioning cost
Annual Costs		
O&M (none)	***0***	per year for 10 yrs

Item			Unit	Quantity	Cost/Unit	Cost per Item	Subtotal/Total
1	**Capital Costs**						
2	Construct PRB enhancement direct		lump sum	1	***$43,750***	$43,750	
3	Decommission PRB enhancement direct		lump sum	1	***$36,887***	$36,887	
4							
5							
6	Construct PRB enhancement indirect		lump sum	20%	$43,750	$8,750	
7	Decommission PRB indirect		lump sum	20%	$36,887	$7,377	
8	Decommission enhancement indirect		lump sum	20%	$0	$0	
9	Total direct capital costs						$80,637
10	Total indirect capital costs						$16,127
11	**Total capital costs**						**$96,764**
12	**Annual Costs**						
13	O & M (none)		lump sum	0	***$0***	$0	
14							
15							
16	Total direct annual cost						$0
17	OH&P		lump sum	***40%***		$0	$0
18	**Total annual cost**						**$0**
19	**Net Present Value**						
20							
21		Total annual cost				$ -	
22	*	Present worth mulitplier				***7.024***	
23		Present value of annual cost					$0
24							
25	Total capital cost						$96,764
26							
27	**Net present value of alternative**						**$96,764**

Option 6 Mending									
Ferrous Iron Injections									
Qty	**Description**	**Crew**	**Daily Output**	**Labor Hours**	**Unit**	**Bare Mat.**	**Bare Labor**	**Bare Equip.**	**Total**
1	Mobilization and demobilization of drill rig	A3E	2.50	6.400	Ea.	$ -			$ 2,000.00
140	Well, domestic water, drilled in normal soil, 8" to 10" dia	B23	95	0.42	L.F.	$ -	$ 854.00	$ 2,870.00	$ 3,724.00
791	Injection of FeSO4				lb Fe	$ 711.90	$ 10,000.00	$ 2,000.00	$ 10,711.90
0	Backfill wells	B23	95	0.42	L.F.	$ -	$ -	$ -	$ -
								Subtotal	$ 16,436
								40% OH&P	$ 6,574
								Total	$ 23,010

			BOE
Mob and Demob of drill rig	$ 2,000	$	Based on recent actuals
Number of injection wells	4	ea	Based on 40 ft linear width
Average borehole depth	35	ft	Based on geologic cross sections
Mass of Fe required	791.00	lb	Calculation based of DO and U content of PW-17
Cost of ferrous sulfate	$0.90	$/lb of Fe	Vendor data, delivered to Monticello

Assumes: Ferrous sulfate left in ground.

Option 6: Ferrous Iron Injection

Alternative Components and Basis of Estimate	Quantity	
Capital Costs		
Construct PRB enhancement direct cost	***1***	lump sum in year 2005
Construct PRB enhancement contractor oversight	***20%***	of total construction cost
Decommission PRB & enhancement direct cost	***1***	lump sum in year 2015
Decommission PRB & enhancement contractor oversight	***20%***	of total decommissioning cost
Annual Costs		
O&M (none)	***0***	per year for 10 yrs

Item		Unit	Quantity	Cost/Unit	Cost per Item	Subtotal/Total
1	**Capital Costs**					
2	Construct PRB enhancement direct	lump sum	1	***$23,010***	$23,010	
3	Decommission PRB enhancement direct	lump sum	1	***$36,887***	$36,887	
4						
5						
6	Construct PRB enhancement indirect	lump sum	20%	$23,010	$4,602	
7	Decommission PRB indirect	lump sum	20%	$36,887	$7,377	
8	Decommission enhancement indirect	lump sum	20%	$0	$0	
9	Total direct capital costs					$59,897
10	Total indirect capital costs					$11,979
11	**Total capital costs**					**$71,877**
12	**Annual Costs**					
13	O & M (none)	lump sum	0	***$0***	$0	
14						
15						
16	Total direct annual cost					$0
17	OH&P	lump sum	***40%***		$0	$0
18	**Total annual cost**					**$0**
19	**Net Present Value**					
20						
21	Total annual cost				$ -	
22	* Present worth mulitplier				***7.024***	
23	Present value of annual cost					$0
24						
25	Total capital cost					$71,877
26						
27	**Net present value of alternative**					**$71,877**

Option 7 Mending									
Dithionite Injections									
Qty	Description	Crew	Daily Output	Labor Hours	Unit	Bare Mat.	Bare Labor	Bare Equip.	Total
1	Mobilization and demobilization of drill rig	A3E	2.50	6.400	Ea.	$ -			$ 2,000.00
140	Well, domestic water, drilled in normal soil, 8" to 10" dia	B23	95	0.42	L.F.	$ -	$ 854.00	$ 2,870.00	$ 3,724.00
1	Process monitoring				Ea.				$ 10,000.00
300	Dithionite injection				lb	$ 1,584.00	$ 600.00	$6,000.00	$ 8,184.00
0	Backfill wells	B23	95	0.42	L.F.	$ -	$ -	$ -	$ -
								Subtotal	$ 23,908
								40% OH&P	$ 9,563
								Total	$ 33,471

			BOE
Mob/demob drill rig	$ 2,000	$	Base on actual costs
Number of injection wells (for 40 ft zone)	4	Ea.	Calculations for Pantex proposal (and data from the Handford site)
Average borehole depth	35	ft	Tim's estimate
Total mass of dithionite required	300.00	lb	Calculations for Pantex proposal (and data from the Handford site)
Cost of dithionite	$5.28	$/lb	Calculations for Pantex proposal (and data from the Handford site)
Labor for injection	$2.00	$/lb	
Equipment for injection	$6,000.00	Ea.	

Assumes: Dithionite left in ground.

Option 7: Dithionite Injection

Alternative Components and Basis of Estimate	Quantity	
Capital Costs		
Construct PRB enhancement direct cost	*1*	lump sum in year 2005
Construct PRB enhancement contractor oversight	*20%*	of total construction cost
Decommission PRB & enhancement direct cost	*1*	lump sum in year 2015
Decommission PRB & enhancement contractor oversight	*20%*	of total decommissioning cost
Annual Costs		
O&M (none)	*0*	per year for 10 yrs

Item		Unit	Quantity	Cost/Unit	Cost per Item	Subtotal/Total
1	**Capital Costs**					
2	Construct PRB enhancement direct	lump sum	1	***$33,471***	$33,471	
3	Decommission PRB enhancement direct	lump sum	1	***$36,887***	$36,887	
4						
5						
6	Construct PRB enhancement indirect	lump sum	20%	$33,471	$6,694	
7	Decommission PRB indirect	lump sum	20%	$36,887	$7,377	
8	Decommission enhancement indirect	lump sum	20%	$0	$0	
9	Total direct capital costs					$70,358
10	Total indirect capital costs					$14,072
11	**Total capital costs**					**$84,430**
12	**Annual Costs**					
13	O & M (none)	lump sum	0	***$0***	$0	
14						
15						
16	Total direct annual cost					$0
17	OH&P	lump sum	***40%***		$0	$0
18	**Total annual cost**					**$0**
19	**Net Present Value**					
20						
21	Total annual cost				$ -	
22	* Present worth mulitplier				***7.024***	
23	Present value of annual cost					$0
24						
25	Total capital cost					$84,430
26						
27	**Net present value of alternative**					**$84,430**

Appendix B

Environmental Sciences Laboratory Notes

Batch Tests

BATCH MPERT-02-05-01

9/28/04 1630

Starting bench-scale tests of "Mending" for EPA - Region VIII (Paul Mushovic) project. Bench-scale tests will be used to determine if Fe^{2+} can be used to stabilize U. If so, an injection of dissolved Fe^{2+} could be used to stop the flow of U around the south end of the slurry wall at the Monticello PRB.

First, we will determine if freshly ppt $Fe(OH)_2$ ~~$FeSO_4$~~ is capable of tying up U.
Prepare 0.1 M Fe^{+2} solution from $FeSO_4 \cdot 7H_2O$ (Fisher, I146-500, Lot 904658)
FW = 278.02 thus 27.802 g/L made 1L. 20.1% Fe, thus 27.802 g/L is 5.6 g Fe, 9 g $Fe(OH)_2$
Solution is cloudy pale yellow. Does not dissolve readily. pH = 3.46. On mag stir.

$$Fe^{2+} + 2H_2O = Fe(OH)_2 + 2H^+$$

Thus it should take 2 M of base per mol of Fe. For 100 mL of 0.1 M Fe^{+2} should use 0.02 mol base
Using 10 N NaOH $10\frac{mol}{L} \times \frac{L}{1000 mL} = 0.01$ mol/mL
Should take 2 mL to ppt all the Fe^{2+}.

17:44 Added 0.5 mL of conc. H_2SO_4 to the 0.1 M $FeSO_4$. Back on mag. stir.
17:47 Soln is no longer cloudy. Has a faint green cast. Appears to be in solution. pH = 2.21
Conc H_2SO_4 has N ~ 36 (M ~ 18)
So I added $0.5 mL \times \frac{L}{1000 mL} \times \frac{36 m H^+}{L} = 0.018 \frac{m H^+}{L}$ (will need another 1.8 mL of 10 N NaOH to neutralize the H_2SO_4)
17:51 Turned off stirplate. Glass stopper in flask.

TOTAL NaOH = 2 + 1.8 = 3.8 mL

9/29/04
0653 0.1 M $FeSO_4$ solution is still clear with slight greenish tint. All is dissolved. pH = 2.21, ORP = 312.2 mV
0726 Added 1 mL of 10 N NaOH. Formed lgt green flakes. Placed on stir plate to stir.
0728 Appears to have redissolved. Yellow soln. ORP = 315.8 mV pH = 2.55
0734 Added 1 mL of 10 N NaOH. Formed lgt green flakes. Stirred. Golden yellow (oxidized?)
0736 Appears to have some (oxidized?) ppt. pH = 5.28, ORP = 54 ↓ slowly decreasing
0745 Added 1 mL 10 N NaOH. Gray ppt. Stirred. Suspension now dark green.
0748 Dark green suspension. ORP = -90 ↓ dropping fast pH = 7.58 0804; ORP = -624 mV ↓ dropping fast!

BATCH MPERT-02-05-02

Note: It appears that the very first ppt is oxidized, probably due to O_2 dissolved in the DI. Appears to be only a very small amount of the $Fe(OH)_2$ so will ignor it for now.

0805 Turned off STIR to settle.

0850 Make a uranium soln w/ bicarbonate. Use 50 mg/L C
Use ~~0.1~~ 2 mg/L U. 10,000 mg/L STD

$$\frac{2\ mg\ U}{L_{soln}} \times \frac{1000\ mL_{STD}}{10{,}000\ mg\ U} = \frac{0.20\ mL\ of\ U\ STD}{L_{soln}}$$

$$\frac{50\ mg\ C}{L} \times \frac{84\ g\ NaHCO_3}{12\ mg\ C} = 350\ mg\ NaHCO_3/L$$

~~$\frac{84\ g\ NaHCO_3}{mol} \times \frac{12\ g\ C}{84\ g\ NaHCO_3}$~~ — 14.3% C

2 mg/L U, 350 mg/L $NaHCO_3$ Solution: pH = 7.34

0914 Purging U soln w/ He to removed DO.

1124 D/C He purge. Capped flask. pH of U soln = 7.72 ORP = 54 mV

1335 Poured $Fe(OH)_2$ suspension into 4 - 250 mL Nalge. Centrifuged 1500 rpm for 30 m.

1420 Decanted (pipetted) and transferred to 4 - 50 mL Cent. Tubes. Centrifuged 3500 rpm for 20 min.

1500 Decanted and transferred to a 50 mL volumn. About 1% lost (guess). This suspension should have 5.6/50 = <u>0.112 g of Fe per mL.</u>

Added appropriate volumes of U-HCO_3 soln and $Fe(OH)_2$ suspension in 50 mL Cent. tubes (see table).

AMPAD EFFICIENCY LINE® 22-210

BATCH MPERT-02-05-03

Sample #	Vol of Fe Susp (mL)	Vol. of U Soln (mL)	Total Vol (mL)	Final pH	Final ORP (mV)	Final U (µg/L)	Sorbed U (µg)	* µg U/mg Fe Sorbed Density	* mol U/mol Fe Sorbed Density
MEN-1	0	40	40	8.20	46	1858	—	—	—
MEN-2	0.25	40	40.25	7.00	56	717.6	45.44	1.62	3.82×10^{-4}
MEN-3	0.5	40	40.5	6.72	58	126.6	69.19	1.24	2.91×10^{-4}
MEN-4	1.0	40	41	6.20	56	20.9	73.46	0.66	1.54×10^{-4}
MEN-5	1.5	40	41.5	5.51	58	31.4	73.02	0.43	1.02×10^{-4}
MEN-6	2.0	40	42	4.80	59	118.4	69.35	0.31	7.28×10^{-5}
MEN-7	5.0	40	45	5.81	20↓	19.9	73.42	0.13	3.09×10^{-5}

* Based on no loss of Fe (unlikely)

01:5:10 Placed on end-over-end stir
MEN-2 and MEN-3 very orange (oxidized). MEN-4 partially oxidized. Others mostly black

15:43 ALL Tubes MEN 2 – 6, except the 5mL (MEN-7) are oxidized. The cent. tubes must leak air.

16:35 ALL $Fe(OH)_2$ tube show distinct oxidation

17:10 Removed MEN-1 through 7 from stir. Centrifuged 3500 RPM for 20 min. ~~Measured~~ Decanted into tubes. measured pH and ORP.

1746 Preserved each effluent w/ 0.30 mL of conc HNO_3

9/30/04 0818 Diluted 0.5 mL of $Fe(OH)_2$ suspension to 200 mL. Added 4 mL HNO_3 conc. To check Fe content. MEN-8

Fe = 23.4 mg/L

0.5 → 200 DF = 400

TOTAL Fe in Suspension = 9360 mg/L (23.4 × 400)

9.36 g/L ~~(9.36 mg~~

0.00936 g/mL

measured Fe in MEN-8 = 23.4 mg/L
23.7 mg/L after Acidification

Total in 200 mL = $\frac{9.36\,g}{1000\,L} \times .2L$ = 1.87 g

Should be ~~0.112 g/mL~~ ~~0.056 g/mL~~ 0.112 g/mL

lost ~~91.6%~~ ~~83.2~~ 91.6% loss

Batch - Calculations

MEN-1 through MEN-7

Recovery from MEN-1. $\frac{1858}{2000} = 92.9\%$

$40.25\,mL \times \frac{L}{1000\,mL} \times \frac{1858\,\mu g}{L} =$ ~~74.78~~ 74.32 µg available in 40 mL of U soln

MASS of U in MEN-2 uptake $= (~~188~~ 717.6)\frac{\mu g}{L} \times \frac{L}{1000\,mL} \times 40.25\,mL = 28.88$ ~~µg/mg~~ µg of U left in soln

$74.32 - 28.88 = 45.44$ µg sorbed

$$1.62\,\frac{\mu g\,U}{mg\,Fe} \times \frac{mol\,U}{238 \times 10^6\,\mu g\,U} \times \frac{56000\,mg\,Fe}{mol\,Fe} = (2.3529e^{-4})\,1.62 =$$

In excel. mending → Batch Tests

Column Test 1

Mending
Column 1   MPERT-02-05-05

9/30/04 Setting up column apparatus. Calibrate probes for data collection (Vernier data logger)

CH 1	pH(in)	Probe = F9107,	Int. = 13.7812,	slope = -3.7867	
CH 2	pH(out)	Probe = G9107,	Int. = 13.8631,	slope = -3.8220	
CH 3	ORP(in)	Probe = C3540,	INT = -389.76,	slope = 222.6	From Factory
CH 4	ORP(out)	Probe = A05990-53,	"	"	From Factory

-389.76 ORP_{Zobell} = +183
222.6 ORP_{Zobell} = ~~+230~~ +224

10/1/04 Set up column 2" Acrylic. Empty. Leak test and cleaning w/ 2% HNO_3 (2 Liters). Running at 10 mL/min. Measureing pH and ORP of influent and effluent.

DATE	Time	LOGGER PRO File	LOGGER Time	Flow Rate	Collect Tube	Pressure psi	pH 1	pH 2	ORP 3	ORP 4	Comments
10/1/04	0800	OCT01_01	0	10 mL/min	0	0	1.82	—	350	—	
	0802										1st influent to column. Stop Eff. collect.
	0919		80.134			0.5					Column 75% full
	0924	Added 1 L of milli-Q (should change pH) (Logger = 85.1)									Took PHOTOS of setup.
	0945 ~~0937~~		~~97.934~~ 105.800		1	0.8	1.86	~~4.19~~	432	—	1st outflow. Started Eff. frac. collector.
	0953		113.101			1.9	1.94	1.76	430	445	1st frac collected.
	1004		125	3 mL/min							Leaks. Decreased Flow

D/C system to stop leaks and determine why pressure is building

~1400 D/C System

14:17 Dissassembled column. Dried. Packed for test.

FROM BOTTOM:

Length	Wgt (g)	MATERIAL
4"	317.0 g	SAND - Unimin. Prod 2075. 75% retained on 20 mesh (med. grd. well sand) — Qtz/Felds ABD
3 3/8"	281.9 g	SAND As Above w/ 4.7% w/w powdered calcite* (13.3 g of calcite)
4"	323.1 g	SAND (as above)
3 7/8"	285.4 g	SAND w/ 5.0% w/w $Ca(OH)_2$**
2 1/2"	145.2 g	SAND

* Aldrich 23-921-6
** Aldrich 23-923-2

Column 1   MPERT-02-05-06

14:53 Finished packing column. Took photo of dry column.
Purged column w/ N_2 (2 Lpm for 30 min)

DO of milli-Q mixed w/ $FeSO_4$ ≤ 0.5 mg/L

10/4/04 06:30 Started N_2 purge of source tank H_2O (milli-Q to be used to make $FeSO_4$ soln), and column + tubing. 2 Lpm through each
Data file is Oct04_01 (Logger Pro). Collecting inlet and outlet, pH and ORP at 30s intervals.
Collecting samples 25 m to drain, then 25 min collect. Placed 55.604 g $FeSO_4 \cdot 7H_2O$ (Fisher) in 2L glass flask (0.1 M)
Added 1 mL conc H_2SO_4 and 2 L of Deoxy. water to $FeSO_4$, stirred under N_2. Purged rest of lines. Fe
Purging air space in source tank throughout test. Placed ~~200~~ 400 µL of conc. HNO_3 in each tube.

Data Table

Date	Time	LoggerPro file	Logger Time	Flow Rate	Collect tube	PSI Pressure (at inlet)	pH 1	pH 2	ORP 3	ORP 4	Comments
10/4/04	8:04	Oct04-01	0	230 mL/m	—						Start flow at 230 mL/min. Start data collect
	8:06	'	3.866	10 m/m	—	1.0					Slow to 10 mL/min. Green in $Ca(OH)_2$ layer.
	8:13		8.832	"	—	1.0	2.29	–	278	–	
	8:16		12.132	"	—	1.0	2.30				1st outflow from column.
	8:19		14.699	"	1st Drain	1.0	2.30	7.08	279	259	Start frac. collector
	8:20			↓	Drain						First drips to frac. collector
	8:22				1						First tube collecting
	8:37		33.597		4	1.2	2.30	7.73	278	-389	Green on upper filter disk of column
	9:10		66.594	"	11	1.2	2.31	7.44	278	-389	Random tubes are dark green / clear.

Upper sand is green. Clearly $Fe(OH)_2$ is mobile to some extent.

Date	Time	LoggerPro file	Logger Time	Flow Rate	Collect tube	PSI Pressure (at inlet)	pH 1	pH 2	ORP 3	ORP 4	Comments
	9:58	"	113.922	10 mL/m	20	1.2	2.31	7.14	277	-389	
	10:32		148.083	"	27	1.2	2.31	6.93	276	-389	

10:40 O/C system - end of $FeSO_4$

18:35 Sampled Solids (photo)

Top ↑	MEN-C1-S5	Sand layer	some overlap between layers
	MEN-C1-S4	Lime layer	Sample 50 mL of each - tried to get representative sample from each layer
	MEN-C1-S3	Sand layer	
	MEN-C1-S2	Calcite layer	
Bottom	MEN-C1-S1	Sand layer	

Column 1 MPERT-02-05-07

17:01 Cleaned out column. Running milli-Q through system. File = Oct04-02
Followed by 2 L of 5% HNO_3

Sarah is diluting the effluents by DF=10. Separate notes.

10/5/04 Purged column and tubes w/ 5% HNO_3 followed by milliQ

Mending Experiments Column 1

MPERT-02-05-08

Tube	As Collected	Homogenized
1	pale yellow, no layering	pale yellow
2	light yellow, sl. layering 1/4 way up tube	" "
3	as above #2	med. yellow
4	med yellow, dark band 1/4 way up, lighten toward top.	dk green
5	as 4	dk yellow
6	as 4	dk green
7	pale yellow, no obvious layering	pale yellow
8	as 7	" "
9	Very pale yellow, almost clear	Very pale yellow
10	Very pale @ bottom, dark band 1/4 way up, fading to pale yellow	dark green/brown
11	as 10	↓
12	as 10	↓
13	as 10	↓
14	as 10	↓
15	as 10	↓
16	as 10	↓
17	as 10	↓
18	as 10	↓
19	as 10	↓
20	as 10	↓
21	as 10	↓
22	as 10	↓
23	as 10	↓
24	as 10	↓
25	as 10	↓
26	as 10	↓
27	as 10	↓
28	as 10	↓

Tubes had HNO_3 added prior to collection

10/5/04 Tubes observed 16 hrs after homogenization. No layering, sl lighter in color, no obvious oxidation

22-210

Mending Experiments, Col 1 10/04/04 MPERT-02-05-09

10/04/04 Record appearance of liquid in tubes. Cork and homogenize. Samples mix easily and remain mixed. No apparent layering.

After homogenization, take 3mL split and place in 30mL centrifuge tube that has 2% conc. HNO_3 - (0.6mL). Fill to 30 mL vol. with Milli-Q.

Samples are clear with 2% HNO_3.

10/05/04 Analyze samples for Fe, Ca,. No matrix interference. Sample spike recovery is 100%

Remaining undiluted samples in test tubes allowed to sit out overnight. No layering. Sl. lightening of soln. No obvious orange oxidation

Column Test 2

Mendins Column 2 MPERT-02-05-10

10/5/04 Materials used in column fill
(1) SAND - Unimin Product 2075. 75% retained on 20 mesh. (well grained well sand)
(2) Bentonite - Colloid Environmental Technologies Co., Crumbles#8 (Arlington Heights, Ill).
(granular bentonite)
(3) Calcite - powdered Aldrich 23-921-6

Fill MATERIAL

Thickness (in.)	Weight	Material		
			TOP	
4 3/4"	350.0	SAND		
5"	392.6g	SAND/Bentonite		Mixture 356.3g SAND + 36.3g bentonite (9.2% Bent)
2 3/4	212.6g	SAND		
2 3/8 in	236.6g	CALCITE/SAND		Mixture 12.2g calcite + 224.6g SAND (5.2% calcite
2.5 in.	211.4 g	SAND	BOTTOM	

17:09 CALIBRATE PROBES

~~pH#1~~	4	7	10		ORP zobell
pH #1	3.94	7.00	10.08	ORP #3	179
pH #2	3.98	7.06	10.10	ORP #4	184

10/6/04 Start column 2. 1 N NaOH solution (2L Batch).
0630 Prime. DATA File = OCT06-01. Start data collect
0633 Start into bottom of column. 5 mL/min

Column 2 (Mending)　　　　　　　　　　　　　　　MPERT-02-05-11

Date	Time	Logger Pro File	Logger Time	Flow Rate	Collect Tube	Pressure psi	pH 1	pH 2	ORP 3	ORP 4	Comments
10/6/04	6:33	OCT06-01	0.033	570 ml/m	—	0.0	11.72	1.81	217	—	Start flow to col. bottom.
	6:40	"	0.150	5	—	0.1	12.27	—	158	—	
	6:55	"	0.400	5	—	0.3	12.57	—	86	—	Starting into calcite zone.
	7:[illegible]2	"	1.183	5	—	0.6	12.89	—	16		
	7:56	"	1.433	5	1st Drain	0.8	12.88	2.46	13	446	1st DRIPS from top of column. Start frac. coll.*
	8:09	"	1.650	5	2nd "	1.0	12.88	11.92	13	18	*
	8:57	"	2.450	5	6	1.0	12.91	12.59	-106	-77	
	9:44	"	3.233	5	11	1.0	12.91	12.72	-144	-82	
	13:28	NaOH jug was out. Turned off pumps and frac. coll. and data collector.									
"	13:37	OCT06-02	0.000	5	1	1.0	12.87	12.97	-188	-102	New rack of tubes. Start Milli-Q (Deoxygenated <0.5 mg/L O_2). Had some air from pumping air.
		"									
	14:00	"	0.367	5	3	1.0	12.24	12.98	-154	-95	
	14:36	"	0.967	5	6	1.0	11.06	13.04	-100	-97	Added 0.5ml conc H_2SO_4 to Milli-Q source. About 200 mL left in source.
	14:46	Stopped pump. All else running									
	14:58	"	1.333	5		1.1	1.92	13.03	227	-96	Restart w/ $FeSO_4$ soln (0.1m)
	16:22	$Fe(OH)_2$ particles flowing into frac collector and plugging it									
	16:32	"	2.900	5	18	1.0	2.50	7.41	263	-389	
Took photo dark green in column in ORANGE calcite →	17:11	"	3.567	5	22	1.0	2.41	6.42	276	-389	Tube 17-21 were green. Added 0.5mL of conc. HNO_3 to 17-44.
	18:08	"	4.500	5	27	1.0	2.37	6.22	276	-389	D/C TEST. (1 L of $FeSO_4$ soln used)

*Fraction collector collects 5 mins then 5 mins drain.... Some residual water will be in first tube or more. Actually, most residual went to drain. 1st sample should be good. No preservative unless stated (did not acidify NaOH samples). Tubes MEN-C2-1 thru 6 are slightly yellow. ~~#~~ 1 thru 27.

Porosity Calculation: $1.433 - 0.033 = 1.4\ Hr \times \frac{60\ mins}{Hr} \times \frac{5\ mL}{min} = 420\ mL$

1 PV = 420 mL

Labeled Tubes MEN-C2-1....
TuBi

1443 Made 1L of $FeSO_4 \cdot 7H_2O$ 0.1m (27.80 g in 1L) + 0.5 mL conc H_2SO_4
made w/ deoxygenated milli-Q

MPERT-02-05-12

10/7/04 1420 Sample C2 solids (Photos)

Top	MEN C2-S5	Sand, no clay, red stain, top of column
	MEN C2-S4	more Bentonite
	MEN C2-S3	Sand (looks like some green clay)
	MEN C2-S2	Calcite zone ?
Bottom	MEN C2-S1	Clean (white) sand at base of column

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Mending Column 2

MPERT-02-05-13

Tubes		1 Vol	2 Appearance in Tube	3	4	5	6	7	8	9	10 Homogenized	11	12	13
1	1	25	Clear								clear			
2	2	25												
3	3	25												
4	4	25												
5	5	25												
6	6	25												
7	7	25												
8	8	25												
9	9	25												
10	10	25												
11	11	25												
12	12	25												
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19	19	25												
20	20	25												
21	21	25												
22	22	25												
23	23	25												
24	24	25												
25	25	25												
26	26	25												
27	27	25												
28	28	25												
29	29	16												
30	30	4												
31	31	25												

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Mending Column 2

MPERT-02-05-14

Tube	Vol	2	Homogenized
32	25	clear	clear
33	25		
34	25		
35	25		
36	21		
37	Ø	Ø	Ø
38	25		
39	25		Ø 5ml
40	25		
41	20		
42	24		
43	24		
44	24		
45	21	sl. amber	pale yellow
46	20	clear bottom half, dk band @ 1/2 to pale yellow at top	med amber
47	25	clear	clear
48	25		
49	25		
50	25		
51	25	clear to last mL. Dark brown green @ top.	lt amber
52	25	bottom 1/3 clear, dk brown green band clearing to top	dk green brown
53	25		
54	25		
55	25		
56	20		

MPERT-02-05-15

Mending Columns - Fe extraction

10/8/2004 Five samples each from Col's 1 & 2 were obtained at the end of solution flow when columns were disassembled. Each was obtained to be a representative sample of each column segment. Samples chosen by S. Morrison.

Samples placed in pans to air dry.

Obtain 5g split of each of the following. Samples were sieved to $<$2mm (10 mesh) to disaggregate clump. There was no residual $>$2mm for any sample.

Place 5g split in 200 mL Vol flask. Add ≈ 50mL of 20% HNO_3 soln (v/v). Observe effervescence. Once effervescence subsided, fill to volume with 20% HNO_3 soln.

1400 Add magnetic stir bar. Place on stir plate. Check pH of each with pH paper. All <1. Start stir bars at med-low speed.

1530 Place glass stopper in each Vol flask. Speed on stir plate set so stir bars dont bog down - slowest each can maintain rotation

10/11 0830. Samples have stirred over weekend. D/C stirbar

10/12 Decant ≈ 100 ml from 200 vol flask into 125 ml nalge. Filter ≈ 30ml split from nalge bottle for analysis Fe, Ca

22-210

Mending – Leach Col 1 & 2

MPERT-02-05-16

Sample	Effervescence	Soln Color 10/8	Soln Color 10/11	Filter
C1-S1		Clear	~~V. sl. cloudy~~ Clear	clean
S2	aggressive, faded quickly	med. cloudy yellow	pale cloudy yellow	Sl orange
S3		pale clear yellow	sl. cloudy	"
S4	aggressive, faded quickly	med. cloudy orange	pale cloudy yellow	"
S5		pale cloudy orange	V. cloudy pale yellow	"
C2-S1		cloudy clear white	med cloudy white	Clean
S2	slight,	med. cloudy yellow	med cloudy white	V pale orange
S3	Very slight	pale cloudy yellow	milky white	V pale orange clogged @20
S4	Very slight	pale cloudy yellow	milky white	V pale orange clog @20
S5		V. pale, sl. cloudy yellow	V. pale white	Clean
Control (Unmin Oregon Sand)		Clear	V. sl. cloudy	

Results Mending - Fe extraction liquid results

MPERT-02-05-18

	#		Cr (mg/L)	Fe (mg/L)
1-S1	1	M	0.12	12.9
S2	2		119/119.5	14.3/13.7
S3	3		42.8	17.2
S4	4		150	55.4
S5	5		0.27	8.95
2 S1	6		0.04	5.36
S2	7		144.5	17.4
S3	8		0.14	25.7
S4	9		0.04	33.1
S5	10		0.00	13.6
Uni	11		<0.01	0.85
1-S1	12	L	0.46	23.0
S2	13		472	25.2
S3	14		131	31.9
S4	15		628	183
S5	16		0.50	30.7
2 S1	17		0.20	25.8
S2	18		634	35.1
S3	19		0.31	49.3
S4	20		0.58	70.5
S5	21		0.27	33.0
	22			
Uni	23	M	<0.01	0.85
Uni	24	L	0.12	0.76

Column Test 3

#1

~~Col 1~~ COL 3

MPERT-02-06-01

	Time	log time min. (NOV15-01, 2 5 collects)	pH	ORP	psi	Fluid	7	8	Event
11/15/04	1545	0.000			14	PW-17 (SYN) / 1N NaOH			1st outflow switch to 1N NaOH source
	1550	5.000							Start frac collector
	1552	7.700							Start 1st collect. liquid @ probes
	1558	12.600	6.95	-20.75	19				probes completely submerged. - felt holders
	1604	17.733	7.06	-21.84	20				start tube 1-3 for flow calc. 23mL/2.5min
	1626	40.00	7.17	-21.84	15				↓ flow to 2.5 ml/min 1N NaOH
	1628	43.100	7.18	-22.38	14.2				Start tube 1-8 for flow calc
	1651	65.467	7.20	-27.00	14.5				end tube 1-12
	1702	76.100	7.23	-29.18	15.1				
	1731	105.734	7.27	-31.62	16.9				end tube 1-20
	1811	145.901	7.31	-26.19	19				end tube 1-28
	1838	171.935	7.34	-18.85	20				jostled tubing transferring NaOH to smaller jar
NOV15_02	1848	0.000	7.36	-15.59	20				restart data collect. miss ~2 min data
2 5 collects	1852	3.600	7.36	-13.96	20				note outflow now pale clear yellow for past 5"
	1857	8.666	7.45	-12.06	20				end tube 1-36
	1859	10.666	8.59	-10.97	20				end 1-37 pH starting to ↑ faster
	1902	13.665	12.15	-8.28	20				end 1-38
	1905	16.265	12.37	-6.08	20				Start 1-39
	1907	18.665	12.43	-80.53	20				end 1-39
	1910	21.331	12.55	-84.07	20				start 1-40
	1912	23.698	12.66	-87.05	20				end 1-40 D/C flow
hr	1915	27.631	12.75	-96.84	20	↓			
NOV16_01	0820	0.000	13.17	-237.32	2.1	PW-17 Syn. no U, Mo			Start frac collector. Use PW17 source
11/16/04	0833	0.217	13.17	-242.48	11.5				Start 1-43
	0852	0.517	13.13	-234.87	16				Start 1-45 (1st 10" collect)
10 S collects	0922	1.022	13.12	-228.35	17.2				end 1-46
	0942	1.353	13.12	-224.82	17.8				end 1-47
	1002	1.686	13.12	-223.73	18.1				end 1-48
	1052	2.522	13.12	-218.52	20+				start tube 51 - tapping column.
	1107	2.792	13.14	-219.39	20+				D/C flow to col (drain during p51) remove top
	1125	3.072	13.14	-219.39	2.5				restart flow, frac collector drain prior to 52

Col 1 MPERT-02-06-02 #2

Date	#	1 Time	2 log time	3 pH	4 ORP	5 psi	Fluid	7 Event	9–13
10/16_01 11/16/04	1	1135	3.239	13.14	-219.66	2.8	PW-17	start 1-52	note; pushing air now, refilling column
	2	1155	3.572	13.14	-222.92	9.1	↓	start 1-53	pushing air - no outflow @ probes
	3	1235	4.239	13.18	-208.79	18.5		start 1-55.	outflow has resumed, tilt probe holders to resubmerg
	4	1255	4.572	13.18	-200.37	>20		start 1-56.	probe tubes full
	5	1335	5.236	13.18	-196.29	>20 psi		D/C flow, remove top.	
	6	1410	5.831	13.17	-194.66	1.2		restart flow	outflow muddy lots of fines
	7	1420	5.994	13.16	-193.84	1.2		start 1-59	" " " "
	8	1520	6.997	13.04	-194.39	1.4		start 1-62	" " " "
	9	1550	7.500	12.96	-185.42	1.4		end 1-63	" " " "
	10	1640	8.333	12.89	-179.44	1.5		start 1-66	" " " "
	11	1730	9.167	12.81	-178.36	1.5	↓	end tube 1-68	"
NOV16_02	12	1745	0.167	12.80	-178.63	1.5	$FeSO_4$	start 1-69	" 1st off after start of $FeSO_4$ soln
305 collects	13	1805	0.500	12.77	-178.90	1.5	0.1 M	start 1-70	
	14	1912	1.608	12.62	-178.90	1.5		Filling 1-73	
	15	2138	4.050	10.45	-179.44	1.5		Drain after 1-80	
	16	2256	5.342	10.03	-189.77	1.6		END 1-84	
	17	2326	5.842	9.79	-201.45	1.6		START 1-86	
	18	2357	6.367	9.58	-217.21	1.6	↓	END 1-87, Switched to SYN PW-17 + U + Mo.	nothing shut down, just switched tube to source.
	19	2357	Switched to PW-17 SYN + U + Mo.						
11/17/04	20	0026	6.850	9.34	-231.34	1.6	PW-17+U,Mo	START 1-89	
	21	0636	13.017	8.09	-314.22	1.5	↓	END ~~107~~ 1-107	
	22	0736	14.183	8.08	-317.48	1.5		start 1-111	
	23	0916	15.683	8.06	-319.38	1.5		end 1-115	
	24	1026	16.858	8.04	-319.65	1.4		start 1-119	
	25	1316	19.692	7.99	-318.57	1.4		end 1-127	change to 30" drain 10" collect
	26	1559	22.375	7.96	-317.21	1.4		end 1-131	
11/18/04	27	0829	38.892	7.80	-309.60	1.3		start 1-156	
	28	1108	41.558	7.77	-310.42	1.2		START 1-160	
	29	1349	44.225	7.74	-311.55	1.0		START 1-164	
	30	1748	48.233	7.70	-314.76	1.0		START 1-170	
11/19/04	31	0919	63.733	7.70	-295.47	1.1	↓	END 1-193	
		1640	71.092	7.71	-282.16			END 1-204	STOPPED test

Col 1 #1

MPERT-02-06-03

11/10/2004 Prepare 20L PW17. No U added. pH, DO meters Calibrated.

11/12/04 Filled column w/ blend from Monticello. (see page 2) 1389g

11/15/2004 Initial pH = 7.42 Initial DO = ~~7.52~~ 8.52 mg/L 6.52

1100 Start UHP Helium @ ≅ 15 ml/min

1210 pH = 7.42, DO = ~~8.7.66~~ 6.41 mg/L ↑ He to 40 ml/min

1225 pH = 7.41 DO = 5.82 mg/L

1240 pH 7.47 DO = 5.86 mg/L ↑ He to 60 ml/min

1325 pH = 7.51 DO = 5.38 mg/L ↑ He to 80 ml/min

1340 pH 7.52 DO = 5.15 mg/L ↑ He to 100 ml/min

1355 Change flowmeter to LPM Entrain ~ 1 Lpm

1423 pH = 7.82 DO = 1.33 mg/L

1425 Entrain CO_2 to source tank @ 25 ml/min pH = 7.74

Online probes pH 10 buffer = 10.09
pH 7 buffer = 7.02
pH 4 buffer = 4.00
ORP Zobel = 181.14 mV

1445 pH source tank = 7.46 DO = 0.56 mg/L

1455 pH source tank = 7.16 ↓ 15 ml/min

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~~Col 1~~ Col 3 — MPERT-02-06-04 — #2

11/15/04 1500 Start flow to column. (Syn PW-17 no U, no Mo?) Use prime to fill tubing. Rate set @ 10 mL/min

source tank pH = 7.10 CO_2 @ 15 ml/min
DO = 0.43 mg/L He @ 1 LPM.

Column has 1389 g of Mont. <2mm sediment.

1520 Col filled to ~290 mm (from flange) P ≈ 9 psi

1545 1st outflow. Start data logger, frac collector. time 0.000 start 1.0N NaOH
tubing to probes start to fill

1600 Notice free shift @ 60 mm gap of ~10 mm - soil column pushed up 20 psi

1615 pop connection. loose ~100 ml vol, secure connections c hose clamps

1620 ↓ flow to 2.5 mL/min tube 1-8 = 7.5 ml/2.5 min

Measure alk x3 160 on source tank ~180 mg/L as $CaCO_3$
185
190

tube 1-12 = 7.20

1857 start seeing NaOH breakthrough

1912 D/C flow to column @ 23.698 of 2nd data collect. Let data collect continue running

11/16/04 0750 Start CO_2 @ 10 ml/min and He 1 Lpm flow to source tank. Cal DO meter, ck pH meter. Both ok
pH = 7.04 DO = 1.38 mg/L

0820 Restart flow to column c PW17 conditioned source tank file NOV16_01 set for 12 hours c collects @ 10 sec.
restart fraction collector @ tube 1-41 2.5" drain, 2.5" collect.

Col 1 MPERT-02-06-06 #4

11/16/04 1237 Column appears to be running ok. P=14 psi. No outflow to tubes, but rate is ~2.5ml/min
Probe holder tilted to resubmerge probes.

1300 Restart CO_2 to source tank 10ml/min pH=7.18 DO=0.76 mg/L

He still bubbling $FeSO_4$ soln.

Alk of PW17 source tank 170, 175, 180 = 175 mg/L as $CaCO_3$

1335 leak @ T to pressure gauge D/c flow. Open column. remove ~3 spoons solids
Use pinflag wire to probe, stir remaining solids/liquid. Replace col. top

1410 Restart flow 1st tube will be 1-59

1420 D/C CO_2 to source pH=6.58 DO=1.03 mg/L He still bubbling $FeSO_4$ soln
pump is pushing plug of air in front of soln into column. Probes will soon be out of
outflow. Rack tilted to facilitate submersion when outflow restarts

1518 Outflow has resumed - sl muddy, lots of fines

Source tank pH still low 6.56 DO=1.04 mg/L He still bubbling $FeSO_4$ soln
still no CO_2 to source tank

1650 Reset frac collector @ end of 1-66 still 10" drain 10" collect.

1735 D/C flow of PW17 to column. Reset frac collector (10" drain, 10" collect) New data file = NOV16-0
100 hours, data point every 30 seconds

Start $FeSO_4$ flow to column - 1st tube will be 1-69

#3

Col 1

MPERT-02-06-05

11/16 0840 Reprogram frac collector for 10" drain, 10" collect. Start with drain p tube 44, before 45

source tank 1.18 mg/L DO pH = 6.85 ↓ CO_2 flow to ~10 mL/min

Note that outflow from column is dark amber.

When restarting flow and changing back to PW17 source tank, a small split was poured into beaker to prevent contamination of source tank with NaOH. With the tube place in beaker, soln became cloudy white and ppt. formed. Used soln in beaker x 15" to clear NaOH from tubing. Wipe tubing and place in larger source tank.

Total Vol 1.0N NaOH through column ≅ ~~1~~ 700 ml - 750 ml

Calc PV fill time 45", rate set @ 10 ml/min actual = 9.2 ml/min 1 PV = 414 ml

0940 DC CO_2 to source tank pH = 6.77 DO = 0.82 mg/L

DC He to source tank to move to DI cube. Need Deoxygenated H_2O for $FeSO_4$ soln.

1035 Restart He to source tank. pH = 6.88 DO 1.02

Prepare $FeSO_4$ soln add 1 ml conc H_2SO_4 to deoxygenated water prior to $FeSO_4$ addition

0.1 M soln = 27.8 g/L $FeSO_4 \cdot 7H_2O$

1045 Tap column to let soil fall back to bottom to fill gap. P > 20 psi

~~Start $FeSO_4$ soln (@ end of tube 57)~~

1107 D/C flow - column plugged @ 2.792 13.14 -24.39

Remove top to ck filter. filter clear Remove ~ 75-100 mL soil = 3 spoons. replace top.

Col 1

MPERT-02-06-07 5 #8

1/16/04 19:05 pH of $FeSO_4$ source tank = 2.15
21:40 Tube 1-76 is the first to be relatively sed. free. 1-76 thru 1-80 are relatively clear. Slightly cloudy
21:41 Column is brown. No obvious dark green coloration.
21:46 Small particulates of greenish material ($Fe(OH)_2$?) flow through sampling line - being collected.
22:19 Added 2mL of 10,000 mg/L U to PW17 (SYN) source tank. Should give roughly 1mg/L U
Initial pH = 6.50. Bubbled He. 22:41 pH = 6.82 22:50 pH = 6.95 U = 1055 µg/L
23:31 Added 20mL of 1,000 mg/L Mo to PW17 (SYN) source tank. Should give roughly 1mg/L Mo
23:46 PW17 Source pH = 7.05, DO < 0.95 mg/L U (after adding Mo) = 1073 µg/L
23:57 Tube 1-87 will be first to collect after switching to PW-17 + U + Mo source tank
23:57 Switched tube to PW-17 SYN + U + Mo
11/17/04 00:05 Source tank (PW-17 + Mo + U) DO < 1 mg/L, pH = 6.96
00:27 " " " pH = 6.87
06:38 " " " pH = 6.85
07:40 " " " pH = 6.86
07:55 Reset frac collector @ end of 1-111
09:50 Measure vol of all tubes collected overnight. Acidify ~1% (200µL) c̄ HNO_3 tubes 87-115
Filter tubes 87-115 through 0.45µm syringe filter. Note: switch to Cole Parmer filters c̄ tube 107
(tube 111 filtered c̄ Gelman)
13:16 Reset frac collector @ end of 1-127 start 30" drain 10" collect. Acidify each tube c̄ 200µL HNO_3
pH source tank = 7.37 adjust CO_2 to ≈ 10mL/min
1559 pH source tank = 6.68
11/18/04 0830 pH source tank = 6.70
1106 " = 6.70 O/C CO_2
11:53 " = 7.08 Started CO_2 ~ 2mL/min
13:44 " = 6.79
14:45 pH source = 6.89 (Before adding new batch) Sampled Source ST 11-18-14:45
14:50 Added 4L of SYN PW17 + Mo + U to source tank. pH (after) = 7.00. Inc. He bubbling
15:16 Source pH = 7.10. DO = 1.68 mg/L. Still bubbling vigorously. Sampled ST-11-18-15:16
18:07 " pH = 6.88
11/19/04 09:20 " pH = 7.90 start CO_2
10:02 " pH = 6.84 cut back CO_2, Sampled ST ST-11-19-10:02
10:24 " pH = 7.28
16:40 Stopped test

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Col 1

MPERT-02-06-08

		Vol	Cum Vol	Time	Rate	PV(1=414)	6	Comments	8	9	10	11	C(ug/L)	13
1-1	1	22	22	2.5"	8.8			Flow set 10mL/min						
	2	18	40	2.5	7.2									
1-2	3	14	54	2.5	5.6									
	4	19	73	2.5	7.6									
1-3	5	23	96	2.5	9.2									
	6	24	120	2.5	9.6									
1-4	7	24	144	2.5	9.6									
	8	15	159	2.5	6.0									
1-5	9	5	164	2.5	2.0			pop connection, loose vol. into column						
	10	6	170	2.5	2.4									
1-6	11	7	177	2.5	2.8									
	12	11	181	2.5	4.4									
1-7	13	14	195	2.5	5.6									
	14	7.5	202.5	2.5	3.0									
1-8	15	7.5	210	2.5	3.0			↓ Flow to 2.5 ml/min – ↑ pressure						
	16	7.5	217.5	2.5	3.0									
1-9	17	7.5	225	2.5	3.0			soln clear						
	18	7.5	232.5	2.5	3.0									
1-10	19	7.5	240	2.5	3.0									
	20	7	247	2.5	2.8									
1-11	21	7	254	2.5	↓									
	22	7	261	2.5										
1-12	23	7	268	2.5										
	24	7	275	2.5										
1-13	25	7	282	2.5										
	26	7	289	2.5										
1-14	27	7	296	2.5										
	28	7	303	2.5										
1-15	29	7	310	2.5										
	30	7	317	2.5										
1-16	31	7	324	2.5		0.78								
drain		7	331	2.5	↓									

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②

Col 1

MPERT-02-06-09

		Vol	CumVol	Time ~~Rate~~	Rate ~~PV (1=~~	PV (1=414)		Comments						
1-17	1	7	338	2.5	2.8			Soln Clear						
	2	7	345											
1-18	3	7	352											
	4	7	359											
1-19	5	7	366											
	6	7	373											
1-20	7	7	380											
	8	7	387											
1-21	9	7	394											
	10	7	401											
1-22	11	7	408											
	12	7	415											
1-23	13	7	422											
	14	7	429											
1-24	15	7	436											
	16	7	443											
1-25	17	7	450											
	18	7	457											
1-26	19	7	464											
	20	7	471											
1-27	21	7	478											
	22	7	485											
1-28	23	7	492											
	24	7	499											
1-29	25	7	506											
	26	7	513											
1-30	27	7	520											
	28	7	527											
1-31	29	7	534											
	30	7	541											
1-32	31	7	548			1.32								
drain		7	555	↓	↓									

Col 1

MPERT-02-06-10

Sample		1 Vol	2 CumVol	3 time	4 Rate	5 PV(1=414)	6	7 Comments
1-33	1	7	562	2.5	2.8			Soln clear
	2	7	569	2.5	↓			
1-34	3	7	576	2.5				" "
	4	7	583	2.5				
1-35	5	7	590	2.5				" "
	6	7	597	2.5				
1-36	7	7	604	2.5				V. pale yellow outflow
	8	7	611	2.5				
1-37	9	7	618	2.5				V. pale yellow
	10	7	625	2.5				
1-38	11	7	632	2.5				V. pale yellow
	12	7	639	2.5				
1-39	13	7	646	2.5				V. pale yellow
	14	7	653	2.5				
1-40	15	7	660	2.5	↓			V. pale yellow /DC flow to column. Sit overnight
	16	1	661	2.5	0.4			
1-41	17	1	662	2.5	0.4			Restart c̄ PW17 Source tank dark amber outflow
	18	1	663	2.5	0.4			
1-42	19	1	664	2.5	0.4			dk amber
	20	1	665	2.5	0.4			
1-43	21	2	667	2.5	0.8			dk amber
	22	3	670	2.5	1.2			
1-44	23	4	674	2.5	1.6			dk amber
	24	14	688	10	1.4			
1-45	25	24	712	10	2.4			dk amber 1st 10" collect
	26	24	736	10	2.4			
1-46	27	24	760	10	2.4			V dark amber
	28	24	784	10	2.4			
1-47	29	23	807	10	2.3			Coffee colored
	30	23	830	10	2.3			
1-48	31	23	853	10	2.3	2.06		" "

MPERT-02-06-11

	Vol	CumVol	Time	Rate	PV(1=4.14)	Comments:
drain	23	876	10	2.3		
1-49	23	899		2.3		
	23	922		2.3		
1-50	23	945		2.3		
	20	965		2.0		
1-51	15	980		1.5		
	13	993		1.3		
1-52	12	1005		1.2		D/c flow to column (between 51 & 52 collect) then restart pushing air
	9	1014		0.9		
1-53	6	1020		0.6		pushing air
	15	1035		1.5		
1-54	22	1057		2.2		pushing Omant air
	15	1072		1.5		
1-55	6	1078		0.6		rate ok - air outflow to resubmerge probes
	8	1086		0.8		
1-56	9	1095		0.9		column pressure ↑
	10	1105		1.0		
1-57	13	1118		1.3		column pressure ↑
	5	1123		0.5		
1-58	0	1123		~~0~~		D/c flow
	10	1133		1.0		restarted flow
1-59	15	1148		1.5		restart flow - pushing air, dk coffee color
	15	1163		1.5		
1-60	15	1178		1.5		dk coffee color, pushing air
	18	1196		1.8		
1-61	23	1219		2.3		1/2 coffee colored, 1/2 fines
	18	1237		1.8		
1-62	13	1250		1.3		suspended fines throughout, air out, resubmerge probes
	18	1268		1.8		
1-63	23	1291		2.3		" " "
	23	1314	↓	2.3	3.17	

MPERT-02-06-12

	Vol	CumVol	Time	Rate	PV (414)	Comments	Fe (mg/L)
1-64	23	1337	10	2.3		Suspended fines, no settling	
	23	1360	↓	2.3			
1-65	23	1383		2.3		" " "	
	23	1406		2.3			
1-66	23	1429		2.3		" " "	
	23	1452		2.3			
1-67	23	1475		2.3		" " "	
	23	1498		2.3			
1-68	23	1521	↓	2.3		" " "	
	23	1544		↓		Start flow of $FeSO_4$ Soln to column	
1-69	23	1567				1st tube off after start of $FeSO_4$ soln	
	23	1590					
1-70	23	1613					
	23	1636					
1-71	23	1659					
	23	1682					
1-72	23	1705					
	23	1728					
1-73	23	1751					
	23	1774					
1-74	23	1797					
	23	1820					
1-75	23	1843					
	23	1866					
1-76	23	1889					
	23	1912					
1-77	23	1935					4.9
	23	1958					
1-78	23	1981				last of tubes c̄ obvious fines	52.4
	23	2004					
1-79	23	2027	↓	↓			216

MPERT-02-06-13

	Vol	CumVol	Time	Rate	PV(1=414+)	Comments	Fe (mg/L)	U (µg/L)	Mo (mg/L)
	23	2050	10	2.3					
1-80	23	2073	↓	↓			452		
	23	2096							
1-81	23	2119					560		
	23	2142							
1-82	23	2165					915		
	23	2188							
1-83	23	2211					980		
	23	2234							
1-84	23	2257					1220		
	23	2280							
1-85	23	2303					1350		
	23	2326							
1-86	23	2349					1360		
	23	2372							
1-87	23	2395				1st tube p switch to spiked ST	1405	<1	<0.12
	23	2418							
1-88	23	2441					1570	<1	
	23	2464							
1-89	23	2487					1980		
	23	2510							
1-90	23	2533					2160		<0.12
	23	2556							
1-91	23	2579					~~2160~~ 2020		
	23	2602							
1-92	23	2625					1710 ~~2020~~	<1	
	23	2648							
1-93	23	2671					1570		
	23	2694							
1-94	23	2717					1230		<0.12
	23	2740	↓	↓					

MPERT-02-06-14

	Vol	Cum Vol	Time	Rate	PV(1=414?)	Fe(mg/L)	U(ug/L)	Mo(mg/L)
1-95	23	2763	10	2.3		1065		
	23	2786						
1-96	23	2809				920	26.6	
	23	2832						
1-97	23	2855				815		
	23	2878						
1-98	23	2901				680		<0.12
	23	2924						
1-99	23	2947				617.5		
	23	2970						
1-100	23	2993				522.5	27.5	
	23	3016						
1-101	23	3039				504		
	23	3062						
1-102	23	3085				434		<0.12
	23	3108						
1-103	23	3131				399		
	23	3154						
1-104	23	3177				365	28.3	
	23	3200						
1-105	23	3223				338		
	23	3246						
1-106	23	3269				295		<0.12
	23	3292						
1-107	23	3315				292		
	23	3338						
1-108	23	3361				268	28.5	
	23	3384						
1-109	23	3407				254		
	23	3430						
1-110	23	3453				238		<0.12

MPERT-02-06-15

	Vol	CumVol	Time	Rate	Comments	Fe (mg/L)	U (ug/L)	Mo (mg/L)
	23	3476	10	2.3				
1-111	23	3499	↓	↓		234		
	23	3522						
1-112	23	3545				213	30.0	
	23	3568						
1-113	23	3591				193		
	23	3614						
1-114	23	3637				186		<0.12
	23	3660						
1-115	23	3683	↓	↓		172		
	23	3706						
1-116	23	3729			U = 33.2 ug/L 1.33L after start of spiked ST	164	33.2	
	23	3752						
1-117	23	3775				152		
	23	3798						
1-118	23	3821				145		<0.12
	23	3844						
1-119	23	3867				138		
	23	3890						
1-120	23	3913				130.5	34.2	
	23	3936						
1-121	23	3959				126.5		
	23	3982						
1-122	23	4005				122.5		<0.12
	23	4028						
1-123	23	4051				118.5		
	23	4074						
1-124	23	4097			U = 37.6 ug/L 1.7 L after start of spiked ST316	112		
	23	4120						
1-125	23	4143				111		
	23	4166	↓	↓				

MPERT-02-06-16

	Vol	CumVol	Time	Rate	PV(1=414r)	Comments	Fe (mg/L)	U (ug/L)	Mo (mg/L)
1-126	23	4189	10	2.3 mL/m			106.5		<0.12
	23	4212	10						
1-127	23	4235	10				103.5		
	* 69	4304	30			Reset frac collector for 30" drains			
1-128	23	4327	10				99.5	40.1	
	69	4396	30						
1-129	23	4419	10				93		
	69	4488	30						
1-130	23	4511	10				88.5		<0.12
	69	4580	30						
1-131	23	4603	10				82		
	69	4672	30						
1-132	23	4695	10				79	50.9	
	69	4764	30						
1-133	23	4787	10				76		
	69	4856	30						
1-134	23	4879	10				75		<0.12
	69	4948	30						
1-135	23	4971	10				69.5		
	69	5040	30						
1-136	23	5063	10				68	89.7	
	69	5132	30						
1-137	23	5155	10				65		
	69	5224	30						
1-138	23	5247	10				61.6		<0.12
	69	5316	30						
1-139	23	5339	10				59.6		
	69	5408	30						
1-140	23	5431	10				58.2	148.7	
	69	5500	30						
1-141	23	5523	10				56.8		
	69	5592	30						

Col 1

MPERT-02-06-17

	Vol	Cum Vol	Time	Rate	PV(1=414+)	Comments	Ce(mg/L)	Cl(mg/L)	Mo(mg/L)
1-142	23	5615	10	2.3 ml/m ↓			56		<0.12
	69	5684	30						
1-143	23	5707	10				54.6		
	69	5776	30						
1-144	23	5799	10				53	197.3	
	69	5868	30						
1-145	23	5891	10				50.6		
	69	5960	30						
1-146	23	5983	10				48.4		<0.12
	69	6052	30						
1-147	23	6075	10				46.4		
	69	6144	30						
1-148	23	6167	10				45.2	243.4	
	69	6236	30						
1-149	23	6259	10				44.6		
	69	6328	30						
1-150	23	6351	10				43.6		<0.12
	69	6420	30						
1-151	23	6443	10				42		
	69	6512	30						
1-152	23	6535	10				40.6	291.0	
	69	6604	30						
1-153	23	6627	10				38.2		
	69	6696	30						
1-154	23	6719	10				37.8		0.14
	69	6788	30						
1-155	23	6811	10				36.6		
	69	6880	30						
1-156	23	6903	10				35.2	337.5	
	69	6972	30						
1-157	23	6995	10				34		
	69	7064	30						

MPERT-02-06-18

	Vol	Cum Vol	Time	Rate	PV	Comments	Fe(mg/L)	U(ug/L)	Mo(mg/L)
1-158	23	7087	10	2.3 ml/min			33.2		<0.12
	69	7156	30						
1-159	23	7179	10				32.2		
	69	7248	30						
1-160	23	7271	10				30.7	384.1	
	69	7340	30						
1-161	23	7363	10				30.3		
	69	7432	30						
1-162	23	7455	10				29.2		0.14
	69	7524	30						
1-163	23	7547	10				28.3		
	69	7616	30						
1-164	23	7639	10				27.3	422.1	
	69	7708	30						
1-165	23	7731	10				26.5		
	69	7800	30						
1-166	23	7823	10				26.8		0.18
	69	7892	30						
1-167	23	7915	10				25.6		
	69	7984	30						
1-168	23	8007	10				24.7	456.5	
	69	8076	30						
1-169	23	8099	10				23.9		
	69	8168	30						
1-170	23	8191	10				23.4		0.20
	69	8260	30						
1-171	23	8283	10				22.6		
	69	8352	30						
1-172	23	8375	10				22.2	490.7	
	69	8444	30						
1-173	23	8467	10				21.2		
	69	8536	30						

MPERT-02-06-19

	Vol	CumVol	Time	Rate	PV	Comments	(mg/L) Fe	U (µg/L)	Mo (mg/L)
1-174	23	8559	10	2.3 ml/min			20.8		0.22
	69	8628	30						
1-175	23	8651	10				20.2		
	69	8720	30						
1-176	23	8743	10				19.8	510.5	
	69	8812	30						
1-177	23	8835	10				19.2		
	69	8904	30						
1-178	23	8927	10				18.8		0.38
	69	8996	30						
1-179	23	9019	10				18.2		
	69	9088	30						
1-180	23	9111	10				17.7	528.7	
	69	9180	30						
1-181	23	9203	10				16.9		
	69	9272	30						
1-182	23	9295	10				16.8		0.26
	69	9364	30						
1-183	23	9387	10				15.8		
	69	9456	30						
1-184	23	9479	10				15.4	563.8	
	69	9548	30						
1-185	23	9571	10				14.0		
	69	9640	30						
1-186	23	9663	10				14.2		0.48
	69	9732	30						
1-187	23	9755	10				13.8		
	69	9824	30						
1-188	23	9847	10				13.7	559.8	
	69	9916	30						
1-189	23	9939	10				13.0		
	69	10008	30						

MPERT-02-06-20

	Vol	Cum Vol	Time	Rate	PV	Comments	Fe(mg/L)	U(ug/L)	Mo(mg/L)
1-190	23	10031	10	2.3ml/min			12.7		0.44
	69	10100	30	↓					
1-191	23	10123	10				12.2		
	69	10192	30						
1-192	23	10215	10				11.9	552.1	
	69	10284	30						
1-193	23	10307	10				11.7		
	69	10376	30						
1-194	23	10399	10				10.9		0.62
	69	10468	30						
1-195	23	10491	10				10.8		
	69	10560	30						
1-196	23	10583	10				10.7	580.4	
	69	10652	30						
1-197	23	10675	10				10.5		
	69	10744	30						
1-198	23	10767	10				10.2		0.46
	69	10836	30						
1-199	23	10859	10				9.9		
	69	10928	30						
1-200	23	10951	10				9.5	671.1	
	69	11020	30						
1-201	23	11043	10				9.5		
	69	11112	30						
1-202	23	11135	10				9.2		0.62
	69	11204	30						
1-203	23	11227	10				8.8		
	69	11296	30						
1-204	23	11319	10				8.8	689.0	
Source	TANKS								
11/18/04	14:45						<0.1	1042.2	1.04
11/18/04	15:16						<0.1	997.2	1.12
11/19/04	10:02						<0.1	972.8	1.18

Control Column

~~Col 2~~ (CONTROL) COLUMN LAB NOTES MPERT-02-07-01

11/18/04 10:57 Placed probes on line to CALIBRATE. pH2 and ORP2 → File NOV16_02
(Col 1 is also running). LOS time = 41.358 hrs
Source tank is SYN PW-17 w/ U and Mo (Same source tank as for Col 1)
U ~ 1055 ug/L Mo ~ 0.80 mg/L
CALIBRATION: pH 4_{STD} = 4.00, pH 7_{STD} = 6.99 ORP_{ZOBELL} = 198.8 mV

11:18 START FLOW. 2.5 mL/min. Collection not on. See Notes on $FeSO_4$ (Col 1) column for weights of sed, etc.

11:40 1st wetting of column bottom.

11:53 pH source tank = 7.08, started CO_2 ~ 2 mL/min

13:42 Start Frac. coll. - no fluid yet.

13:44 pH source = 6.79, Place 200 uL of conc. HNO_3 in each of tubes 2-1 thru 2-44

14:34 First outflow from col., not to probes yet. 1 PV = 435 mL Call it 400 mL due to losses to pipe etc

14:45 pH source = 6.89 (Before adding new batch), Sampled ST. = ST 11-18-14:45

14:50 Added 4L of SYN PW 17 + Mo + U to source tank. pH (after) = 7.00, Inc. He bubbling

15:16 Source pH = 7.10. DO = 1.68 mg/L Still bubbling vigorously Sampled ST ST-11-18-15:16

18:07 " " = 6.88

11/19/04 09:20 " " = 7.90 Start CO_2

10:02 " " = 6.84 cut back CO_2 Sampled ST ST-11-19-10:02

16:24 " " = 7.28. Stopped test

Col #2 1396.0g Monticello Sediment <2MM (10 mesh)

MPERT-02-07-02

Drain 30 min
*collect 10 mins
@ 2.5 mL/min

~~Col 2~~ Control Column

	Time	Log Time	pH	ORP	pS 2 (psi at inlet)	Event.
1/18/04 le NOV 16.02						
	11:18	41.708	NA	NA	NA	Start Flow (SYN PW-17) to column. Flow = 2.5 mL/min
	11:50	42.250	NA	NA	0.0	1st wetting of base at 11:40
	13:42	44.117	NA	NA	2.5	Start Frac. Coll.* - no Flow to outlet yet. First 30min drain
	14:01	44.442	NA	NA	2.9	Still no outflow, but close
	14:12	44.617	NA	NA	3.0	Start 2-1 (no outflow yet), Entire col is wet
	14:34	44.992	NA	NA	3.4	First outflow from col
	15:02	45.442	6.98	-15.32	3.8	Finish 2-2
	17:32	47.942	7.32	-38.23	3.8	Start 2-6
1/19/04	09:~~19~~43	64.108	7.71	-38.21	3.3	END 2-30
	16:23	70.800	7.29	~~-28~~ -18.85	3.2	END 2-40. Stopped test.

~~Col 2~~ Control Column

MPERT-02-07-03

Sample	Vol (mL)	Cum Vol (mL)	Time (min)	Rate (mL/min)	PV (1=400 mL)	Comments	U (μg/L)	Mo (mg/L)
2-1	~~23~~ 0	0	10	2.3				
	69	69	30	↓				
2-2	~~23~~ 20	89	10				~~16.3~~ 37.7	
	69	158	30					
2-3	23	181	10					0.12
	69	250	30					
2-4	23	273	10				277.1	
	69	342	30					
2-5	23	365	10					
	69	434	30					
2-6	23	457	10					0.30
	69	526	30					
2-7	23	549	10					
	69	618	30					
2-8	23	641	10				593.6	
	69	710	30					
2-9	23	733	10					
	69	802	30					
2-10	23	825	10					0.16
	69	894	30					
2-11	23	917	10					
	69	986	30					
2-12	23	1009	10				687.7	
	69	1078	30					
2-13	23	1101	10					
	69	1170	30					
2-14	23	1193	10					0.44
	69	1262	30					
2-15	23	1285	10					
	69	1354	30					
2-16	23	1377	10				632.3	
	69	1446	30	↓				

~~Col 2~~ Control Column

MPERT-02-07-04

	Vol	CumVol	Time	Rate	PV	Comments	U(ug/L)	Mo(mg/L)
2-17	23	1469	10	2.3 ↓				
	69	1538	30					
2-18	23	1561	10					0.40
	69	1630	30					
2-19	23	1653	10					
	69	1722	30					
2-20	23	1745	10				561.5	
	69	1814	30					
2-21	23	1837	10					
	69	1906	30					
2-22	23	1929	10					0.56
	69	1999	30					
2-23	23	2021	10					
	69	2090	30					
2-24	23	2113	10				500.1	
	69	2182	30					
2-25	23	2205	10					
	69	2274	30					
2-26	23	2297	10					0.44
	69	2366	30					
2-27	23	2389	10					
	69	2458	30					
2-28	23	2481	10				475	
	69	2550	30					
2-29	23	2573	10					
	69	2642	30					
2-30	23	2665	10					0.52
	69	2734	30					
2-31	23	2757	10					
	69	2826	30					
2-32	23	2849	10				456.2	
	69	2918	30					

MPERT-07-02-05

Col 2

	Vol	CumVol	Time	Rate	PV	Comments	U(ug/L)	Mo(mg/L)
2-33	23	2941	10	2.3				
	69	3010	30	↓				0.61
2-34	23	3033	10					
	69	3102	30					
2-35	23	3125	10					
	69	3194	30				530.9	
2-36	23	3217	10					
	69	3286	30					
2-37	23	3309	10					
	69	3378	30					0.84
2-38	23	3401	10					
	69	3470	30					
2-39	23	3493	10					
	69	3562	30				658.6	
2-40	23	3585	10	↓				