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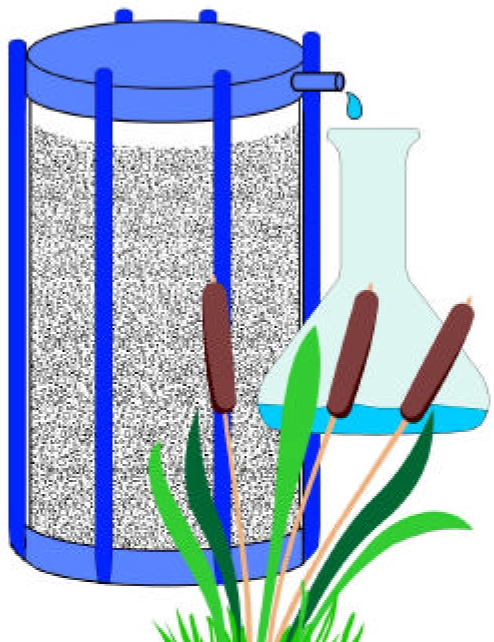
Environmental Sciences Laboratory

Final Report
Phase II: Performance Evaluation of Permeable Reactive Barriers and Potential for Rejuvenation by Chemical Flushing

U.S. Environmental Protection Agency
Region 8 Support

January 2004



Prepared for
U.S. Department of Energy
Grand Junction Site
Grand Junction, Colorado

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Signature Page

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Acronyms

AFO	amorphous ferric oxyhydroxide
Ca	calcium
CBD	citrate bicarbonate dithionite
CCD	citrate carbonate dithionite
cm	centimeters
cm/s	centimeters per second
CO_2	carbon dioxide
DOE	U.S. Department of Energy
dpm	disintegrations per minute
EDTA	ethylenediaminetetraacetic
EPA	U.S. Environmental Protection Agency
ESL	Environmental Sciences Laboratory
Fe	iron
ft	feet (foot)
ft/day	feet per day
g	gram
gal/min	gallons per minute
HCl	hydrochloric acid
L/min	liters per minute
lb	pound
M	mol
mg/g	milligrams per gram
mg/kg	milligrams per kilogram
$mg \cdot kg^{-1} \cdot mo^{-1}$	milligrams per kilogram per month
mg/L	milligrams per liter
mL	milliliter
mL/min	milliliters per minute
mm	millimeter
mM	millimols
mV	millivolts
µg/L	micrograms per liter
NaOAc	sodium acetate
ORP	oxidation-reduction potential
pCi/L	picocuries per liter
PRB	permeable reactive barrier
psi	pounds per square inch
U	uranium
UMTRA	Uranium Mill Tailings Remedial Action
UO_2	uraninite
USGS	United States Geological Survey
XPS	x-ray photoelectron spectroscopy
ZVI	zero-valent iron

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Executive Summary

A permeable reactive barrier (PRB) is a zone of chemically reactive material placed in the flow path of contaminated ground water that can stabilize or degrade contaminants as ground water moves through the zone. The most common reactive material employed in PRBs is zero-valent iron (ZVI). PRBs are rapidly becoming a widely used means of remediating ground water.

Unfortunately, reactions of ZVI with contaminants, dissolved oxygen, and water molecules result in an increase in pH values. Carbonate minerals precipitate within the ZVI because of the increase in pH values. Alkalinity decreases of as many as several hundred milligrams per liter (as calcium carbonate) from influent to effluent indicate that large volumes of carbonate minerals have precipitated in the PRBs. In addition to carbonate precipitation, oxidation causes the precipitation of iron oxide minerals. The buildup of carbonate and oxide minerals within the reactive zone could disrupt the performance of the PRB by causing (1) preferential pathways within the reactive zone, (2) ground water mounding and bypassing the PRB, and (3) a reduction in the reactivity of the media because of mineral deposition on the surface of the ZVI.

The U.S. Environmental Protection Agency (EPA) is funding this project to evaluate performance of PRBs and to investigate chemical methods of rejuvenating ZVI-based PRBs. The work is being conducted by Environmental Sciences Laboratory (ESL) personnel at the U.S. Department of Energy (DOE) office in Grand Junction, Colorado, in two phases. The goal of Phase I was to characterize ZVI core samples collected in February 2002 from the Monticello, Utah, PRB site. The purpose of Phase II was to characterize the time-dependent chemical changes using core samples collected August 2003 and to conduct bench-scale research to develop means of rejuvenating ZVI. This report discusses the results of Phase II.

Fresh samples of the reactive media were collected in August 2003 from the Monticello and Fry Canyon, Utah, sites by coring with a Geoprobe. Three PRBs were installed at the Fry Canyon site in 1997 as a joint project with the U.S. Geological Survey, EPA, DOE, the State of Utah, and Bureau of Land Management. Ninety-one samples (about four from each core) from various depths were collected in approximately 6-inch increments. The distributions of calcium (Ca), iron (Fe), and uranium (U) in these samples were measured to help determine if significant changes have occurred in the Monticello samples for the study period of February 2002 through August 2003.

Twenty-two vertical cores and four angle cores were obtained at the Monticello site. Most of the cores were collected near the two well transects that are currently used to monitor ground water. Because of the limited access at Fry Canyon, only the following borings were possible: two vertical and two angle borings in the amorphous ferric oxyhydroxide (AFO) PRB, three vertical borings in the ZVI PRB, and two vertical borings in the bone charcoal PRB. The most favorable coring method was to push an open core barrel to bedrock and collect a continuous core. A plug of bedrock at the bottom prevented the core from falling out of the pipe when the pipe was withdrawn from the subsurface.

Calcium inventories in the gravel/ZVI zone at Monticello increased in 60 percent of the cores during the study period. At some locations, Ca was apparently removed from the gravel/ZVI during the study period. The mean Ca deposition rate (110.4 milligrams per kilogram per month [$mg \cdot kg^{-1} \cdot mo^{-1}$]) during the study period is lower than the mean rate (931.2) for the initial period (June 1999 through February 2002), suggesting that the rate of calcium carbonate precipitation is decreasing in the gravel/ZVI zone. The Ca inventory increased in 73 percent of the cores collected from the ZVI zone with a mean increase of 8,400 milligrams per kilogram (mg/kg). The mean Ca deposition rates are similar for the initial and study periods (459 and 467 $mg \cdot kg^{-1} \cdot mo^{-1}$, respectively), suggesting that precipitation of calcium carbonate is relatively constant in the ZVI zone. Ground water flux, based on mass balance, ranges from 2.1 to 10.4 gallons per minute (gal/min) through the Monticello PRB for the study period, which is similar to the range (3.0 to 6.3 gal/min) calculated for the initial period in February 2002. The similarity suggests that ground water flow through the PRB has not been significantly impeded by ZVI corrosion products during the study period.

In all but one core from the gravel/ZVI zone at Monticello, the U inventory increased during the study period. The mean rate of U deposition in the gravel/ZVI zone increased by 18.2 $mg \cdot kg^{-1} \cdot mo^{-1}$ from the initial period to the study period. The mean U inventory in the ZVI zone increased by 8.63 mg/kg during the study period. The U deposition rate (0.48 $mg \cdot kg^{-1} \cdot mo^{-1}$) in the ZVI zone during the study period is higher than the rate (0.03 $mg \cdot kg^{-1} \cdot mo^{-1}$) for the initial period but is significantly less than the rate (25.9 $mg \cdot kg^{-1} \cdot mo^{-1}$) in the gravel/ZVI zone. Although U deposition rates appear to increase substantially for the study period, the means of the rates in both the gravel/ZVI and ZVI zones are biased by one high value.

The concentrations of U in the August 2003 ZVI PRB core samples from the Fry Canyon site are relatively low with a mean of 8 mg/kg. The U concentrations are similar to the concentration (9.8 mg/kg) measured in a single sample collected in September 1999. On the basis of the U gradient across the ZVI PRB and the ground water flow rates that were measured in tracer studies, much higher concentrations of U were expected. The low U concentrations may be a result of inadequate sampling of a highly concentrated U zone. Another possibility is that ground water flow through the PRB is less than indicated by the ground water monitoring program. The bone charcoal PRB had the highest U concentrations (mean 996 mg/kg) of the three Fry Canyon PRBs. One sample from the bone charcoal PRB had the highest U concentration (3,130 mg/kg) ever encountered in a PRB. The mean uranium concentration (197 mg/kg) in the AFO PRB is intermediate to the other two Fry Canyon PRBs. On the basis of Fe to U ratios, it appears that AFO has continued to sorb U since 1999, but the number of samples is too few to be conclusive.

The mean Ca concentration in the August 2003 Fry Canyon samples from the ZVI PRB is 35,046 mg/kg, and the Ca concentration in the September 1999 sample is 10,900 mg/kg. These values are much higher than the Ca concentration (1,710 mg/kg) in a fresh sample of Cercona ZVI pellets used in the PRB, indicating that Ca (probably as calcium carbonate) is accumulating in the ZVI PRB. No significant amount of Ca appears to be accumulating in the bone charcoal or AFO PRBs.

A simple method to determine the amount of reactive ZVI remaining in a sample from a PRB was developed during this project. The method is useful to determine reactivity loss of PRB material over time. The test is based on the principle that ZVI generates hydrogen gas (H_2) when in contact with a weak acid and is the only material in these samples to do so. The method uses an increase in gas pressure in a closed vessel to determine the relative reactivity of samples containing ZVI. Calcium carbonate also reacts with HCl to produce carbon dioxide (CO_2), which adds to the pressure, but CO_2 generation occurs much faster than H_2 generation from ZVI.

Mean reactivity values of samples collected from the Monticello gravel/ZVI zone appear to have declined during the study period. The relatively small difference in reactivities, however, could be statistically insignificant. ZVI in the gravel/ZVI zone is less reactive than that of the ZVI zone for both sampling periods. The lower reactivity of ZVI in the gravel/ZVI zone compared to the ZVI zone is consistent with other data, such as the predominance of U in the gravel/ZVI zone. Mean reactivity values of samples collected from the ZVI zone were slightly lower in February 2002 than in August 2003, but the differences may be statistically insignificant.

When bombarded with neutrons, U atoms fission and, when properly etched, the fission products produce visible tracks in a sheet of mica. This effect was used to map the U distributions in PRB samples to determine the association between U and mineral grains in the samples. Samples from the ZVI zones at Monticello and Fry Canyon have few fission tracks, consistent with their low U concentrations. Fission track densities were highest in the samples from the gravel/ZVI zone at Monticello, where U is associated with the rims of many of the ZVI grains. Fission-tracked rims do not occur on grains of any other minerals, indicating a close association between U and ZVI surfaces. It appears that much more U is directly associated with ZVI than with the fine-grained corrosion products in the matrix. The distribution of U suggests that U uptake by ZVI surface-mediated processes dominates over uptake by corrosion products dispersed in the matrix.

In contrast to the ZVI grains, fission tracks are distributed relatively evenly throughout bone charcoal grains in samples from Fry Canyon. This distribution suggests that U-bearing solutions are able to penetrate the Cercona bone charcoal pellets and contact the internal surfaces that are available for U uptake. Etched samples from the AFO PRB contain fission tracks throughout most of the AFO, but the tracks are often concentrated in small hot spots. The hot spots may result from grains or floccules of AFO or they may be crystallization centers. The U distribution suggests that most of the AFO surface adsorption sites were accessible to the ground water.

On the basis of August 2003 slug test results, geometric means of hydraulic conductivity for the alluvium, gravel/ZVI zone, and ZVI zone at the Monticello PRB are 0.011, 0.012, and 0.011 centimeter per second (cm/s), respectively. Slug test results for the three wells and data from two time periods suggest that hydraulic conductivity decreased by about 80 to 90 percent in the ZVI zone from June 2000 to August 2003. Tracer dilution data from August 2003 suggest a ground water flux through the Monticello PRB of between 1.0 and 1.6 gal/min, which is lower than previous estimates.

Bench-scale tests were conducted to evaluate the potential for rejuvenation of ZVI PRBs using chemical solvent flushing. We tested five solvents: tetrasodium ethylenediaminetetraacetic (EDTA), ammonium oxalate, sodium dithionite, sodium citrate, and hydroxlyamine hydrochloride. Some tests were conducted with combinations of these solvents and sometimes included bicarbonate or carbonate as a pH buffer. Suitable rejuvenation agents were defined by high dissolution of calcite (a ZVI corrosion product that occludes porosity), low dissolution of ZVI, and low toxicity. The ability to dissolve AFO, magnetite, and hematite was also considered favorable. Most of the solvents and combinations were able to dissolve some calcite, but most also dissolved some ZVI. Of the solvents tested in batch mode, EDTA was considered to be the most suitable and was selected for a preliminary column test. The column test results indicate that EDTA was able to remove all the calcite deposited during ZVI corrosion and some of the calcite initially present in the column fill material. While some Fe was also dissolved by EDTA, the change in the Fe inventory was insignificant.

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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 to stabilize or degrade contaminants as ground water moves through the zone. The most common reactive material employed in PRBs is zero-valent iron (ZVI). PRBs are rapidly becoming a widely used means of remediating ground water.

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Phase I of this project was completed in December 2002, and the results were presented in a report (DOE 2002b). Three tasks were completed in Phase I: (1) published literature was reviewed for information related to ZVI PRBs and in particular to rejuvenation; (2) an investigation was conducted to determine the nature of ZVI corrosion products, particularly carbonate minerals and iron oxides, from core samples collected from the Monticello PRB in February 2002; and (3) a determination was made of the amount of uncorroded ZVI remaining in the Monticello core samples. A test was developed that determines the reactivity of a ZVI sample by measuring pressure buildup, which is due to H_2 generated by reaction of ZVI with weak HCl, in a closed system.

Objectives of this Phase II study are

1. Determine how PRBs at Monticello and Fry Canyon, Utah, are changing over time.
2. Determine the hydraulic conductivity of the Monticello reactive media and if ground water continues to flow through it freely.
3. Determine the micro-scale distribution of uranium contained by the reactive media.
4. Bench test several chemical agents that might be capable of rejuvenating ZVI.

This report describes the results of the Phase II activities and the five different tasks that were conducted: (1) bulk chemical analysis of cores, (2) reactivity testing, (3) fission track analysis, (4) hydrologic testing, and (5) bench-scale rejuvenation testing.

1.1 Background on Permeable Reactive Barriers Used To Treat Ground Water for Uranium

More than 150 million tons of uranium mill tailings have been removed from 22 former uranium ore-processing sites in the United States. Remediation of ground water at these sites is mandated by Congress and was formerly conducted by the DOE Uranium Mill Tailings Remedial Action (UMTRA) Ground Water Project (NRC 1980) and now is being performed by the DOE Office of Legacy Management. EPA promulgated a ground water concentration limit of 30 picocuries per liter (pCi/L) (approximately 44 micrograms per liter [µg/L]) for U to ensure protection of human health and the environment near these sites (EPA 1995); this U concentration is also being used as a ground water cleanup goal at a former uranium-ore processing site near Monticello, Utah. At many of these former ore processing sites, U has entered the ground water system and has contaminated more than 10 billion gallons of ground water (DOE 1996). Uranium ore processing outside the United States, particularly in Australia, Canada, South Africa, and Europe, has also resulted in significant ground water with U contamination. In addition to tailings sites, U has been reported in ground water at 12 of 18 major DOE facilities because of contamination from the weapons production cycle (Riley et al. 1992).

Cost-effective means of cleaning up ground water contaminated by U are needed. Ground water at some of the tailings sites is being extracted and treated ex situ, but costs are high and no site has yet been remediated to EPA's prescribed standards. PRBs to treat ground water contaminated by U are currently being tested at four sites (Monticello, Utah; Fry Canyon, Utah; Durango, Colorado; and Oak Ridge National Laboratory Y-12 Plant, Tennessee) as a low-cost alternative to pumping and treating ground water.

ZVI, a scrap-metal product that is available from the automotive industry, is being used as a reactive material in the PRBs at these four sites. Contact with ZVI causes U concentrations in ground water to decrease to a few micrograms per liter. Results of numerous laboratory experiments have confirmed the ability of ZVI to remove U from ground water. Because of the promising results of laboratory and field studies, project managers are expressing increasing interest in using ZVI to treat U. Research is still needed, however, to understand the mechanisms of U uptake to support optimal designs for remediation systems and to make accurate predictions of the length of time that PRBs will remain effective. Research has also been conducted to evaluate the efficiency of using amorphous ferric oxyhydroxide (AFO) or phosphate minerals in PRBs (Morrison et al. 1996; Fuller et al. 2002).

Researchers have proposed two fundamentally different reaction mechanisms to explain the uptake of U by ZVI (Cantrell et al. 1995; Morrison et al. 2002b). In one mechanism, ZVI causes the oxidation state to decrease, resulting in reduction of solubilized U(VI) to immobile U(IV) via Reaction 1:

$$Fe(0)[solid] + UO_2(CO_3)_2^{2-} + 2H^+ = UO_2[solid] + 2HCO_3^- + Fe^{2+} . \qquad \text{(Reaction 1)}$$

Uranium(IV) is transferred from the aqueous phase to low-solubility minerals, such as uraninite (UO_2). In the other mechanism, ferric oxyhydroxides are formed as ZVI is oxidized by ground water. The ferric oxyhydroxides subsequently adsorb the dissolved U(VI). Cantrell et al. (1995) suggested that reductive precipitation is more dominant than adsorption and demonstrated its feasibility with thermodynamic calculations.

Fiedor et al. (1998) conducted experiments with a small disk (1.4 centimeters [cm] in diameter by 1.6 millimeters [mm] thick) of mild steel immersed in 300 milliliters (mL) of aqueous solution and concluded that the dominant mechanism for U removal by ZVI is adsorption on ferric oxyhydroxide corrosion products. When their experiments were conducted under aerobic conditions, U sorbed rapidly to the ferric oxyhydroxides, but U was slowly and incompletely reduced under anaerobic conditions. The surfaces of the solid phases in the aerobic experiments contained only U(VI); whereas the surfaces of the solid phases under anaerobic conditions contained about 75 percent U(IV) as determined by x-ray photoelectron spectroscopy. Fiedor et al. (1998) deduced that some reductive precipitation occurred, but the reaction was too slow to account for the observed rate of U removal in the experiments. They also concluded that reductive precipitation would not contribute significantly to U uptake in a PRB containing ZVI.

In contrast, Gu et al. (1998) provided experimental data confirming that reductive precipitation caused by ZVI is the dominant U uptake mechanism. Their experiments consisted of agitating 2 grams (g) of granular ZVI with 10 mL of a solution containing 42 millimols (10,000 milligrams per liter [mg/L]) U for 3 weeks. The reaction products were separated from ZVI by decanting and filtering. Less than 4 percent of the U was associated with the suspended reaction products. A 0.1 mol (M) Na_2CO_3 solution readily removed U from suspended reaction products but not from ZVI, signifying that U was adsorbed to reaction products but not to ZVI. Fluorescence spectroscopy confirmed that the U on the surfaces of the ZVI was in the U(IV) oxidation state, whereas U associated with suspended corrosion products was in the U(VI) oxidation state. Gu et al. (1998) demonstrated that the rate of U uptake in the presence of ZVI was slower than adsorption rates and that the shape of sorption isotherms indicated precipitation rather than adsorption, further evidence supporting a mechanism of reductive precipitation.

1.2 Background on the Monticello and Fry Canyon Permeable Reactive Barriers

This project is directly applicable to the Monticello, Utah, Mill Tailings National Priorities List site and the Fry Canyon, Utah, site. An in situ PRB was installed downgradient of the Monticello site in 1999; it is a funnel-and-gate system with a three-zone PRB (Morrison et al. 2002a). The furthest upgradient zone (the pretreatment zone) has 13-percent ZVI by volume mixed with pea gravel. Downgradient from the pretreatment zone is a zone of 100-percent ZVI, followed by the third zone that contains 100-percent gravel and an air sparging unit. At Fry Canyon, three PRBs were emplaced (Naftz et al. 2002). Each Fry Canyon PRB has a different reactive media: (1) Cercona ZVI pellets, (2) Cercona bone charcoal (phosphate) pellets, and (3) AFO mixed with pea gravel.

1.3 Project Operations

Fieldwork at both PRB installation sites was conducted from August 17 through August 29, 2003. Participants in the fieldwork included personnel from S.M. Stoller Corporation (Stoller), Grand Junction, Colorado, Office (Joe Trevino, Stan Morrison, Sarah Morris, and Tim Bartlett); Monticello, Utah, Office (Joe Slade and Todd Moon); EPA, Region VIII (Paul Mushovic and Rich Musa); Utah Department of Environmental Quality (David Bird); Kayenta Consulting (Bob Schlosser); and the U.S. Geological Survey (USGS) (Dave Naftz).

DOE Task Order ST03-304 directs Stoller to conduct the Phase II work scope. The Task Order is based on a Statement of Work prepared by Stoller, DOE, and EPA (EPA IAG – DW-89-95376701-7). A fieldwork plan, based on the Statement of Work, was used to manage the fieldwork (DOE 2003a). A kick-off meeting was held on August 15 to discuss the fieldwork scope with the participants. The Stoller Health and Safety organization was responsible for radiological control and project health and safety. Because of possible radiological emission from the cores, radiological controls were implemented. Radiological controls were also used to conduct laboratory investigations of the core material. A permit for bromide injections was received from the Utah Department of Environmental Quality.

Bench-scale investigations were conducted in the ESL at Grand Junction. Copies of the ESL notes are provided as Appendix A.

2.0 Bulk Chemistry Analyses

To address Objective 1 and part of Objective 2 (Section 1.0), fresh samples of the reactive media were collected in August 2003 from the Monticello and Fry Canyon sites with a Geoprobe. The distributions of Ca, Fe, and U in these samples were measured to help determine if significant changes have occurred in the Monticello samples since the February 2002 coring of this PRB. Locations of cores are provided in Figures 1 and 2.

Twenty-two vertical cores and four angle cores were obtained at the Monticello PRB site. Most of the cores were collected near the two well transects that are currently used to monitor ground water. The upper 6 feet (ft) or so of each core, consisting mostly of fill, was discarded at the field site. Because of limited access at Fry Canyon, only the following borings were possible: two vertical and two angle borings in the AFO PRB, three vertical borings in the ZVI PRB, and two vertical borings in the bone charcoal PRB. Five samples were recovered from the AFO PRB, ten from the ZVI PRB, and two from the bone charcoal PRB. All cores are 1.75 inches in diameter and were collected in plastic sleeves (except in the case of problems discussed in the following section).

2.1 Field Methods

Some problems were encountered during the coring. Only the upper 3 ft or so (fill material) was rigid enough to remain open as the core barrel was withdrawn. To core below this depth, a closed barrel with a pointed tip was used to penetrate to the desired coring depth; the tip was then released by unthreading a holding pin to initiate the coring. In some borings, the closed core barrel could not penetrate the ZVI, probably because of increased compaction of the ZVI with depth. If penetration was not possible, the boring location was moved slightly and attempted again.

In some borings, the release pin came unthreaded as the pipe was vibrated into the subsurface; causing the core barrel to fill prior to the target depths. To overcome this problem, an open barrel was pushed to bedrock and a continuous core was collected. A plug of bedrock at the bottom prevented the core from falling out of the pipe as the pipe was withdrawn from the subsurface. Removing the core from the barrel required extensive pounding with a steel mallet.

Ninety-one samples (about 4 from each core) from various depths were collected in approximately 6-inch increments. Samples were placed in plastic zip-lock bags and were surveyed for radioactivity before being transported to the ESL. Samples with above-background radioactivity were appropriately labeled and manifested for transportation. Descriptions of alluvium samples from the Monticello site are provided in Appendix B. Some samples obtained near the front edge of the PRB had sticky clay. While not conclusive, the clay suggests a possible smear zone that may have formed while driving sheet piling.

2.2 Laboratory Methods

Samples were dried at 90 ºC, and were weighed before and after drying to calculate moisture content. Density was not calculated because the coring methods prevented an accurate volume determination. Radioactivity was measured before and after drying the samples; radiologic controls, including a limited access controlled area, were implemented in the ESL. One sample split from each Monticello core was stored in acetone to help preserve the chemically reducing conditions in the PRB. Additional splits of these samples were archived in glass jars without drying. Oven-dried samples were submitted to the on-site Analytical Chemistry Laboratory where they were digested in nitric acid using microwave energy. The digestates were analyzed for Ca and Fe by inductively coupled plasma – emission and for U by inductively coupled plasma – mass spectrometry. The coring locations were determined by measuring from wells located within a few feet of the borings.

The same analysis methods for Ca, Fe, and U were used for the Fry Canyon samples. Fewer samples were available from each Fry Canyon core than at Monticello because of a thinner zone of reactive material and because the angle borings only penetrated a portion of the reactive zone. Each 6-inch core of reactive material was sampled, and all samples were processed for chemical analysis in the same manner as the samples from Monticello.

2.3 Results of Bulk Chemical Analyses

Results of bulk chemical analyses were used to estimate the change in chemical conditions in the PRBs over time as addressed in Objective 1 (Section 1.0).

2.3.1 Monticello

Raw data from the chemical analyses are provided in Appendix C; core locations are shown on Figure 1. Tables 1 through 4 present the solid-phase chemistry for cores collected August 2003 and for cores collected at the same locations in February 2002. Each value listed in the tables is the mean of the individual sample results (usually four) from that core. Values in columns 5 and 6 are the rates of constituent deposition based on an initial period of 32 months (June 1999 through February 2002) and a study period (February 2002 through August 2003) of 18 months, respectively.

The U inventory increased during the study period in all but one core (PE 10) from the gravel/ZVI zone (Table 1). The mean rate of U deposition in the gravel/ZVI zone increased by 18.2 mg $\cdot$ kg^{-1} $\cdot$ mo^{-1} from the initial period to the study period. The mean U inventory in the ZVI zone increased by 8.63 mg/kg during the study period (Table 2). The U deposition rate (0.48 mg $\cdot$ kg^{-1} $\cdot$ mo^{-1}) in the ZVI zone during the study period is higher than the rate (0.03 mg $\cdot$ kg^{-1} $\cdot$ mo^{-1}) for the initial period but is significantly less than the rate (25.9 mg $\cdot$ kg^{-1} $\cdot$ mo^{-1}) in the gravel/ZVI zone. Although the U deposition rates appear to increase substantially for the study period, the means in both the gravel/ZVI and ZVI zones are biased by one high value (PE 9 and PE 3; Table 1 and Table 2).

Calcium inventories in the gravel/ZVI zone increased in 60 percent of the cores during the study period (Table 3). At some locations, Ca was apparently removed from the gravel/ZVI. The mean deposition rate (110.4 mg $\cdot$ kg^{-1} $\cdot$ mo^{-1}) during the study period is lower than the mean rate (931.2) for the initial period, suggesting that calcium carbonate precipitation is decreasing in the gravel/ZVI zone. The Ca inventory increased in 73 percent of the cores collected from the ZVI zone with a mean increase of 8,400 mg/kg (Table 4). The mean Ca deposition rates are similar for the initial and study periods (459 and 466.7 mg $\cdot$ kg^{-1} $\cdot$ mo^{-1}, respectively) suggesting that precipitation of calcium carbonate is relatively constant in the ZVI zone.

Dissolved-phase and solid-phase concentration data were obtained along two transects across the PRB (R1-M3 and R1-M4; see Figure 1 for locations). Table 5 presents dissolved-phase concentration gradients for the study period and for the initial period. The U gradient (368 micrograms per liter [µg/L]) across the gravel/ZVI zone in transect R1-M3 during the study period is similar to the mean U gradient (334 µg/L) during the initial period. The U concentration gradient at transect R1-M4 is only 163 µg/L, indicating variability in the reactivity along the length of the gravel/ZVI zone. The Ca concentration gradient in the gravel/ZVI zone has decreased from 47.0 mg/L during the initial period to values of 2.8 and 14 mg/L for the two study-period transects. The similar Ca concentration gradients across the ZVI zone during the study period (99 and 141 mg/L) and the concentration gradient (118.4 mg/L) during the initial period (Table 5), suggest that reaction removal rates have remained relatively constant across the zone.

Ground water flux for the study period was calculated along each transect using dissolved phase concentration gradients and the increases in solid-phase inventories. Details of the calculation method are available in Morrison (2003). Calculated ground water flux ranges from 2.1 to 10.4 gallons per minute (gal/min) for the study period, which is similar to the range (3.0 to 6.3 gal/min) calculated for the initial period (Table 6). The similarity in flux rates suggests that ground water flow through the PRB has not been significantly impeded by ZVI corrosion products.

2.3.2 Fry Canyon

Fry Canyon was not cored in February 2002. Table 7 presents analytical results for one core sample from the ZVI PRB, one from the bone charcoal PRB, and two from the AFO PRB that were collected and analyzed in September 1999 as part of a previous project. Bulk chemical concentrations were also determined for samples of the same material that had not been used in a PRB ("fresh" samples). The bulk chemical results for the current study are listed in Table 8, and core locations are shown on Figure 2.

The concentrations of U in the August 2003 ZVI PRB core samples are relatively low with a mean of 8 mg/kg (Table 8). The U concentrations are similar to the concentration (9.8 mg/kg) measured in a single sample collected in September 1999. On the basis of the U gradient in samples collected across the ZVI PRB and the ground water flow rates measured in tracer studies, much higher concentrations of U were expected (Naftz et al. 2002). The low U concentrations may be because a highly concentrated U zone was not adequately sampled. Another possibility is that ground water flow through the PRB is less than indicated by the monitoring program, but this scenario seems less likely because the ground water deposited a significant mass of U in the other two PRBs.

The bone charcoal PRB had the highest U concentrations (mean 996 mg/kg in the August 2003 samples) of the three PRBs (Table 8). The bone charcoal PRB also had the highest U value (216 mg/kg) among all samples collected in September 1999 (Table 7). One sample from August 2003 had the highest U concentration (3,130.0 mg/kg) ever encountered in core samples from a PRB. One explanation for the high concentrations is the ability of the bone charcoal to sorb U throughout the pellets, not just on the outside surface (Section 4.0). The mean U concentration in the August 2003 sample (996 mg/kg) is considerably higher than the concentration of the single sample (216 mg/kg) collected in September 1999, but there are too few samples to accurately determine the rate of accumulation.

Uranium concentrations (mean 197 mg/kg) in the AFO PRB samples are intermediate to U concentrations in the other two PRBs (Table 8). One U value (19.0 mg/kg) is much lower than U concentrations in other samples, and this sample also has a much lower Fe concentration, reflective of less AFO. The samples have different proportions of AFO and gravel; ratios of U to Fe can be used to establish the amount of U uptake that is due solely to the AFO. Ratios of U to Fe in the samples collected August 2003 range from 1.51 to 2.30 milligrams per gram (mg/g); whereas the two samples collected September 1999 have U to Fe ratios of only 0.85 and 0.77 mg/g (Table 9). From these results, it appears that the AFO has continued to sorb U since 1999, but the number of samples is too few to be conclusive. The bulk U concentrations remain well below the concentration (19 mg U/g Fe) encountered in a laboratory test using Fry Canyon site ground water with a dissolved U concentration of 2 mg/L.

The mean Ca concentration in the August 2003 samples from the ZVI PRB is 35,046 mg/kg (Table 8), and the Ca concentration in the September 1999 sample is 10,900 mg/kg (Table 7). These values are much higher than the Ca concentration (1,710 mg/kg) in a fresh sample of Cercona ZVI pellets, indicating that Ca (probably as calcium carbonate) is accumulating in the ZVI PRB. Significant Ca does not appear to be accumulating in the bone charcoal or AFO PRBs.

3.0 Reactivity Tests

To further evaluate the changes taking place in the ZVI PRBs (Objective 1), an investigation was conducted to determine the reactivity of the ZVI at the two project sites. As ZVI reacts with ground water, some of the ZVI is lost by dissolution and formation of corrosion products. In addition, ZVI grains can lose reactivity as mineral precipitants coat their surfaces. In an effort to determine the proportion of ZVI remaining in the PRB, a hand magnet was used to separate ZVI in some samples. It was readily apparent, however, that magnetic separation was inadequate for determining ZVI composition because the magnetic separates contained a large proportion of corrosion products that could not be separated by physical means. Electron microprobe examination revealed relatively thick mineral coatings on many ZVI grains (DOE 2002b), confirming the strong association of corrosion products with the ZVI grains.

Because ZVI generates H_2 gas when in contact with a weak acid (HCl) and ZVI is the only material in these samples to do so, a test was devised that measures the ZVI concentration based on gas pressure (DOE 2003b). Gas pressure increase that was due to H_2 generation in a closed vessel was used to determine the relative reactivity of samples containing ZVI. Other components of the sample also react with HCl. For example, calcium carbonate reacts with HCl to produce CO_2, which adds to the pressure. CO_2 generation from calcium carbonate usually occurs much faster than H_2 generation from ZVI, and the two processes can be differentiated on time and pressure plots. The term “reactivity” as used in this report refers to 10,000 times the rate constant (min^{-1}) for generation of H_2 (Section.3.1).

The reactivity method was developed during this project and has not been used previously. The gas generation curves yield a great deal of information regarding the mineralogy of the samples and is simple to implement. The curves were useful in making a preliminary evaluation of the PRB reactivity. With additional method development, particularly in the evaluation of complex gas-generation curves, more detailed information about the reactivity and mineralogy of the PRB could be interpreted. Appendix D presents reactivity values for all samples.

3.1 Analysis and Calculation Methods

A glass OMNI glass chromatography column (Omnifit cat no. 006412) (15 mm diameter by 150 mm length) was used as the reaction vessel. A sample (0.2 g within 2 mg) was placed in the column. A 5-mL aliquot of 5 percent HCl was injected into the bottom of the column to make contact with the sample. A valve was used to close the column, and pressure data were collected every second for 1 hour.

An Excel spreadsheet model was used to evaluate the pressure curves. Several different approaches were tested to model the reactivity curves, including both first order (dependent on ZVI concentration only) and second order (dependent on ZVI and hydrogen ion [H^+] concentrations). Similarly, the carbonate dissolution was modeled with various rate laws. The modeling is still being refined; however, a model using first-order dissolution of both ZVI and carbonate fit the data reasonably well and was used to evaluate reactivities for this project. It was assumed that the gas pressure is due only to CO_2 from calcite dissolution and H_2 from ZVI corrosion. Factors considered in the model include (1) mol-for-mol dissolution of calcite and generation of CO_2; (2) calcite dissolution is first-order rate controlled; (3) 1 M of ZVI dissolution generates 2 M of H_2, the reaction is first-order rate controlled; (4) ideal gases are assumed; and (5) gas solubilities are controlled by Henry's law.

3.2 Reactivity Tests on Standards

Reactivity tests were conducted on a number of ZVI standards and on standard specimens of potential corrosion products (aragonite, calcite, hematite, magnetite, and siderite). Duplicate tests on standards were conducted to determine the reproducibility of the reactivity tests. Figure 3 presents the results of duplicate runs on three different ZVI samples and one calcite sample; these results indicate that the pressure curves are reasonably reproducible. The small variations observed are probably due to sample heterogeneity or inconsistent pressure readings at pressures above about 25 pounds per square inch (psi) (the upper limit of the pressure gauge is about 35 psi).

Figure 4 shows examples of reactivities of a range of standard ZVI samples. Reactivity curves for magnetite powder (with virtually zero reactivity) and calcite powder (with rapid CO_2 evolution) are shown for comparison. Fisher –100 mesh ZVI has the highest rate of H_2 evolution, followed by Peerless –60 +100 mesh ZVI, then Fisher –40 mesh. Coarse-grained Peerless –4 +20 ZVI has the lowest reactivity.

Figure 5 presents reactivity curves for a variety of carbonate minerals. Calcite powder generates CO_2 at the highest rate; coarser crystalline sparry calcite and aragonite evolve CO_2 at slightly lower rates. Siderite generates little CO_2 gas in contact with the 5 percent HCl. Magnetite and hematite generate little or no gas (Figure 6).

Three reactivity curves using various masses (0.1, 0.2, and 0.3 g) of Fisher –40 mesh ZVI were used to test the model (Figure 7). As expected, the tests that used more ZVI generated pressure at a higher rate. The first-order rate model, although not perfect, is able to reproduce the results reasonably accurately. The rate constant for carbonate dissolution was fit so that the model curve was between the measured curves for sparry and powdered calcite (Figure 8).

3.3 Reactivity Tests on PRB Samples

The gas generation curves for many of the PRB ZVI samples did not fit the model-generated curves. In some cases, a poor fit appeared to result from generation of CO_2 gas for longer time periods than for standard samples. Anomalously long periods of CO_2 generation could result if carbonate minerals are intergrown with other corrosion products. For the purpose of assigning reactivities, it was assumed that the rate of H_2 generation was best quantified by the slope of the curve after most of the carbonate had dissolved and before pressure increased to near the limit of the gauge. Therefore, the fit of the first-order model at 60 minutes was used to determine reactivity values. With this method, the reactivity values are interpreted to be a function of the rate of H_2 generation that is directly related to ZVI corrosion rates. The amount of carbonate in the samples could be qualitatively assessed by observing the early pressure increase but the amount was not quantified (Figure 9).

The reactivity of a sample is affected by the size fraction. Therefore, the results could be biased by the sample splitting method used to yield the 0.2-g samples in the test. Figure 10 demonstrates the effects of sample grain-size fraction. It is clear that nearly all the carbonate in the sample is in the –200 mesh fraction; the coarser fractions contain a higher proportion of ZVI. The slope at 60 minutes on the bulk sample is nearly the same as the slope on both coarse-grained fractions; thus, the reactivity determined from the bulk sample should reasonably approximate the ZVI content of the sample. A small laboratory spatula was used to collect a 0.2-g sample for analysis; efforts were made to collect the sample without grain size bias. In samples containing gravel (gravel/ZVI zone at Monticello and AFO from Fry Canyon), the sample consisted of matrix only, the gravel was purposely avoided.

Table 10 presents a summary of the reactivity values of the PRB samples. A fresh (unused in a PRB) sample of Peerless ZVI –8 +20 mesh (the ZVI used in the ZVI zone at Monticello) has a mean reactivity value of 4.4. The reactivity of ZVI-zone samples collected from above the water table should also represent original ZVI reactivity; the mean reactivity of ZVI zone samples collected from above the water table is 3.5 (Appendix D). The difference between the mean reactivities of fresh ZVI (4.4) and ZVI collected from the unsaturated zone (3.5) suggests a small amount of corrosion of the ZVI while residing in the unsaturated zone, but the difference could result from sample heterogeneity.

Mean reactivity values of samples collected from the gravel/ZVI zone appear to have declined from February 2002 to August 2003 (1.7 versus 1.3) (Table 10). Although reactivity likely reduces over time in the gravel/ZVI zone, the relatively small difference in reactivity values between February 2002 and August 2003 could be statistically insignificant, as suggested by the high standard deviations presented in Table 10. If we assume that the fine-grained matrix of the gravel/ZVI zone material is composed of only ZVI and its corrosion products, then the ZVI in the gravel/ZVI zone is less reactive than that of the ZVI zone for both sampling periods. This observation is also supported by the relatively high abundance (determined qualitatively from reactivity curves) of carbonate minerals in the gravel/ZVI samples. The lower reactivity of ZVI in the gravel/ZVI zone compared to the ZVI zone is consistent with other data, such as the predominance of U in the gravel/ZVI zone.

Mean reactivity values of samples collected from the ZVI zone were slightly lower in February 2002 than in August 2003 (3.0 versus 3.7) (Table 10). The difference between these mean reactivity values is likely due to the high variance of the populations as suggested by the relatively high standard deviations.

The reactivity value of a fresh sample of the Cercona ZVI pellets used at Fry Canyon was 2.9; whereas, the mean reactivity value of samples collected from the PRB was 1.3 (Table 10). These results suggest that the samples have lost some reactivity even though little U precipitated in the PRB samples (Section 2.3.2).

End of current text

4.0 Fission Track Analysis

Uranium atoms fission when bombarded with neutrons, and the fission products produce visible tracks in a sheet of mica when properly etched. This effect was used to map the U distributions in PRB samples to determine the association between U and mineral grains in the samples. This activity supports Objective 3 (Section 1.0)

4.1 Methods

PRB samples preserved in acetone were used for the fission track investigation. The samples were air dried and additional acetone was added during the drying process to displace any residual water. Uncovered polished thin sections were made of six samples from the Monticello PRB and six samples from the Fry Canyon PRB (Table 11). A thin sheet of muscovite mica was taped over each thin section directly in contact with the sample. A carbide stylus was used to make location marks through the mica and into the underlying slide. The thin sections, with the mica sheets, were irradiated for 1 hour in a reactor at the Denver Federal Center to achieve a neutron dose of about 0.8×10^{16} neutrons per square centimeter. The neutron bombardment causes U in the sample to fission, and the energized fission products produce atom dislocations in the mica sheet.

Some elements, such as sodium in the glass slide, become radioactive during irradiation. The samples were retained at the reactor site for about 2 weeks to allow some of the induced radiation to decay, then the samples were returned to the ESL. Because the samples were still radioactive, they were placed in a radioactive materials area; however, the samples were still radioactive after another 2 weeks, with counts up to 3 millirems per hour. A few flakes of mica were removable, so the analysis at the ESL was conducted under radiological controls.

The mica was etched for 1 minute in hydrofluoric acid. The etching causes the dislocations to become tracks that are visible at high magnification. Thus, the final product is a detailed map, on the mica sheet, of the U distribution in the sample. The samples were viewed with a petrographic microscope. Using the location marks, the fission-track maps (mica sheets) were oriented the same as the thin section so that the fission tracks could be associated with individual grains.

4.2 Results

Samples from the ZVI zones at Monticello and Fry Canyon have few fission tracks, consistent with their low U concentrations (Table 11). Fission track densities were highest in the samples from the gravel/ZVI zone at Monticello, where U is associated with the rims of many of the ZVI grains. Also in the gravel/ZVI zone, U is dispersed at low levels throughout some of the fine-grained matrix but is also concentrated into “hot spots” within the matrix. The hot spots may be remnant ZVI grains that are too small to be recognized petrographically or are due to larger grains mostly buried below the surface of the thin section. Fission-tracked rims do not occur on grains of any other minerals in the samples, indicating a close association between U and ZVI surfaces. It appears that much more U is directly associated with ZVI than with the fine-grained corrosion products in the matrix. The distribution of U suggests that U uptake by ZVI surface-mediated processes dominates over uptake by corrosion products.

In contrast to the ZVI grains, fission tracks are distributed relatively evenly throughout bone charcoal grains in samples from Fry Canyon. This distribution suggests that U-bearing solutions are able to penetrate the Cercona bone charcoal pellets so that internal surfaces are available for U uptake. Samples from the AFO PRB contain fission tracks throughout most of the AFO, but tracks are often concentrated in small hot spots. The hot spots may result from grains or floccules of AFO or may be crystallization centers. The U distribution suggests that most of the AFO surface adsorption sites were accessible to the ground water.

5.0 Hydrology Tests at Monticello

Hydrologic investigations at the Monticello site included hydraulic conductivity determinations at 42 locations and tracer dilution tests at 20 locations. These activities support Objective 2 (Section 1.0).

5.1 Hydraulic Conductivity Determinations

Forty-two rising-head slug tests were conducted August 26 to 28, 2003, to determine hydraulic conductivity of the gravel/ZVI and ZVI treatment zones of the PRB. Three wells completed in the alluvial channel were also tested. Slug test locations are shown on Figure 11. Field methodology consisted of using pressurized nitrogen gas to displace the water table within a test well. After the water level had stabilized, which typically occurred at the top of the well intake, the gas pressure was relieved and the ground water recovered to its static level. A pressure transducer coupled to a data logging system and a portable computer were used to measure and record the water level data. Real-time viewing of test progress was possible using hydrogeological software designed for aquifer test analysis (AquiferWin32 Version 3.5). Test conditions were similar for each well: in general, the depth to ground water was about 5 ft below ground surface and well intakes spanned the lower half of the aquifer, which is about 10 to 15 ft below ground surface. Four wells that were tested (T2-S, T3-S, T4-S, T5-S [Figure 11]) are completed about 5 ft higher than other wells.

Three tests were completed at each well. Slug test data were analyzed to estimate hydraulic conductivity using the solution of Bouwer and Rice (1976) embedded in AquiferWin32. Results showed a high level of reproducibility among the triplicate tests; Table 12 presents a summary of the results. Conductivity among all tests ranged from 1.4E–03 to 9.0E–02 cm/s, as determined from results of the three-test average per well. The corresponding arithmetic and geometric means are 1.8E–02 and 1.1E–02, respectively. Bulk conductivity of the gravel/ZVI zone is indicated to be equal to that of the ZVI zone, and the alluvium at the test locations is equally or slightly less conductive than the treatment zones (Table 12).

Spatial distribution of hydraulic conductivity as determined from the August 2003 slug tests is illustrated on Figure 12 and on Figure 13 with proportionally scaled symbols to indicate relative magnitude. Maximum conductivity values appear to correspond to the central region of the PRB (relative to its long axis), although some low values also resulted in that area. The distribution may indicate that flow rates within the central region are more variable than in either end of the PRB, particularly to the south. The limited data set for shallow wells completed in the upper half of the aquifer indicates that there is probably no difference in hydraulic conductivity between the northern and southern portions of the PRB.

Table 13 presents the results of slug tests conducted at five wells in June 2000 and August 2003. Conductivity estimates were similar for both test events at the alluvial wells (wells R1-M2 and R1-M3). However, the conductivity values estimated for the ZVI from the recent tests were almost an order of magnitude less than the June 2000 results, possibly because of precipitation in the ZVI.

5.2 Tracer Dilution Studies

5.2.1 Field Methods

Twenty-four single-well tracer dilution tests were conducted from August 18 to 29, 2003, to determine ground water flow rates within the Monticello PRB. Test locations consisted of 20 wells; 10 wells completed in the gravel/ZVI zone and 10 wells completed in the ZVI treatment zone (Figure 14). Four wells were tested in duplicate.

The tests used a 120-mL slug of 10,000 mg/L sodium bromide solution tagged with red food coloring as the tracer. A peristaltic pump was used to circulate ground water at approximately 250 mL/min from an inlet placed at the top of the well screen to a bromide sensor and then to the pump outlet placed at the bottom of the well screen (upward flow). Dilution data were collected for at least 3 hours per well (data were collected for about 8 hours in two of the tests) after injection of the bromide. Down-hole tubing used to circulate ground water and tracer solution was 0.25-inch (outside diameter) polyethylene. Each well screen measured 5-ft in length and extended upward from near the base of the reactive zones.

Bromide concentrations were measured with Cole-Palmer (Model A-27504-02) ion-selective electrodes, and data were recorded using a Vernier Logger Pro system connected to a laptop computer. The raw measurements are in millivolts (mV) of signal. Calibrations were performed at least daily on samples with 0, 1, 10, 100, 1,000, and 10,000 mg/L concentrations of bromide. A log-linear equation was fit to the calibrations. R-squared values for the curve fits exceeded 0.99 indicating an excellent fit of the calibration data to the calibration equation. The calibrations were conducted on ice-chilled standards made with de-ionized water. Because both temperature and solution matrix can slightly affect the reading, the measurements may have errors to about 10 percent. A 1,000-mg/L bromide standard made from site ground water had nearly the same reading as the standard made from de-ionized water, indicating reasonable accurate calibration using the de-ionized water standards.

In addition to the dilution tests, vertical bromide concentrations in the ground water were measured in 10 wells at various times following tracer injection by the same circulation method. These profiles were measured by lowering a bromide ion-selective electrode into a monitoring well and recording data at every foot of depth. Calibrations were conducted at least daily. Vertical profile tests were conducted from August 18 through August 27, 2003.

5.2.2 Test Results

Test results were developed as a plot of bromide concentration in relation to time for each well. Figure 15 presents example test plots. Under the test conditions, approximately 25 minutes of continuous circulation elapsed after bromide injection and prior to probe detection. Concentrations then peaked within the next several minutes, typically followed by a period of about 25 minutes during which the concentration oscillated significantly through one or more cycles during a net declining trend. A relatively stable tail of decreasing concentration typified the remainder of the test period. Peak concentrations for many of the tests approached the assumed initial value of about 1,100 mg/L for the test interval (tubing, tracer slug, and well screen volumes). Among the remaining tests, peak values generally ranged between about 500 and 2,000 mg/L. The oscillating behavior and the non-ideal peak concentrations may be the result of preferential flow and incomplete mixing of the tracer solution in the well casing early in the tests.

5.2.3 Data Analysis

For the type of dilution test conducted within the PRB, the rate that the concentration of tracer C decreases in the test interval is

$$dC/dt = -Av_sC/W \qquad \text{(Freeze and Cherry 1979; eqn. 9.25),} \qquad \text{(Eq. 1)}$$

where A is the cross-sectional area through the center of the test interval normal to ground water flow, v_s is the ground water velocity across the well screen, t is elapsed time, and W is the volume of the test interval. Integration and rearrangement yields

$$v_s = -W/At \ln (C/C_0) \qquad \text{(Freeze and Cherry 1979; eqn. 9.27),} \qquad \text{(Eq. 2)}$$

where C and C_0 are the final and initial and concentrations, respectively, during the time interval t. Each dilution curve was analyzed using this second relationship to estimate the ground water velocity across the well screen. Effects of diffusion were excluded.

Two sets of velocity determinations are reported in Table 14. Curves were first analyzed to exclude data from the early period of oscillation. In the second analysis, the initial time was assumed to coincide with either a measured concentration approximating the theoretical initial value of 1,100 mg/L or the peak if the maximum concentration was significantly lower. Inclusion of the oscillation period in the analysis generally resulted in greater apparent velocity. Mean velocity for the two sets of analyses were 0.47 (oscillation period excluded) and 0.82 feet per day (ft/day) (oscillation period included). The overall range in velocity for both sets of analyses is about 0.1 to 1.5 ft/day.

Figure 16 presents the results in map view with proportionally scaled symbols to illustrate the relative magnitude of velocity. Spatial variation appears random and the computed values do not display a wide variation. Localized stagnation may be indicated among the lowest values. Figure 17 illustrates the relationship between hydraulic conductivity of the treatment zones, as determined by slug testing (Section 5.1), and estimated ground water velocity (post-oscillation data set). In general, the plot indicates that the measured tracer velocity is not a function of the measured hydraulic conductivity under the conditions of this study.

The preceding analysis estimated the ground water flow velocity in the well screens. Average linear velocity within the surrounding PRB media is calculated by dividing the well-screen velocity by the corresponding porosity, assuming the local flow field is not significantly distorted by the well completions. Installation of PRB wells used direct-push technology and no artificial filter pack, thus supporting this assumption. Therefore, an assumed PRB porosity of 50 percent results in average linear velocities that are twice the well-screen velocities reported in Table 14 and on Figure 16 and Figure 17.

5.2.4 Ground Water Flux Through PRB

The calculated rates of ground water flow through the PRB, using both average well screen velocities presented in Table 14, are 1.8 and 3.1 gal/min, respectively. This estimate assumes a cross-sectional area perpendicular to flow of 105 ft by 7 ft (approximate saturated thickness). Ground water flow through the PRB was previously estimated to be about 9 gal/min from results of a pumping test conducted in December 2001 (DOE 2002) and between about 3 and 6 gal/min averaged for the first 2.7 years of operation as determined from chemical mass balance analysis of PRB core samples obtained in February 2002 (DOE 2002a).

5.2.5 Vertical Dilution Profiles

Tracer injection for the eight dilution tests started on August 18 and 19, 2003, was by the method described in Section 5.2.1. However, circulation was typically maintained only until soon after the peak bromide concentration was attained. Injection at four wells per day was accomplished in relatively rapid succession. Following the concentration peak interval, automated data logging was replaced by manual measurement with a down-hole probe, at 1-ft depth intervals, beginning 3 to 30 hours after the injection and repeated every several hours or more (no overnight readings) through August 27, 2003. Example vertical profiles are shown on Figure 18 for well R5-M9 for times of 27 and 49 hours after bromide injection (Appendix E contains all the profiles). Red shading on Figure 18 from 9.5 to 14.5 ft below ground surface represents the screen interval of well R5-M9.

For this test, ground water and tracer solution were circulated via pump inlet and outlet tubing at about 9.5 and 14.5 ft, respectively (upward flow), for about 1 hour after injection. As in all tests measuring vertical concentration, bromide was detected above the circulation interval. Typical of these tests, relative stagnation above the screen is indicated over time while tracer solution in the screen section becomes diluted (Figure 18). Dilution within the test interval was essentially completed well within 24 hours in all tests, but significant concentrations of bromide commonly persisted in the stagnant zone for 48 hours or more after tracer injection.

Manual measurements were too infrequent or the test was too far advanced to allow calculation of apparent velocity, either by appending the data to the early time results obtained with the data logger or by analyzing only the late-time manually measured values. In general, these first eight tests provided a basis to measure gross test response and to refine the field method for the later tests.

6.0 Rejuvenation Tests (Monticello)

Ground water chemistry data for samples from the PRB at Monticello indicate that reactivity has decreased. Data in this study also indicate that carbonate minerals and iron oxide corrosion products have precipitated in the ZVI matrix. Other PRB sites have experienced similar decreases in reactivity and precipitation of corrosion products (e.g., Wilkin and Puls 2003). Also, data presented in this report indicate that ZVI is still present in zones that have lost reactivity. If the corrosion products could be removed while leaving ZVI intact, the reactivity of the PRB may be improved. This section reports on preliminary laboratory tests conducted to evaluate the efficiency of several solvents for rejuvenating ZVI-based PRBs. Batch tests using standard specimens of ZVI and corrosion products were performed to determine the amount of mineral dissolution after a specific time period. Subsequently, one solvent was used in a column test to determine rejuvenation efficiency under flow conditions. These activities support Objective 4 (Section 1.0).

6.1 Batch Tests

Batch tests were conducted by combining a solid material (Table 15) with a solvent, agitating for a period of time, filtering, and then analyzing the filtrate for Ca and Fe. The amount of Ca or Fe removed was used as an indication of the degree of solution of the solid material.

6.1.1 Rejuvenation Tests With Sodium Acetate Buffer

Sodium acetate (NaOAc) adjusted to a pH value of 5 using glacial acetic acid (NaOAc buffer) is often used to remove calcite from clay samples in preparation for hydrometer tests (Jackson 1979). The NaOAc buffer is used because it can remove calcite without affecting the clay mineral composition.

NaOAc buffer (50 mL) was combined with 50 mg of powdered calcite in a 50-mL plastic centrifuge tube. Three additional tubes contained 2 g of the fresh gravel/ZVI mixture used in the gravel/ZVI zone in the Monticello PRB and 50 mL of NaOAc buffer. The tubes were agitated end-over-end for various periods of time at room temperature. After agitation, they were centrifuged, decanted, and preserved with nitric acid. Calcium and Fe concentrations were determined by flame atomic absorption.

Gas was generated, and consequently, an increase in pressure occurred during agitation in the tests with gravel/ZVI, and a small amount of liquid was lost by leakage. The pressure was probably due to generation of H_2 gas from ZVI corrosion. About 88 percent of the calcite was dissolved, indicating that NaOAc was effective at dissolving calcite (Table 16). Calcium was also removed from the three gravel/ZVI samples in approximately equivalent amounts, suggesting that all the calcite in the samples was dissolved. Unfortunately, much of the ZVI also was dissolved. For the sample that agitated for 39 hours, about 86 percent of the ZVI was dissolved (based on 13 percent by volume ZVI in the gravel/ZVI; the density of the ZVI was 2.4 g/mL, and the density of the gravel was 1.7 g/mL). Because of the capacity to dissolve the ZVI, NaOAc is not suitable as a chemical rejuvenation agent.

6.1.2 Rejuvenation Tests With EDTA

Ethylenediaminetetraacetic acid (EDTA) is an industrial organic chelating agent used in cleansers, vegetable oils, and pharmaceuticals and to decontaminate radioactive surfaces and remove insoluble deposits of Ca. The tetrasodium salt of EDTA with a formula of $(NaOCOCH_2)_2NCH_2CH_2N(CH_2COONa)_2 \bullet H_2O$ (Baker I693-7) was tested in this study as a potential ZVI PRB rejuvenation agent. Its use in many consumable items indicates it is relatively nontoxic.

In one set of tests, 50 mL of 0.1 M EDTA was combined with 2 g of fresh gravel/ZVI samples and various amounts of concentrated HCl to adjust the pH value (Table 17; tests 1 through 3). The mixtures were agitated end-over-end for 9 hours, centrifuged, and decanted. Values of final pH ranged from 8.25 to 11.02. The amount of Ca removed from the sample was similar at all three pH values and was more than the amounts removed by NaOOAc (Table 16). The amount of Fe removed from the gravel/ZVI mixtures increased significantly as pH decreased (Table 17; test 1 through 3). Additional tests evaluated the ability of 0.1 M EDTA to dissolve powdered calcite, ZVI, hematite, and magnetite from standard specimens. The EDTA was moderately effective at dissolving calcite; it did not dissolve much of the Fe minerals (Table 17; tests 4 through 7). In another set of tests, the effect of the EDTA concentration on dissolution of a mixture of calcite and ZVI was examined. Lowering the EDTA concentration from 0.1 M to 0.025 M caused a decrease in the dissolution of both calcite and ZVI (Table 17; tests 7 through 10). The combined results indicate that EDTA in a solution with a high pH value may be beneficial for ZVI PRB rejuvenation because it can remove large amounts of calcite while leaving most of the ZVI intact.

6.1.3 Rejuvenation Tests With Ammonium Oxalate

Ammonium oxalate $[(NH_4)_2C_2O_4 \bullet H_2O]$ solution buffered with oxalic acid to a pH value of 3 is used to selectively remove amorphous, or poorly crystalline, ferric oxides from soil samples (Smith and Mitchell 1987). The extractant is prepared by mixing 0.2 M ammonium oxalate solution with 0.2 M oxalic acid in the proportion 4:3 by volume. The dissolution effects of this extractant were evaluated for calcite, ZVI, and a variety of ferric oxides. A 40-mL volume of extractant was agitated with 0.5 g samples of powdered calcite, ZVI, and a variety of iron oxide standard materials to determine the extent of dissolution. Agitation was conducted in 50-mL glass Erlenmeyer flasks using an orbital motion in a temperature-controlled bath (Precision Model 25) at 25 °C.

The buffered ammonium oxalate extractant was ineffective at removing calcite (Table 18). In the rejuvenation tests with iron-based materials, it was most effective in removing Fe from AFO and magnetite. In addition to its ineffectiveness at removing calcite, ammonium oxalate is one of the most toxic of the compounds tested. Ammonium oxalate is not suitable for ZVI PRB rejuvenation.

6.1.4 Rejuvenation Tests With Buffered Sodium Dithionite and Sodium Citrate

Sodium dithionite ($Na_2S_2O_4$, also called sodium hydrosulfite) is commonly used together with sodium citrate and sodium bicarbonate to selectively remove crystalline ferric iron from soil samples (Jackson 1979). This extractant is often referred to as citrate bicarbonate dithionite (CBD). Each constituent of the CBD extractant has a purpose in helping to dissolve ferric minerals; the citrate chelates Fe, dithionite chemically reduces ferric to ferrous iron, and bicarbonate buffers the pH. Citrate, by itself, is often used to chelate metals and is also used in many consumable products. Citrate and bicarbonate are nontoxic.

Sodium dithionite, by itself, has also been used for remediating chromium contamination by injection of its dissolved form into ground water (Vermeul et al. 2002). As with CBD, dithionite causes reduction of ferric to ferrous iron. In the subsurface, dithionite decomposes rapidly to compounds with low toxicity.

Extraction of Fe and Ca was tested with mixtures containing sodium dithionite, sodium citrate, and/or sodium bicarbonate. A 40-mL volume of solution was agitated with 0.5-g samples of powdered calcite, ZVI, and a variety of iron oxide standard materials to determine the extent of dissolution. Agitation was conducted in 50-mL glass Erlenmeyer flasks using an orbital motion in a temperature controlled bath (Precision Model 25) at 25 °C.

Sodium dithionite, by itself, removed 6.8 mg Ca from the calcite sample (about 3 percent of the calcite) and 5.6 mg of Fe from the ZVI sample (Table 19; items 4 and 5). It removed up to 17.4 mg of Fe from AFO, 8.2 mg of Fe from magnetite, and 10.4 mg of Fe from hematite. Although the sodium dithionite was able to preserve the ZVI reasonably well, it was unable to dissolve a significant portion of calcite. Sodium dithionite may be useful in removing ferric oxides or reducing them to ferrous minerals. As with ZVI, ferrous minerals have the capacity to reduce some metals to an insoluble form.

Sodium citrate, combined with sodium bicarbonate, extracted 10.0 mg of Ca from the calcite sample (about 5 percent of the calcite) and little Fe (Table 19; items 6 through 10). However, the dissolution of iron-based materials was highest for ZVI. These results suggest that sodium citrate may be useful in removing calcite from a PRB but may dissolve some ZVI while leaving Fe corrosion products intact.

A solution of CBD (0.27 M sodium citrate, 0.11 M sodium bicarbonate, and 0.1 M sodium dithionite), mixed in the same proportions as in Jackson (1979), was tested for extraction of calcite, ZVI, and Fe oxides (Table 19, items 11 through 15). CBD removed 8.4 mg of Ca from the calcite sample (about 4 percent of the calcite). It also removed some of the ferric oxides, but the ZVI was least affected. The results with CBD are similar to those with dithionite alone, but more AFO was removed with CBD.

Results of some of the previous tests suggest that an increase in pH values in a CBD extractant may have a positive effect on calcite dissolution. Therefore, an extractant using citrate carbonate dithionite (CCD) was designed that used carbonate (as potassium carbonate [K_2CO_3]) instead of bicarbonate to buffer pH. The pH value of CCD is 9.70 compared to 6.98 for CBD. Tests were conducted in the same manner as previous tests, and the results are presented in Table 19 (items 16 through 20). Less calcite was dissolved using CCD than with CBD; no other significant changes were apparent.

6.1.5 Rejuvenation Tests With Sodium Dithionite and EDTA

The CBD extractant previously discussed combines a chelating agent (citrate) with a chemical reductant (dithionite). The effects of using EDTA instead of citrate as the chelating agent were investigated. A 40-mL volume of extractant solution was agitated with 0.5-g samples of powdered calcite, ZVI, and a variety of iron oxide standard materials to determine the extent of dissolution. Agitation was conducted in 50-mL glass Erlenmeyer flasks using an orbital motion in a temperature-controlled bath (Precision Model 25) at 25 °C.

Extraction of Fe and Ca was tested with a mixture of EDTA and sodium dithionite; for control, the same tests were conducted with only EDTA (Table 20). By comparing the Ca and Fe removal with EDTA alone (Table 20, items 1 through 5) to tests with EDTA and dithionite (Table 20, items 6 through 10), it was determined that the presence of dithionite had little effect on mineral dissolution.

Some of the previous results suggested that the pH values of extractants using EDTA and dithionite may have an effect on the mineral dissolution capability. A titration of EDTA with sodium dithionite solution was conducted to determine a solution composition that has a pH value greater than 9.17 used in the previous tests. The selected solution contains 0.16 M EDTA and 0.057 M sodium dithionite and has a pH value of 9.69 (Table 21; items 6 through 10). Tests were conducted with this high-strength mixture in the same manner as described for the low-strength EDTA/dithionite solution.

Table 21 presents the results of the high-strength EDTA/dithionite solution tests and the tests with 0.1 M EDTA. The tests containing dithionite (Table 21; items 6 through 10) dissolved essentially the same amounts of calcite as 0.1 M EDTA alone (Table 21; items 1 through 5). Slightly more iron oxide minerals were dissolved by the higher strength solution than by the lower strength solution (compare data in Table 20 to data in Table 21). However, the results of the higher strength mixture do not represent a significant improvement over the lower strength mixture.

6.1.6 Rejuvenation Tests With Hydroxylamine Hydrochloride

Hydroxylamine hydrochloride ($NH_2OH \bullet HCl$) mixed with acetic acid (CH_3COOH) has been used as an extractant to selectively remove iron and manganese oxides from soil samples (Landa 1982). The solution used for the tests was made by combining 1 M hydroxylamine hydrochloride solution with 25 percent (by volume) concentrated glacial acetic acid, the same as used by Landa (1982). Agitation was conducted in 50-mL glass Erlenmeyer flasks using an orbital motion in a temperature-controlled bath (Precision Model 25) at 25 °C.

The pH value of the hydroxylamine hydrochloride solution is 1.48. The solution removed 224.8 mg of Ca from the calcite sample, which is essentially total dissolution (Table 22). Unfortunately, this extractant also dissolved 86.4 mg of Fe from the ZVI sample (about 17 percent of the sample). The ferric oxides were relatively unaffected, bringing into question the use of this extractant to selectively remove ferric oxides. Hydroxylamine hydrochloride is more toxic than most of the other extractants tested.

6.1.7 Summary of Batch Rejuvenation Tests

Batch tests described in Sections 6.1.3 through 6.1.6 were conducted with the same methods; orbital agitation of a 40-mL sample in a 50-mL glass volumetric Erlenmeyer flask in temperature controlled bath at 25 °C for 2 hours. Figure 19 presents a summary of the results of these tests. Extractants that remove large amounts of calcite with small amounts of ZVI are considered most favorable for use in rejuvenating a ZVI PRB. Removal of large amounts of AFO, hematite, and magnetite is also considered beneficial.

Sodium citrate/potassium carbonate/sodium dithionite and ammonium oxalate/oxalic acid removed the least calcite. Hydroxylamine hydrochloride removed the most calcite, but also removed the most ZVI. All other extractants were nearly equally effective in removing calcite and ZVI. Of these, 0.05 and 0.1 M EDTA were the most effective. Therefore, EDTA was selected for preliminary column testing. Unfortunately, EDTA was relatively ineffective in removing ferric oxides.

6.2 Column Tests

A preliminary column test was conducted to better evaluate the effectiveness of EDTA as an extractant to rejuvenate ZVI PRBs. EDTA was selected for its ability to remove calcite while leaving most of the ZVI intact.

6.2.1 Methods

The test was conducted in a 2-inch-diameter clear acrylic column packed with a fresh gravel/ZVI mixture (the same material that was used in the gravel/ZVI zone of the Monticello PRB). The gravel/ZVI is a mixture of 2,500 lb of –4 +20 Peerless ZVI to 9 cubic yards of 3/8-inch pea gravel. Dry weight of the gravel/ZVI in the column was 1602.5 g. Influent solution flowed from the bottom to the top of the column using a peristaltic pump.

Influent to the column was synthesized to be similar in major ion composition to ground water from well R1-M3, located immediately hydraulically upgradient of the Monticello PRB. Table 23 presents the compositions of the R1-M3 ground water and the synthesized column influent water. Influent solution was stored in a 20-L plastic carboy feed tank that was constantly stirred with a magnetic stir bar. Gaseous CO_2 flowing into the feed tank through a gas diffuser stone was used to control influent pH and alkalinity values. Flow rates for CO_2 ranged from 0 to 20 milliliters per minute (mL/min).

A programmable fraction collector was used to collect samples for analysis. Calcium and Fe concentrations were determined by atomic absorption on samples preserved with nitric acid. Alkalinity was measured by titration with sulfuric acid. Values of pH and oxidation-reduction potential (ORP) were made with inline probes with data fed to an automated data collection system.

6.2.2 Results

Synthetic ground water flowed through the column at 0.7 mL/min for about 12 days. During that time, the mean influent and effluent pH values were about 6.8 and 7.5, respectively (Figure 20). The mean ORP values were about +180 and less than –400 mV, respectively. The Ca inventory in the column solids increased by about 1 g because of Ca-mineral precipitation as determined from the difference in Ca concentrations between influent and effluent (Figure 21). There was no significant change in the Fe inventory (Figure 21).

After about 12 days (25.8 pore volumes), the influent was changed to 0.1 M EDTA (as the tetrasodium salt; Baker I693-7) and the flow rate increased to 10 mL/min for about 5 pore volumes before switching back to synthetic ground water. The pH value in the column effluent increased to about 11.5, similar to the EDTA influent value of about 11 (Figure 20). Calcium and Fe in the effluent EDTA solution increased to maximum concentrations of 2,520 and 2,000 mg/L, respectively (Figure 20).

Although the concentration of Fe in the effluent increased substantially during EDTA injection, the inventory of Fe decreased only slightly (Figure 21). In contrast, all the Ca precipitated from the influent water and an additional 755 mg was removed by the EDTA solution (Figure 21). The additional Ca was probably present in calcium carbonate minerals in the gravel. These positive results may encourage additional investigations with EDTA as a rejuvenation agent.

7.0 Summary and Conclusions

This report presents data from detailed investigations of the Monticello and Fry Canyon PRBs. Samples for the investigation were collected in August 2003 and represent conditions approximately 4 years after installation of the Monticello PRB and 6 years after installation of Fry Canyon PRB. The investigations included (1) bulk chemical analysis, (2) determination of relative reactivity in ZVI samples, (3) determination of uranium distributions in small samples of reactive material using fission track analysis, (4) hydraulic conductivity measurements by gas slug injection, (5) ground water velocity analysis by tracer dilution analysis, and (6) evaluation of ZVI rejuvenation using various chemicals.

Bulk chemical analysis indicated that the Monticello PRB treated ground water at about the same flux rate (approximately 5 gal/min) from February 2002 through August 2003 as it did from installation (June 1999) through February 2002. Calcium and U continue to be deposited in the PRB. Of the three PRBs at Fry Canyon, U is most concentrated in the bone charcoal PRB and moderately concentrated in the AFO PRB. Samples from the Fry Canyon ZVI PRB have low U concentrations. The unexpectedly low concentrations in the ZVI PRB may be due to sampling bias or may result from low ground water flow through that PRB.

Reactivity of ZVI samples can be easily evaluated by the addition of dilute HCl to the sample in a closed vessel and measuring the pressure increase (because of formation of H_2). Calcium carbonate also causes pressure to increase because of evolution of gaseous CO_2. The rate of gas evolution can be used to differentiate ZVI from carbonate minerals. A simple model was developed during this study to analyze the pressure curves. While this model is insufficient to quantify the amounts of ZVI and calcium carbonate, it was useful in defining relative reactivities (i.e., amounts of ZVI) of the samples. Mean reactivity of samples from the Monticello PRB suggests that ZVI in the gravel/ZVI zone is less reactive than in the ZVI zone. The mean reactivity values in the Monticello gravel/ZVI zone decrease over time, consistent with a gradual decrease in reactivity noted in ground water chemistry data. Mean reactivity values of samples collected from the ZVI zone at Fry Canyon PRB is less than fresh samples, suggesting some loss of reactivity over time.

Fission track maps indicate that U is concentrated on the rims of ZVI grains. In contrast, U is disseminated throughout bone charcoal and AFO grains. This distribution suggests that more surface area is available for U uptake in bone charcoal and AFO PRBs than in ZVI PRBs.

On the basis of the August 2003 slug test results, geometric means of hydraulic conductivity for the alluvium, gravel/ZVI zone, and ZVI zone at the Monticello PRB are 0.011, 0.012, and 0.011 cm/s, respectively. Slug test results for the three wells with data from two time periods show that hydraulic conductivity decreased by about 80 to 90 percent in the ZVI zone from June 2000 to August 2003. Tracer dilution data from August 2003 report a ground water flux through the Monticello PRB of between 1.8 and 3.1 gal/min, which is lower than previous estimates.

Bench-scale tests were conducted to evaluate the potential for rejuvenation of ZVI PRBs using chemical solvent flushing. Solvents tested include (1) tetrasodium EDTA, (2) ammonium oxalate, (3) sodium dithionite, (4) sodium citrate, and (5) hydroxlyamine hydrochloride. Some tests were conducted with combinations of these solvents, sometimes with bicarbonate or carbonate as a pH buffer. Suitable rejuvenation agents were defined by the high ability to dissolve calcite (a ZVI corrosion product that occludes porosity), low dissolution of ZVI, and low toxicity; the ability to dissolve AFO, magnetite, and hematite was also considered favorable. Most of the solvents and combinations were able to dissolve some calcite; however, most also dissolved some ZVI. Of the solvents tested in batch mode, EDTA was considered to be the most suitable and was selected for a preliminary column test. The column test indicated that EDTA was able to remove all the calcite deposited during ZVI corrosion and some of the calcite initially present in the column fill material. While some ZVI was also dissolved by the EDTA, the change in the Fe inventory was insignificant.

8.0 Recommendations

Some recommendations for additional work are

- Mass balance of bulk chemical analysis of reactive material is perhaps the most reliable means to determine the amount of ground water being treated by a PRB. It would be useful to apply this method to other PRBs.
- Better methods for sampling solids in PRBs are needed.
- Additional samples of Fry Canyon reactive media are needed to calculate a reliable mass balance. Because of current access restrictions at the site, these samples will need to be collected during PRB decommissioning.
- On the basis of these high concentrations of U in the Fry Canyon bone charcoal and AFO PRBs, these materials should be reconsidered for use in future PRBs.
- Additional calibration and modeling efforts are needed to perfect the reactivity test. This test is a simple means of evaluating reactive media and could be developed as a field test.
- Slug tests using gas injection are a rapid means of evaluating hydraulic conductivity of PRBs and could be applied at other sites. It would be worthwhile to conduct these tests again at Monticello after another 1 to 5 years of operation.
- Additional laboratory tests of chemical flushing agents are needed prior to implementation in a field test.

End of current text

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Table 1. Comparison of February 2002 to August 2003 Uranium Data for Monticello Gravel/ZVI Zone

Core 2003	Feb 02 Raw Data U (mg/kg)	Aug 03 Raw Data U (mg/kg)	Feb 02 to Aug 03 Delta U (mg/kg)	Jun 99 to Feb 02 Deposition Rate ($mg \cdot kg^{-1} \cdot mo^{-1}$)	Feb 02 to Aug 03 Deposition Rate ($mg \cdot kg^{-1} \cdot mo^{-1}$)
PE 2	157	274	117	4.9	6.5
PE 7	92.65	804	711.35	2.9	39.5
PE 8	156.65	821.93	665.28	4.9	37.0
PE 9	156.65	2,741.33	2,584.68	4.9	143.6
PE 10	437	405	-32	13.7	-1.8
PE 14	371	533.75	162.75	11.6	9.0
PE 15	269	362.75	93.75	8.4	5.2
PE 16	251.75	290.75	39	7.9	2.2
PE 17	190.28	444.48	254.2	5.9	14.1
PE 19	384.43	448.13	63.7	12.0	3.5
Mean	**246.6**	**712.6**	**466.0**	**7.7**	**25.9**

Table 2. Comparison of February 2002 to August 2003 Uranium Data for Monticello ZVI Zone

Core 2003	Feb 02 Raw Data U (mg/kg)	Aug 03 Raw Data U (mg/kg)	Feb 02 to Aug 03 Delta U (mg/kg)	Jun 99 to Feb 02 Deposition Rate ($mg \cdot kg^{-1} \cdot mo^{-1}$)	Feb 02 to Aug 03 Deposition Rate ($mg \cdot kg^{-1} \cdot mo^{-1}$)
PE 3	0.04	86.84	86.8	0.001	4.822
PE 4	0.02	0.61	0.59	0.001	0.033
PE 5	0.01	1.45	1.44	0.000	0.080
PE 6	0.01	0.02	0.01	0.000	0.001
PE 11	0.98	6.08	5.1	0.031	0.283
PE 12	0.09	0.05	-0.04	0.003	-0.002
PE 13	0.16	0.07	-0.09	0.005	-0.005
PE 18	1.75	4.83	3.08	0.055	0.171
PE 21	1.01	0.47	-0.54	0.032	-0.030
PE 23	0.98	3.22	2.24	0.031	0.124
PE 24	6.29	2.61	-3.68	0.197	-0.204
Mean	**1.03**	**9.66**	**8.63**	**0.03**	**0.48**

Table 3. Comparison of February 2002 to August 2003 Calcium Data for Monticello Gravel/ZVI Zone

Core 2003	Feb 02 Raw Data Ca (mg/kg)	Aug 03 Raw Data Ca (mg/kg)	Feb 02 to Aug 03 Delta Ca (mg/kg)	Jun 99 to Feb 02 Deposition Rate ($mg \cdot kg^{-1} \cdot mo^{-1}$)	Feb 02 to Aug 03 Deposition Rate ($mg \cdot kg^{-1} \cdot mo^{-1}$)
PE 2	35,600	18,963	-16,637	1,112.5	-924.3
PE 7	37,575	25,650	-11,925	1,174.2	-662.5
PE 8	35,600	25,550	-10,050	1,112.5	-558.3
PE 9	35,600	40,467	4,867	1,112.5	270.4
PE 10	23,150	42,400	19,250	723.4	1,069.4
PE 14	26,900	40,800	13,900	840.6	772.2
PE 15	27,125	32,848	5,723	847.7	317.9
PE 16	32,300	39,875	7,575	1,009.4	420.8
PE 17	29,050	23,350	-5,700	907.8	-316.7
PE 19	15,075	27,950	12,875	471.1	715.3
Mean	**29,797.5**	**31,785.3**	**1,987.8**	**931.2**	**110.4**

Table 4. Comparison of February-2002 to August-2003 Calcium Data for Monticello ZVI Zone

Core 2003	Feb 02 Raw Data Ca (mg/kg)	Aug 03 Raw Data Ca (mg/kg)	Feb 02 to Aug 03 Delta Ca (mg/kg)	Jun 99 to Feb 02 Deposition Rate ($mg \cdot kg^{-1} \cdot mo^{-1}$)	Feb 02 to Aug 03 Deposition Rate ($mg \cdot kg^{-1} \cdot mo^{-1}$)
PE 3	8,680	25,380	16,700	271.3	927.778
PE 4	28,283	27,600	-683	883.8	-37.944
PE 5	11,465	25,750	14,285	358.3	793.611
PE 6	11,465	23,100	11,635	358.3	646.389
PE 11	11,510	41,200	29,690	359.7	1,649.444
PE 12	5,295	13,905	8,610	165.5	478.333
PE 13	11,485	9,778	-1,707	358.9	-94.833
PE 18	15,185	19,488	4,303	474.5	239.056
PE 21	24,785	14,678	-10,107	774.5	-561.500
PE 23	11,510	22,125	10,615	359.7	589.722
PE 24	21,850	30,910	9,060	682.8	503.333
Mean	**14,683**	**23,083**	**8,400**	**459**	**466.7**

Table 5. Chemical Gradients in Ground Water Samples Collected Across the Monticello PRB

Period	Zone	Transect	Constituent	Gradient
Feb 02 – Aug 03	gravel/ZVI	N/A[a]	Calcium	47.0 mg/L
Feb 02 – Aug 03	gravel/ZVI	N/A[a]	Uranium	334 μg/L
Feb 02 – Aug 03	ZVI	N/A	Calcium	118.4 mg/L
June 02 – Feb 02	gravel/ZVI	R1-M3	Calcium	2.8 mg/L
June 02 – Feb 02	ZVI	R1-M3	Calcium	99 mg/L
June 02 – Feb 02	gravel/ZVI	R1-M3	Uranium	368 μg/L
June 02 – Feb 02	gravel/ZVI	R1-M4	Calcium	14 mg/L
June 02 – Feb 02	ZVI	R1-M4	Calcium	141 mg/L
June 02 – Feb 02	gravel/ZVI	R1-M4	Uranium	163 μg/L

[a] N/A = not applicable; the values presented are means for the entire length of the PRB as provided in Morrison 2003.
Data from See_Pro database.

Table 6. Summary of Monticello Ground Water Flux Calculations; Flux Is Normalized to Total Length of PRB (see text)

Period	Transect	Parameter	Zone	Calculated Flux (gal/min)
June 02 – Feb 02	N/A[a]	Calcium	gravel/ZVI	6.3
June 02 – Feb 02	N/A[a]	Calcium	ZVI	3.0
June 02 – Feb 02	N/A[a]	Uranium	gravel/ZVI	6.3
June 02 – Feb 02	N/A[a]	Vanadium	gravel/ZVI	4.2
Feb 02 – Aug 03	R1-M3	Calcium	gravel/ZVI	Not Possible[b]
Feb 02 – Aug 03	R1-M3	Calcium	ZVI	3.7
Feb 02 – Aug 03	R1-M3	Uranium	gravel/ZVI	10.4
Feb 02 – Aug 03	R1-M4	Calcium	gravel/ZVI	2.4
Feb 02 – Aug 03	R1-M4	Calcium	ZVI	4.1
Feb 02 – Aug 03	R1-M4	Uranium	gravel/ZVI	2.1

[a] N/A = not applicable; the values presented are means for the entire length of the PRB as provided in Morrison 2003.
[b] Calcium was lost from along this transect.

Table 7. Results of Chemical Analysis of Fry Canyon Cores Collected September 1999 and Fresh Material

PRB, depth (ft)	Aluminum (mg/kg)	Calcium (mg/kg)	Iron (mg/kg)	Manganese (mg/kg)	Sodium (mg/kg)
BC[a], 15-15.2	17,500	286,000	1,620	1331	5,270
BC, fresh	17,400	267,000	854	12.4	5,600
ZVI, 12-13	157	10,900	704,000	6,180	6,690
ZVI, fresh	130	1,710	824,000	6,930	6,420
AFO, 13	2,600	30,000	157,000	884	4,020
AFO, 14-14.2	25,600	21,300	22,100	461	6,580
AFO, fresh	40,900	14,900	33,800	494	14,000
PRB, depth (ft)	**Total Inorganic Compounds (mg/kg)**	**Total Organic Compounds (mg/kg)**	**Uranium (mg/kg)**	**Vanadium (mg/kg)**	
BC, 15-15.2	897	3,660	216	<0.68	
BC, fresh	617	19,600	1.9	<0.68	
ZVI, 12-13	7,780	1,180	9.8	79.6	
ZVI, fresh	718	<30	2.3	98.4	
AFO, 13	11,700	1,890	134	31	
AFO, 14-14.2	8,030	3,550	17.1	25.6	
AFO, fresh	1,760	38	2.9	41.9	

[a] BC = bone charcoal.

Table 8. Results of Chemical Analysis of Fry Canyon Cores Collected August 2003 (see Figure 2 for locations)

Sample[a]	Zone	Sample Date	Core Interval start (ft)	Core Interval end (ft)	Bottom Sample Depth (ft)	Radio-activity (dry) (dpm)[b]	Moisture Content (wgt %)[c]	Ca (mg/kg)	Fe (mg/kg)	U (mg/kg)
PEZVI 1-3	ZVI	8/22/2003	4.5	10	10.0	0.00	13.51	11,800	693,000	4.6
PEZVI 1-4	ZVI	8/22/2003	10	11.4	10.4	0.00	13.38	9,760	674,000	4.1
PEZVI 1-5	ZVI	8/22/2003	10	11.4	10.7	0.00	13.61	4,700	771,000	0.5
PEZVI 1-6	ZVI	8/22/2003	10	11.4	11.1	0.00	13.90	46,200	653,000	1.7
PEZVI 2-4	ZVI	8/22/2003	6	11	8.9	3,000	9.45	34,900	643,000	59.0
PEZVI 2-5	ZVI	8/22/2003	6	11	9.6	0.00	10.27	82,200	558,000	7.3
PEZVI 2-6	ZVI	8/22/2003	6	11	10.3	0.00	11.17	27,200	699,000	1.1
PEZVI 3-3	ZVI	8/22/2003	6	9.7	8.2	0.00	8.84	15,400	691,000	1.3
PEZVI 3-4	ZVI	8/22/2003	6	9.7	9.0	0.00	11.60	66,600	563,000	0.9
PEZVI 3-5	ZVI	8/22/2003	6	9.7	9.7	0.00	12.93	51,700	558,000	0.6
Mean						**300**	**12**	**35,046**	**650,300**	**8**
PEBC 1-4	BC	8/22/2003	6	11	9.3	9,000	37.62	266,000	1,010	503.0
PEBC 1-5	BC	8/22/2003	6	11	10.2	28,500	31.77	246,000	3,780	3,130.0
PEBC 2-4	Fill/BC	8/22/2003	6	11	10.0	3,000	26.53	246,000	1,200	206.0
PEBC 2-5	BC	8/22/2003	6	11	11.0	1,500	38.00	271,000	1,740	144.0
Mean						**10,500**	**33**	**257,250**	**1,933**	**996**
PEAFO 1-4	AFO	8/22/2003	4.5	11.5	10.1	3,000	12.13	13,000	170,000	257.0
PEAFO 2-3	AFO	8/22/2003	4	11	8.2	1,000	13.84	24,300	103,000	237.0
PEAFO 2-4	AFO	8/22/2003	4	11	9.6	2,000	12.89	11,100	171,000	275.0
PEAFOA 2-6	AFO	8/22/2003	9	13	11.0	1,000	8.52	35,300	10,400	19.0
Mean						**1,750**	**12**	**20,925**	**113,600**	**197**

[a] PEZVI = ZVI PRB, PEBC = bone charcoal PRB, and PEAFO = AFO PRB.
[b] dpm = disintegrations per minute.
[c] wgt % = weight percent.

Table 9. U to Fe Ratios for AFO PRB Samples

Sample	Collection Date	U:Fe (mg/g)
PEAFO1-4	August 2003	1.51
PEAFO2-3	August 2003	2.30
PEAFO2-4	August 2003	1.61
PEAFO2-6	August 2003	1.83
AFO13	September 1999	0.85
AFO14-14.2	September 1999	0.77
Batch Test[a]	Not Applicable	19

[a]Laboratory batch test conducted with Fry Canyon site water containing 2 mg/L uranium.

Table 10. Summary of Reactivity Values (compiled from data in Appendix D)

Category	Mean	Standard Deviation	Count
Standard: Peerless ZVI –8 +20 mesh	4.4	0.9	7
Standard: Fisher ZVI 40 mesh	7.9	1.6	3
Standard: Cercona ZVI Pellets	2.9	-	1
Monticello: Feb. 2002, ZVI zone	3.0	1.1	25
Monticello: Aug. 2003, ZVI zone	3.7	1.1	49
Monticello: Feb. 2002, gravel/ZVI zone	1.7	0.8	11
Monticello: Aug. 2003, gravel/ZVI zone	1.3	1.0	47
Fry Canyon: ZVI pellets	1.3	0.7	10

Table 11. Summary of Fission Track Analysis

Site	Sample Number	Media	U (mg/kg)	Description of Fission Tracks
Monticello	PE 3-7	gravel/ZVI	95.5	Lightly tracked ZVI rims
Monticello	PE 7-8	gravel/ZVI	1,210	Diffuse tracks with hot centers. Some ZVI grains with heavily tracked rims
Monticello	PE 8-9	gravel/ZVI	1,640	Moderately tracked ZVI rims. Only ZVI grains have tracked rims. Some diffuse tracks in matrix.
Monticello	PE 11-8	ZVI	2.1	No tracks
Monticello	PE 17-11	gravel/ZVI	345	Many diffuse tracks, some grain boundaries are hot
Monticello	PE 18-17	ZVI	5.6	Few tracks, a few diffuse bands
Fry Canyon	PEAFO 1-4	AFO	257	Diffuse tracks and hot grains in AFO
Fry Canyon	PEAFOA 2-6	AFO	19	Few tracks
Fry Canyon	PEZVI 1-2	ZVI	na	No tracks
Fry Canyon	PEZVI 2-6	ZVI	1.1	No tracks
Fry Canyon	PEBC 1-4	BC	503	Moderate track density completely penetrates bone charcoal grains
Fry Canyon	PEBC 2-5	BC	144	Light to moderate tracks completely penetrates bone charcoal grains

Table 12. August 2003 Slug Test Results

Well ID	Completion Zone	Test 1 (cm/s)	Test 2 (cm/s)	Test 3 (cm/s)	Test Avg. (cm/s)
R1-M2	alluvium	6.3E-03	5.4E-03	5.0E-03	**5.6E-03**
R1-M3	alluvium	1.5E-02	2.3E-02	2.0E-02	**1.9E-02**
R1-M5	alluvium	1.3E-02	1.3E-02	1.3E-02	**1.3E-02**
R2-M1	gravel/ZVI	1.9E-02	2.1E-02	2.0E-02	**2.0E-02**
R2-M2	gravel/ZVI	1.0E-02	1.0E-02	1.1E-02	**1.0E-02**
R2-M3	gravel/ZVI	1.0E-02	1.1E-02	1.1E-02	**1.1E-02**
R2-M4	gravel/ZVI	6.0E-03	6.8E-03	7.1E-03	**6.6E-03**
R2-M5	gravel/ZVI	2.1E-02	2.2E-01	2.4E-02	**9.0E-02**
R2-M6	gravel/ZVI	3.3E-02	3.4E-02	3.4E-02	**3.4E-02**
R2-M7	gravel/ZVI	1.2E-02	1.2E-02	1.3E-02	**1.2E-02**
R2-M8	gravel/ZVI	2.7E-03	2.8E-03	2.8E-03	**2.7E-03**
R2-M9	gravel/ZVI	3.5E-02	3.7E-02	3.7E-02	**3.7E-02**
R2-M10	gravel/ZVI	4.0E-03	4.4E-03	5.0E-03	**4.5E-03**
R3-M1	gravel/ZVI	4.0E-03	4.2E-03	4.7E-03	**4.3E-03**
R3-M2	gravel/ZVI	6.4E-03	7.0E-03	7.5E-03	**7.0E-03**
R3-M3	gravel/ZVI	8.7E-03	9.6E-03	9.6E-03	**9.3E-03**
R3-M4	gravel/ZVI	2.5E-02	2.7E-02	2.5E-02	**2.5E-02**
R4-M1	ZVI	3.1E-03	3.0E-03	2.9E-03	**3.0E-03**
R4-M2	ZVI	1.3E-02	1.3E-02	1.3E-02	**1.3E-02**
R4-M3	ZVI	1.4E-03	1.4E-03	1.4E-03	**1.4E-03**
R4-M4	ZVI	1.4E-03	1.3E-03	1.4E-03	**1.4E-03**
R4-M5	ZVI	1.2E-02	1.0E-02	1.0E-02	**1.1E-02**
R4-M6	ZVI	4.7E-03	4.8E-03	4.7E-03	**4.8E-03**
R4-M7	ZVI	8.2E-03	8.6E-03	8.7E-03	**8.5E-03**
R4-M8	ZVI	2.8E-03	2.8E-03	2.7E-03	**2.8E-03**
R5-M1	ZVI	1.9E-02	1.8E-02	1.8E-02	**1.9E-02**
R5-M2	ZVI	5.6E-03	5.5E-03	5.5E-03	**5.5E-03**
R5-M3	ZVI	1.2E-02	1.2E-02	1.2E-02	**1.2E-02**
R5-M4	ZVI	2.9E-02	2.8E-02	2.7E-02	**2.8E-02**
R5-M5	ZVI	1.8E-02	1.9E-02	1.9E-02	**1.9E-02**
R5-M6	ZVI	8.4E-02	8.6E-02	8.6E-02	**8.5E-02**
R5-M7	ZVI	6.3E-02	6.3E-02	6.3E-02	**6.3E-02**
R5-M8	ZVI	3.2E-02	3.1E-02	3.2E-02	**3.2E-02**
R5-M9	ZVI	3.0E-03	2.8E-03	2.8E-03	**2.9E-03**
R5-M10	ZVI	4.4E-03	4.6E-03	3.8E-03	**4.3E-03**
T2-D	ZVI	1.6E-02	1.6E-02	1.7E-02	**1.6E-02**
T2-S	ZVI	2.7E-02	2.9E-02	3.0E-02	**2.9E-02**
T3-D	ZVI	3.5E-02	3.1E-02	3.1E-02	**3.2E-02**
T3-S	ZVI	7.1E-03	9.2E-03	9.1E-03	**8.5E-03**
T4-D	ZVI	6.2E-03	6.0E-03	5.3E-03	**5.8E-03**
T4-S	ZVI	6.4E-02	5.5E-02	6.4E-02	**6.1E-02**
T5-D	ZVI	4.0E-03	3.7E-03	3.5E-03	**3.8E-03**
T5-S	ZVI	8.7E-03	8.3E-03	8.9E-03	**8.7E-03**
TW-12	ZVI	3.6E-02	4.3E-02	4.5E-02	**4.1E-02**
TW-13	ZVI	5.1E-02	5.1E-02	6.0E-02	**5.4E-02**

	alluvium	gravel/ZVI	ZVI
Geometric Mean of Conductivity per Completion Zone [cm/s]	**1.1E-02**	**1.2E-02**	**1.1E-02**
Arithmetic Mean per Completion Zone	**1.3E-02**	**2.0E-02**	**2.1E-02**

Table 13. Hydraulic Conductivity: June 2000 and August 2003

Well	Calculated Hydraulic Conductivity [cm/s]		
	Jun-00	Aug-03	Percent Difference
R1-M2	4.5E-03	5.6E-03	24
R1-M3	2.3E-02	1.9E-02	-15
R4-M2	7.3E-02	1.3E-02	-82
R4-M8	6.0E-02	2.8E-03	-95
T4-D	7.4E-02	5.8E-03	-92

Table 14. Ground Water Velocity in Well Screens (Va)

Well	Start Date	Va ft/day (exclude oscillation)	Va ft/day (include oscillation)	Treatment Zone
R2–M1	8/21/03	0.27	0.33	gravel/ZVI
R2–M2	8/29/03	0.34	0.82	gravel/ZVI
R2–M3	8/29/03	0.21	0.31	gravel/ZVI
R2–M4	8/29/03	0.60	0.90	gravel/ZVI
R2–M5	8/29/03	0.07	0.31	gravel/ZVI
R2–M6	8/28/03	0.58	0.87	gravel/ZVI
R2–M7	8/28/03	0.43	0.77	gravel/ZVI
R2–M7	8/19/03	0.62	1.28	gravel/ZVI
R2–M8	8/28/03	0.43	0.74	gravel/ZVI
R2–M8	8/19/03	0.41	1.03	gravel/ZVI
R2–M9	8/28/03	1.05	1.33	gravel/ZVI
R2–M10	8/18/03	0.68	1.19	gravel/ZVI
R5–M1	8/20/03	0.41	0.34	ZVI
R5–M2	8/29/03	0.60	0.92	ZVI
R5–M3	8/29/03	0.36	0.49	ZVI
R5–M4	8/29/03	0.19	0.50	ZVI
R5–M5	8/29/03	0.21	0.57	ZVI
R5–M6	8/28/03	1.36	1.49	ZVI
R5–M7	8/28/03	0.32	0.37	ZVI
R5–M7	8/18/03	0.59	1.41	ZVI
R5–M8	8/28/03	0.24	0.47	ZVI
R5–M8	8/19/03	0.13	0.20	ZVI
R5–M9	8/28/03	0.22	0.21	ZVI
R5–M10	8/18/03	0.16	0.59	ZVI
Mean gravel/ZVI		0.47	0.82	
Mean ZVI		0.40	0.63	
Mean all		0.44	0.73	
Minimum all		0.07	0.15	
Maximum all		1.36	1.49	

Table 15. Standard Materials Used in Rejuvenation Batch Tests

Name	Vendor	Description
Calcite Powder	Aldrich	Reagent grade. Calcite only (identified by XRD).
AFO	Noah Industries	AFO slurry dried at room temperature
Hematite	Fisher Scientific I-116-3	Reagent grade. Hematite only (identified by XRD).
Magnetite	American Chemical Enterprises A-310	Reagent grade. Magnetite only (identified by XRD).
ZVI	Fisher 40 Mesh	Reagent grade ZVI. Sieved to about 40 mesh.
Gravel/ZVI	ZVI = Peerless –8 +20	Mixture used in Monticello gravel/ZVI zone.

Table 16. Rejuvenation Tests Using Sodium Acetate Buffer

G/Z[a] (g)	Calcite Powder (mg)	Shake Time (hours)	Ca Removed (mg)	Fe Removed (mg)	Final pH
0	50	14	17.6	0.1	5.01
2	0	14	5.1	132.5	5.10
2	0	20	4.6	163.5	5.14
2	0	39	3.8	301.0	5.36

[a]Fresh gravel/ZVI material used at Monticello.

Table 17. Rejuvenation Tests Using EDTA. (50 mL of 0.1 M EDTA)

Test	Solids	EDTA Concentration	Concentration HCl (μL)	Shake Time (hours)	Start pH	Final pH	Ca Removed (mg)	Fe Removed (mg)
1	2 g gravel/ ZVI[a]	0.1 M	0	9	10.85	11.02	7.3	4.2
2	2 g gravel/ ZVI[a]	0.1 M	270	9	9.05	9.70	12.1	49.5
3	2 g gravel/ ZVI[a]	0.1 M	550	9	6.88	8.25	7.1	58.3
4	1 g Calcite	0.1 M	0	7.5	10.85	11.11	191	0.0
5	1 g ZVI[b]	0.1 M	0	7.5	10.85	11.13	0.1	4.0
6	1 g Hematite	0.1 M	0	7.5	10.85	10.76	0.1	0.1
7	1 g Magnetite	0.1 M	0	7.5	10.85	10.85	0.8	0.2
8	1 g Calcite + 1 g ZVI[b]	0.1 M	0	28	10.85	11.11	172.5	0.3
9	1 g Calcite + 1 g ZVI[b]	0.05 M	0	28	nm[c]	11.06	98.5	0.2
10	1 g Calcite + 1 g ZVI[b]	0.025 M	0	28	nm	10.90	46	0.1

[a]Fresh gravel/ZVI material used at Monticello.
[b] –6 + 10 mesh Peerless ZVI.
[c] nm = not measured.

Table 18. Rejuvenation Tests Using 0.2 M Ammonium Oxalate[a]

	Solids[b]	Start Electrical Conductivity (μS/cm)[c]	Final Electrical Conductivity (μS/cm)	Start pH	Final pH	Ca Removed (mg)	Fe Removed (mg)
1	AFO	20,300	20,100	3.00	3.18	0.0	15.8
2	Hematite	20,300	20,100	3.00	3.05	0.0	0.8
3	Magnetite	20,300	20,100	3.00	3.13	0.0	13.8
4	Fisher 40 Mesh ZVI	20,300	20,200	3.00	3.12	0.0	3.9
5	Calcite	20,300	20,200	3.00	3.14	0.0	0.0

[a] Tests conducted with 40 mL of 0.2 M ammonium oxalate buffered to a pH 3 value with 0.2 M oxalic acid and 0.5 g of solids; 2-h agitation at 25 ºC.
[b] Descriptions are provided in Table 15.
[c] μS/cm = microsiemens per centimeter.

Table 19. Rejuvenation Tests Using CBD Type Solutions[a]

Item	Solids[b]	Solvent[c]	Start pH	Final pH	Ca Removed (mg)	Fe Removed (mg)
1	AFO	D	4.53	5.85	0.8	17.4
2	Hematite	D	4.53	4.83	0.0	10.4
3	Magnetite	D	4.53	4.11	0.1	8.2
4	Fisher 40 Mesh ZVI	D	4.53	3.75	0.0	5.6
5	Calcite	D	4.53	4.22	6.8	0.0
6	AFO	CB	8.16	8.49	2.5	0.1
7	Hematite	CB	8.16	8.41	0.1	0.0
8	Magnetite	CB	8.16	8.44	0.7	0.1
9	Fisher 40 Mesh ZVI	CB	8.16	8.57	0.1	2.7
10	Calcite	CB	8.16	8.68	10.0	0.0
11	AFO	CBD	6.98	7.44	2.5	42.0
12	Hematite	CBD	6.98	7.19	0.1	16.2
13	Magnetite	CBD	6.98	7.08	0.5	9.4
14	Fisher 40 Mesh ZVI	CBD	6.98	7.08	0.1	6.0
15	Calcite	CBD	6.98	7.13	8.4	0.0
16	AFO	CCD	9.70	8.58	1.5	15.1
17	Hematite	CCD	9.70	8.56	0.1	2.8
18	Magnetite	CCD	9.70	8.63	0.2	3.0
19	Fisher 40 Mesh ZVI	CCD	9.70	8.83	0.0	4.0
20	Calcite	CCD	9.70	8.44	1.0	0.0

[a]Tests conducted with 40 mL of solution, 0.5 g of solids, and 2-h agitation at 25 ºC.
[b]Descriptions are provided in Table 15.
[c]D = 0.1 M sodium dithionite; CB = 0.27 M sodium citrate with 0.11 M sodium bicarbonate; CBD = same as CB but with 0.1 M sodium dithionite; and CCD = 0.27 M sodium citrate with 0.11 M potassium carbonate and 0.1 M sodium dithionite.

Table 20. Rejuvenation Tests Using Low Strength Sodium Dithionite and EDTA[a]

Item	Solids[b]	Solvent[c]	Start pH	Final pH	Ca Removed (mg)	Fe Removed (mg)
1	AFO	E	10.93	10.61	2.1	0.4
2	Hematite	E	10.93	10.79	0.1	0.0
3	Magnetite	E	10.93	10.82	0.3	0.0
4	Fisher 40 Mesh ZVI	E	10.93	10.88	0.1	1.0
5	Calcite	E	10.93	10.92	11.5	0.0
6	AFO	ED	9.17	9.30	1.7	0.5
7	Hematite	ED	9.17	9.25	0.1	0.0
8	Magnetite	ED	9.17	9.28	0.2	0.1
9	Fisher 40 Mesh ZVI	ED	9.17	9.37	0.0	4.3
10	Calcite	ED	9.17	9.36	9.0	0.0

[a] Tests conducted with 40 mL of solution, 0.5 g of solids, and 2-h agitation at 25 ºC.
[b] Descriptions are provided in Table 15.
[c] E = 0.05 M EDTA; ED = 0.038 M EDTA with 0.025 M sodium dithionite.

Table 21. Rejuvenation Tests Using High Strength Sodium Dithionite and EDTA[a]

Item	Solids[b]	Solvent[c]	Start pH	Final pH	Ca Removed (mg)	Fe Removed (mg)
1	AFO	E	10.95	10.66	2.4	0.4
2	Hematite	E	10.95	10.80	0.1	0.0
3	Magnetite	E	10.95	10.85	0.4	0.1
4	Fisher 40 Mesh ZVI	E	10.95	10.97	0.1	1.1
5	Calcite	E	10.95	10.88	10.1	0.0
6	AFO	ED	9.69	9.21	1.5	6.7
7	Hematite	ED	9.69	9.19	0.1	4.8
8	Magnetite	ED	9.69	9.16	0.3	4.7
9	Fisher 40 Mesh ZVI	ED	9.69	9.16	0.1	4.2
10	Calcite	ED	9.69	9.20	7.3	0.0

[a] Tests conducted with 40 mL of solution, 0.5 g of solids, and 2-h agitation at 25 ºC.
[b] Descriptions are provided in Table 15.
[c] E = 0.1 M EDTA; ED = 0.16 M EDTA with 0.057 M sodium dithionite.

Table 22. Rejuvenation Tests Using Hydroxylamine Hydrochloride[a]

Item	Solids[b]	Start pH	Final pH	Ca Removed (mg)	Fe Removed (mg)
1	AFO	1.48	1.52	1.9	7.4
2	Hematite	1.48	1.32	0.0	0.1
3	Magnetite	1.48	1.33	0.1	0.5
4	Fisher 40 Mesh ZVI	1.48	2.20	0.0	86.4
5	Calcite	1.48	2.67	224.8	0.1

[a]Tests conducted with 40 mL of solution, 0.5 g of solids, and 2-h agitation at 25 ºC.
[b]Descriptions are provided in Table 15.

Table 23. Composition of Well R1-M3 (sampled January 14, 2003) and Synthesized Ground Water Used in Preliminary Column Test

Constituent	Units	Actual Concentration	Synthesized Concentration
Na	mg/L	111.00	150.60
K	mg/L	213.00	222.88
Ca	mg/L	52.80	53.28
MG	mg/L	52.80	53.28
SO_4	mg/L	677.00	655.21
Cl	mg/L	76.60	76.09
TIC[a]	mg/L	76.00[b]	78.57
pH	s.u.	6.65	6.65[c]
Alkalinity	mg/L as $CaCO_3$	317.00	279[c]

[a] Total inorganic carbon.
[b] Estimated from alkalinity.
[c] Varies with CO_2 flow.

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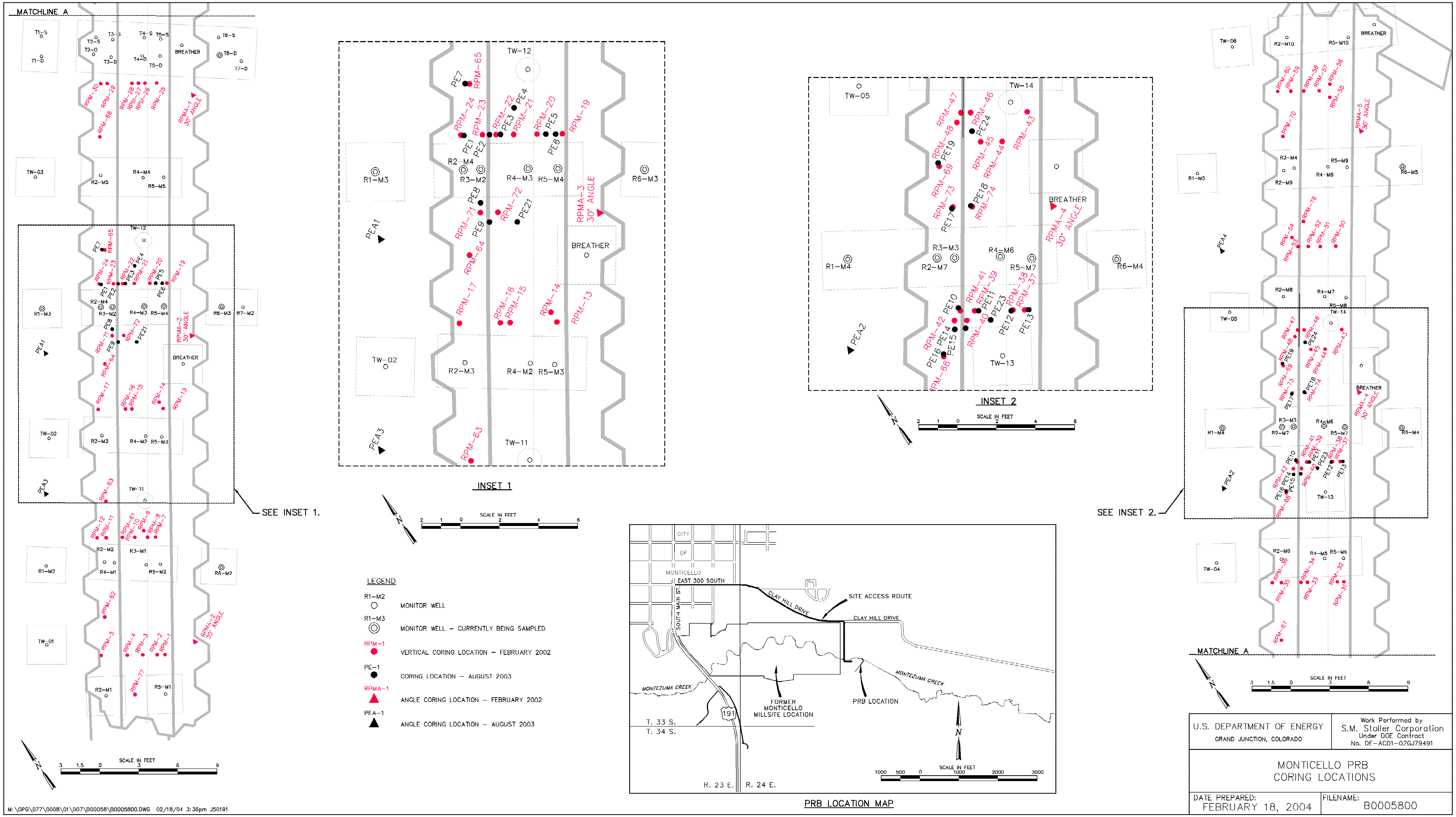


Figure 1.Core Locations at the Monticello, Utah, PRB Site

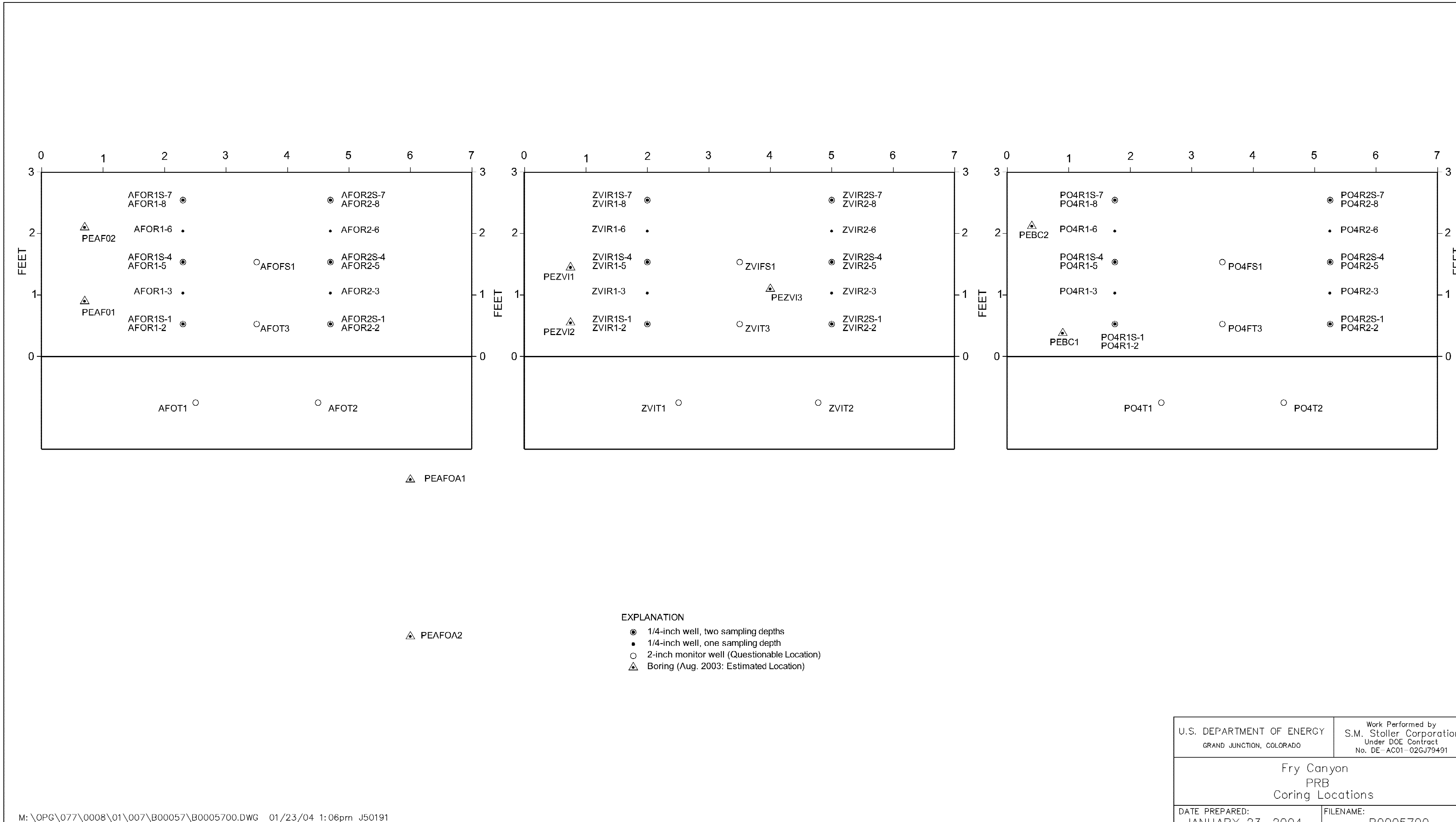


Figure 2. Core Locations at the Fry Canyon, Utah, PRB Site

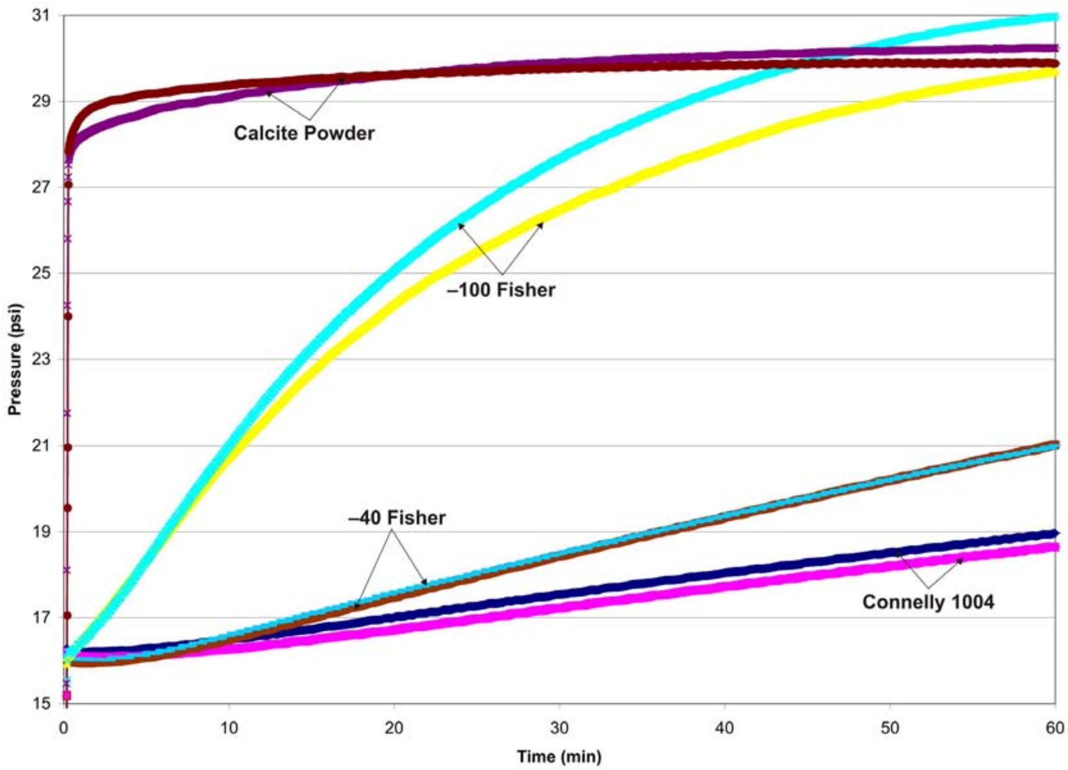


Figure 3. Reproducibility of Reactivity Tests Using Standard ZVI Samples

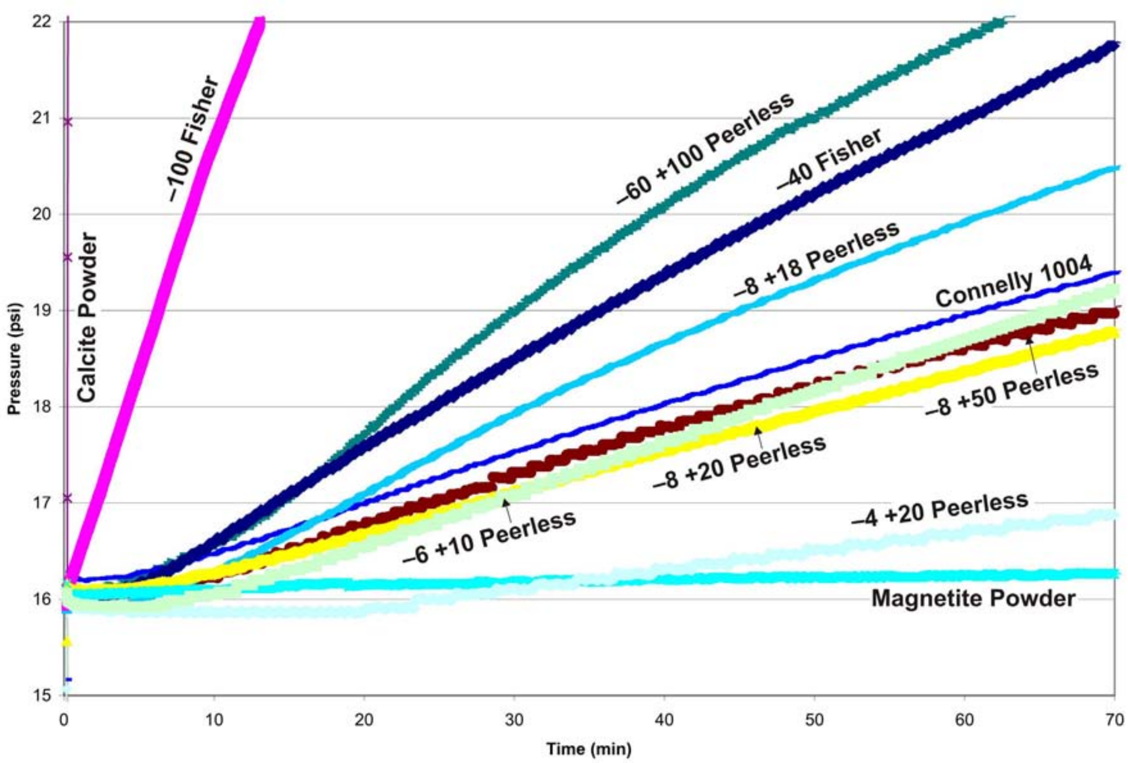


Figure 4. Reactivity Curves for a Variety of ZVI Types

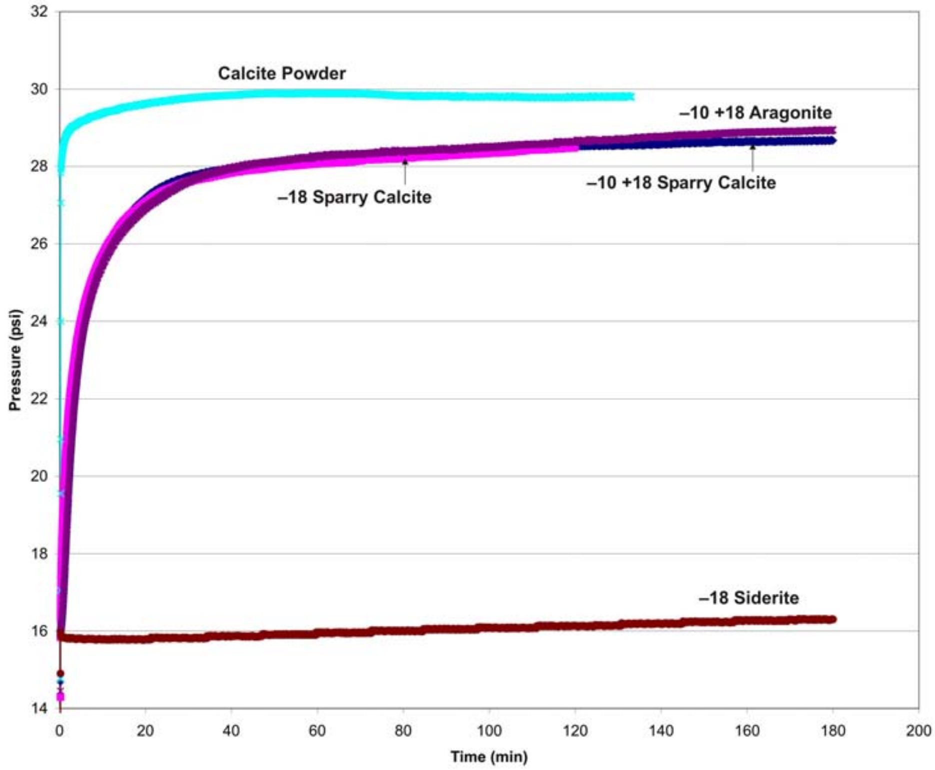


Figure 5. Reactivity Curves for Carbonate Minerals

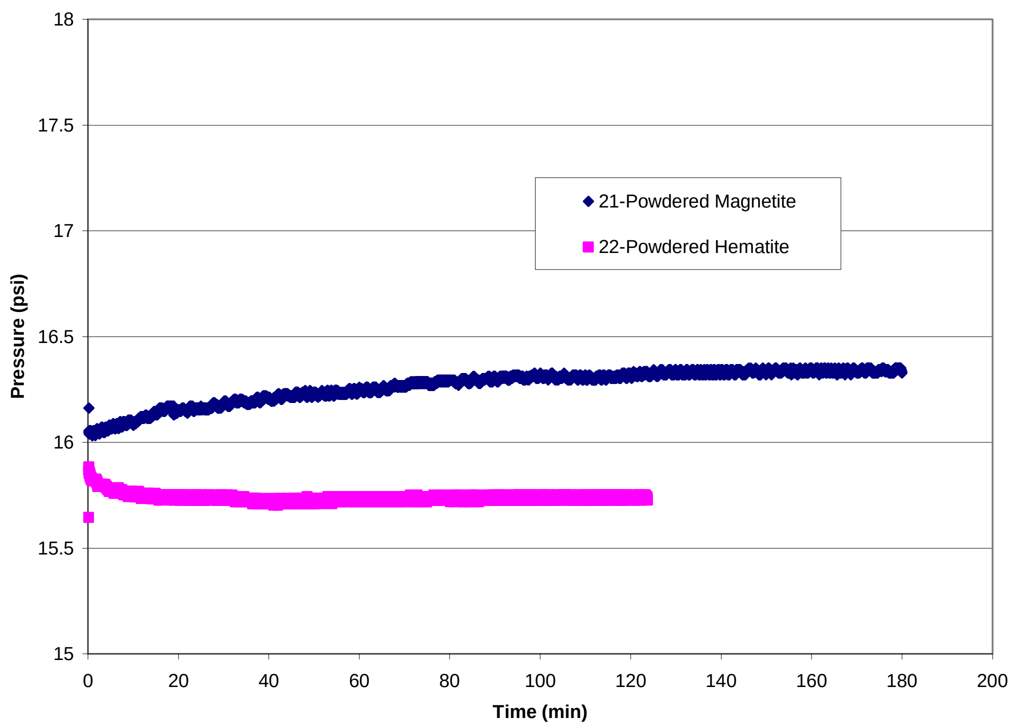


Figure 6. Reactivity Curves for Iron Oxide Minerals

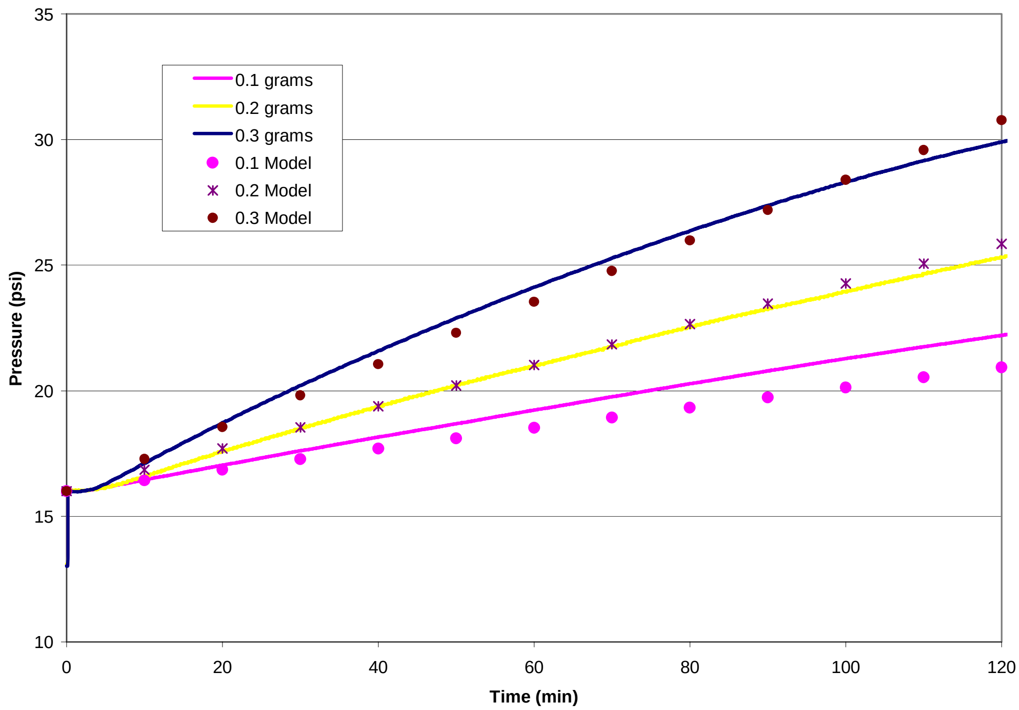


Figure 7. Model Fit to Three Different Masses of Fisher –40 Mesh ZVI

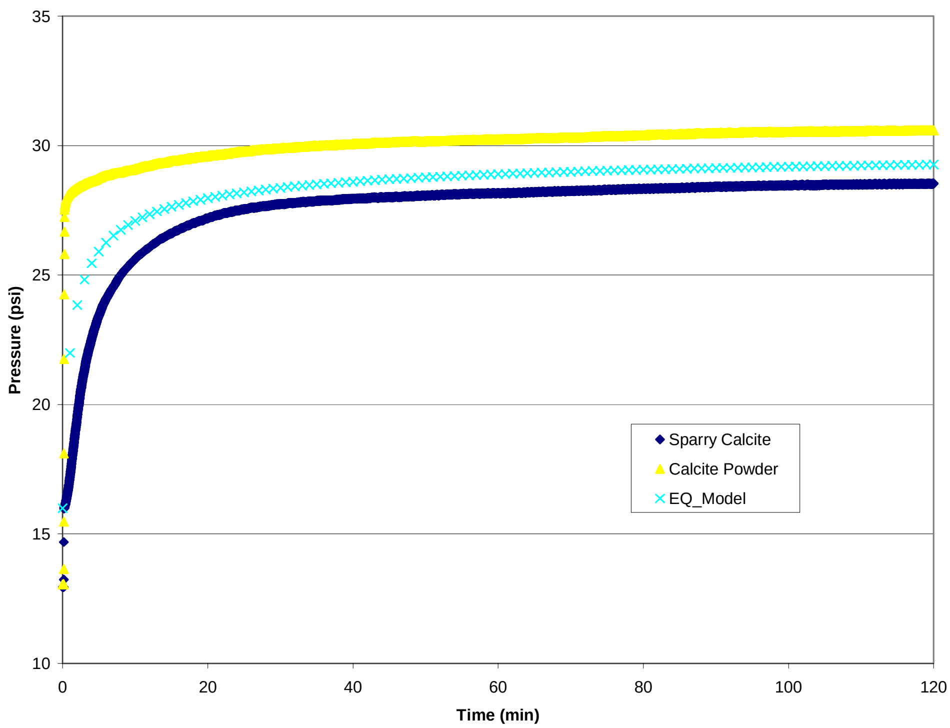


Figure 8. Model Fit to Two Different Crystallinities of Calcite

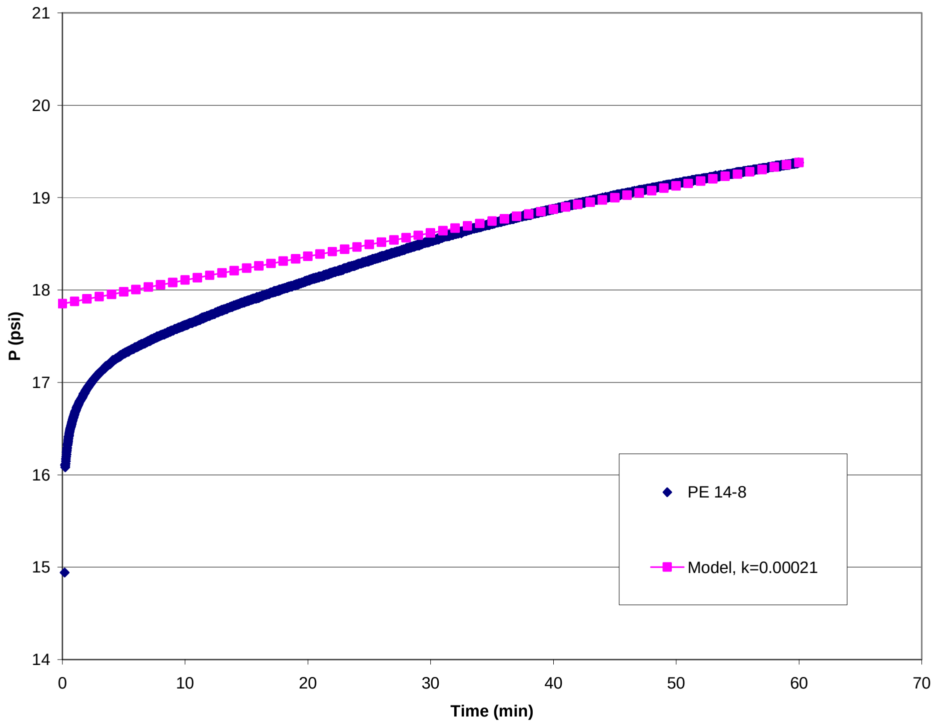


Figure 9. Typical Reactivity Test With Model Curve Fitted to Match Slope at 60 Minutes

(The rate constant in this example is 0.00021/per min. The unitless reactivity value is 2.1. The sample clearly has some carbonate as indicated by the rapid, early increase in pressure.)

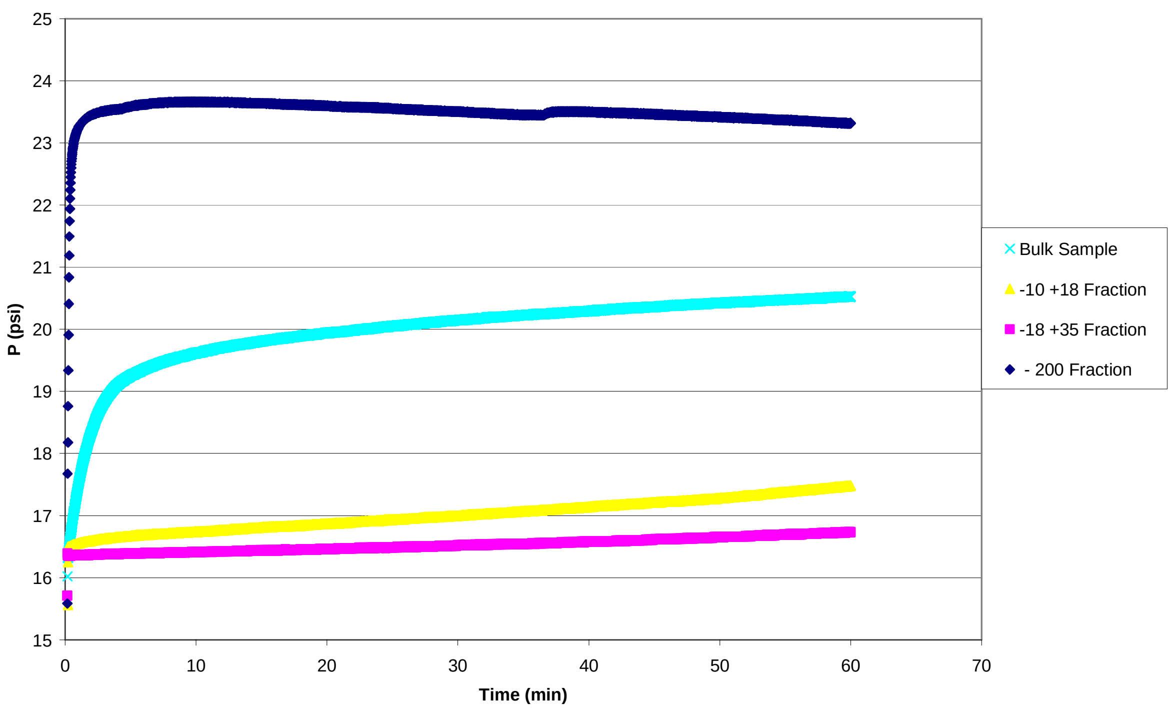


Figure 10. Reactivity Curves for Bulk Sample PE-ZVI-3-4 and Various Size Fractions

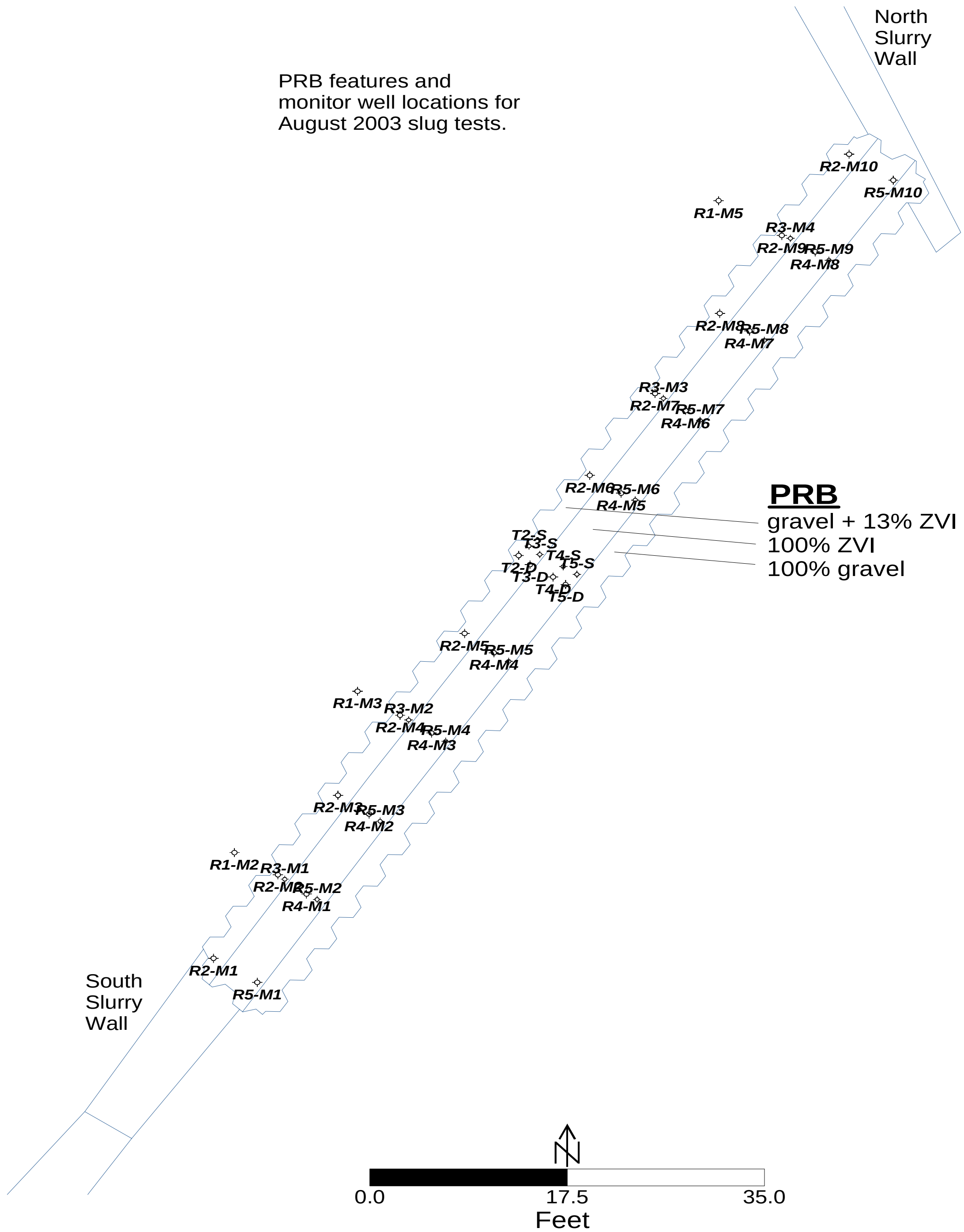


Figure 11. Locations of August 2003 Slug Tests at Monticello PRB

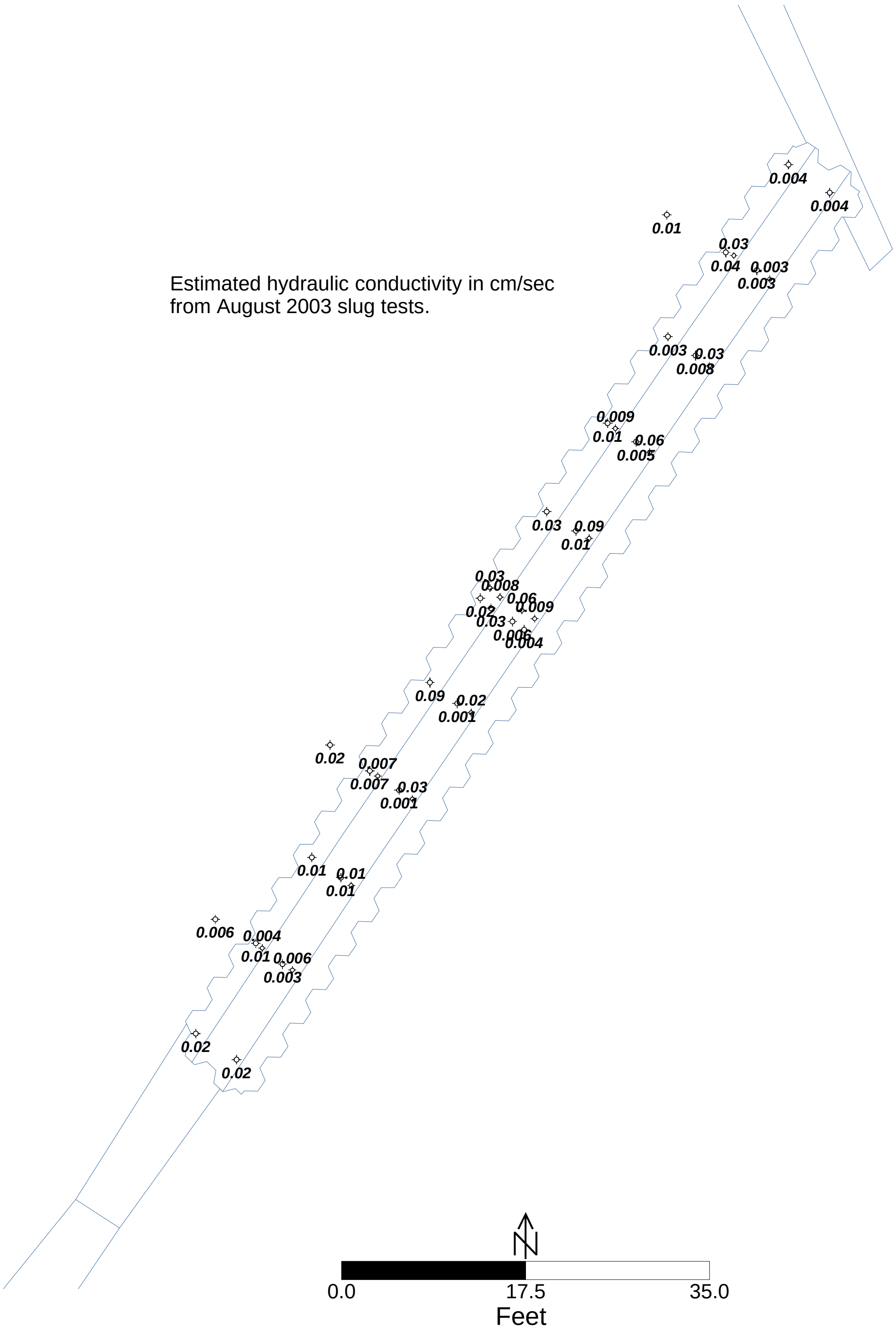


Figure 12. Estimated Hydraulic Conductivity (cm/s) Calculated From August 2003 Slug Tests at Monticello PRB

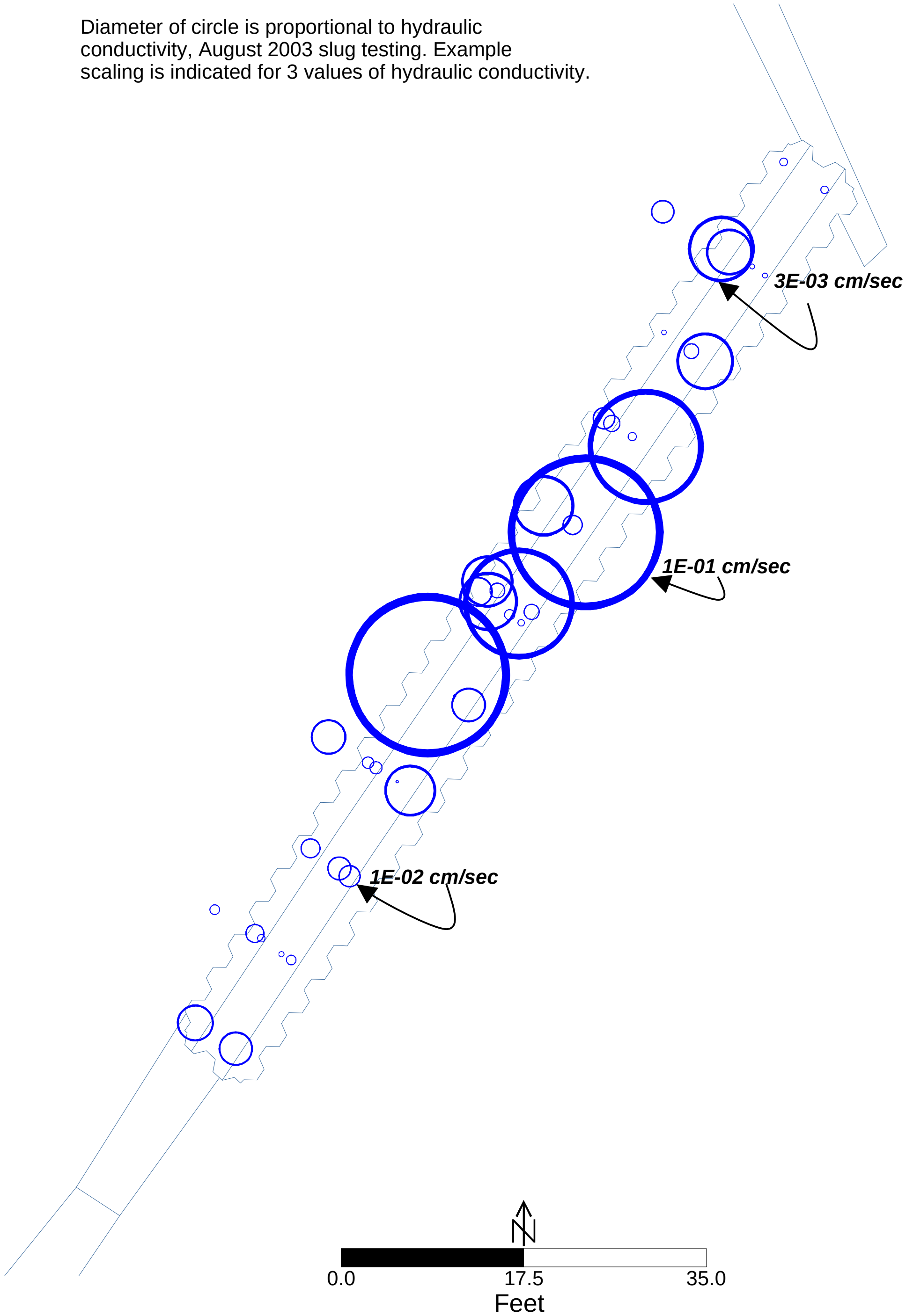


Figure 13. Graphical Representation of Hydraulic Conductivities Determined From August 2003 Slug Tests at Monticello PRB (circle size proportional to hydraulic conductivity)

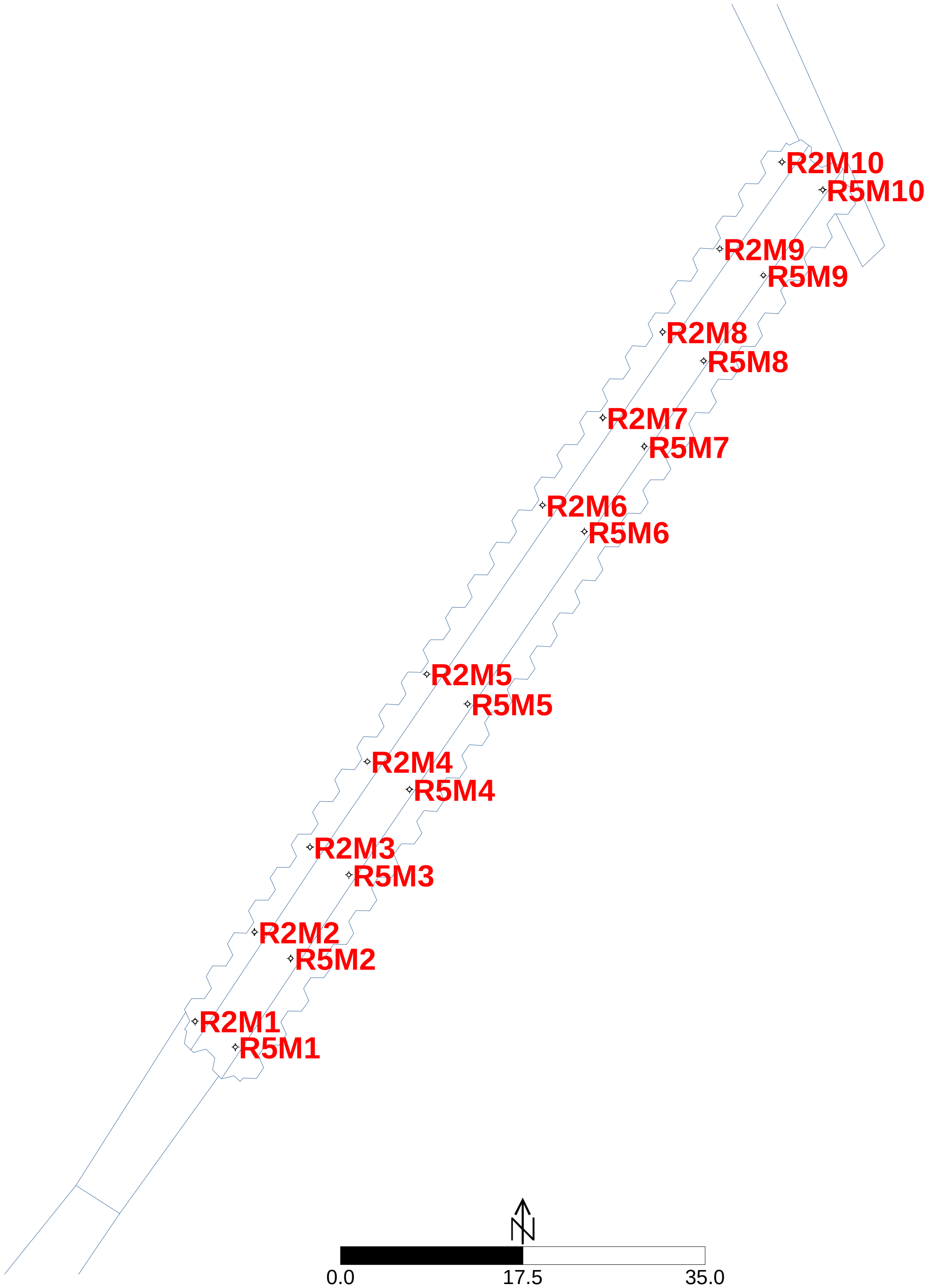


Figure 14. Location of Tracer Tests

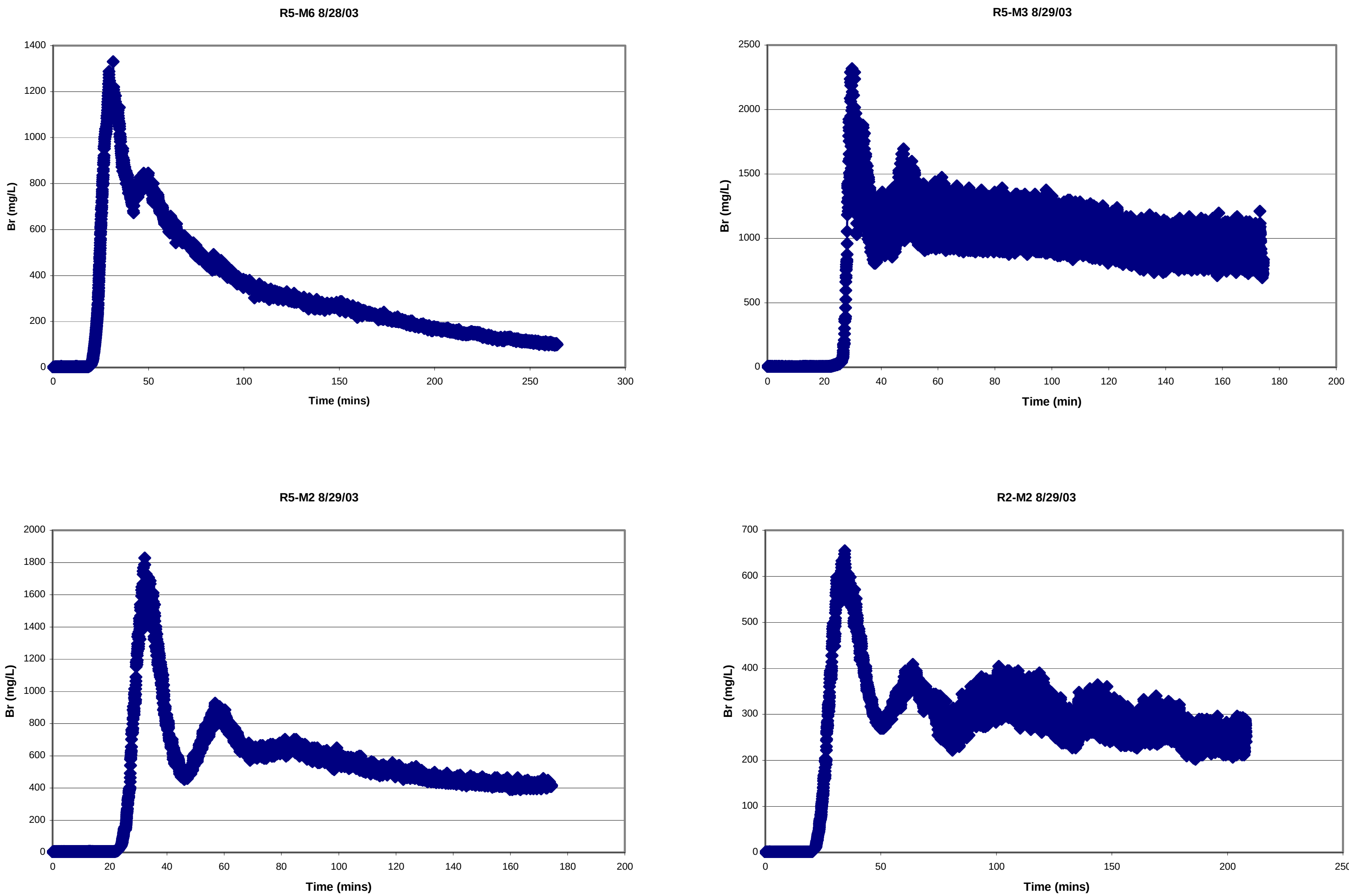


Figure 15. Example Bromide Test Curves

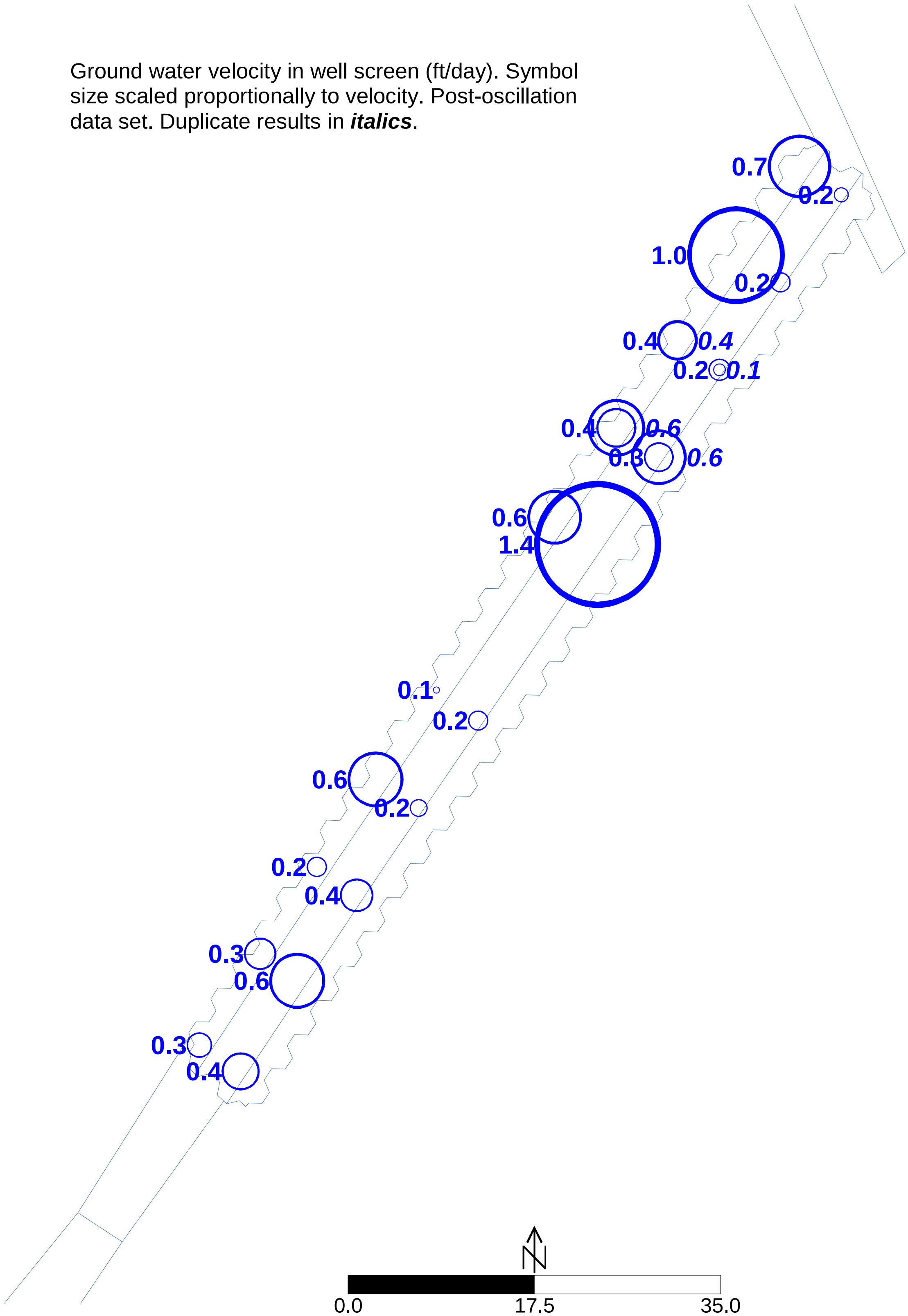


Figure 16. Ground Water Velocity in Well Screen

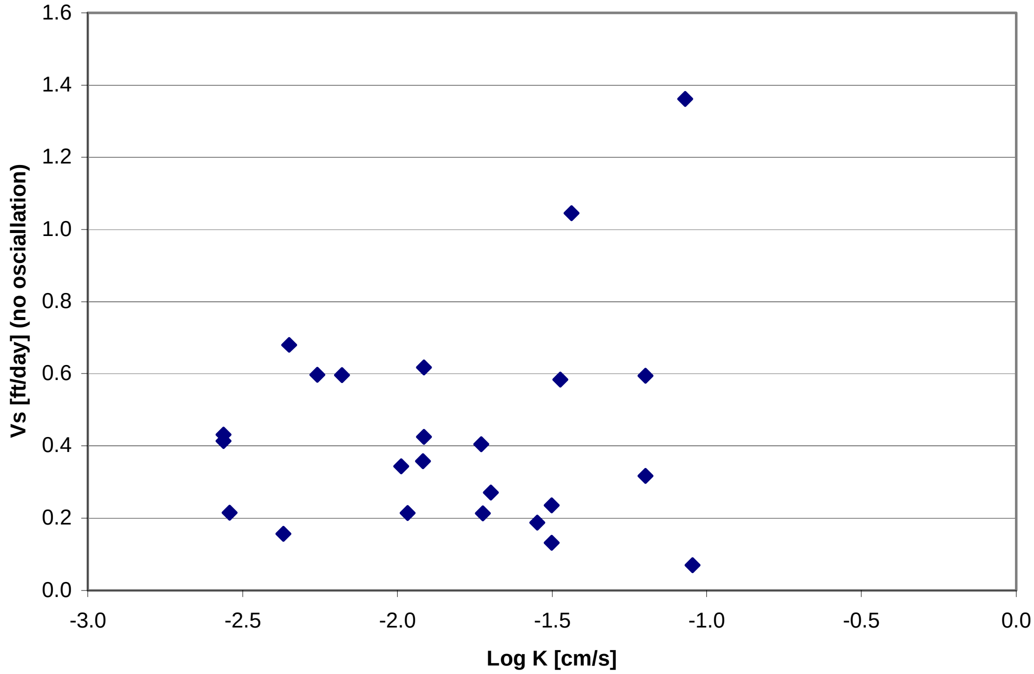
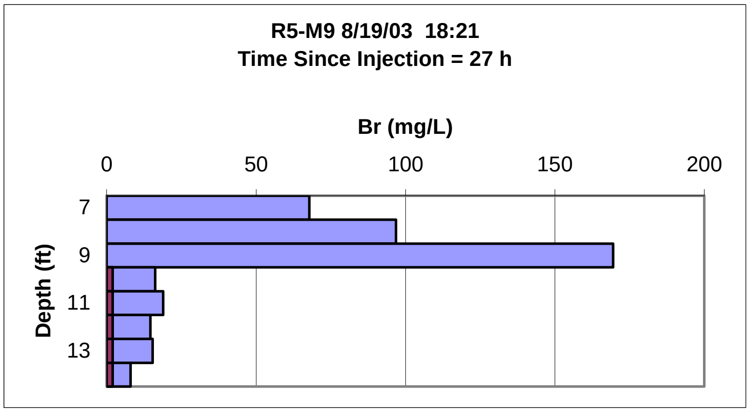


Figure 17. Well Screen Velocity Versus Hydraulic Conductivity Relationship



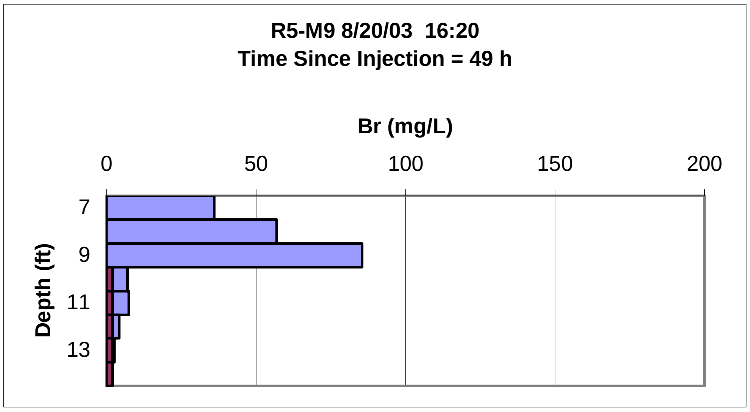


Figure 18. Example Vertical Concentration Profiles

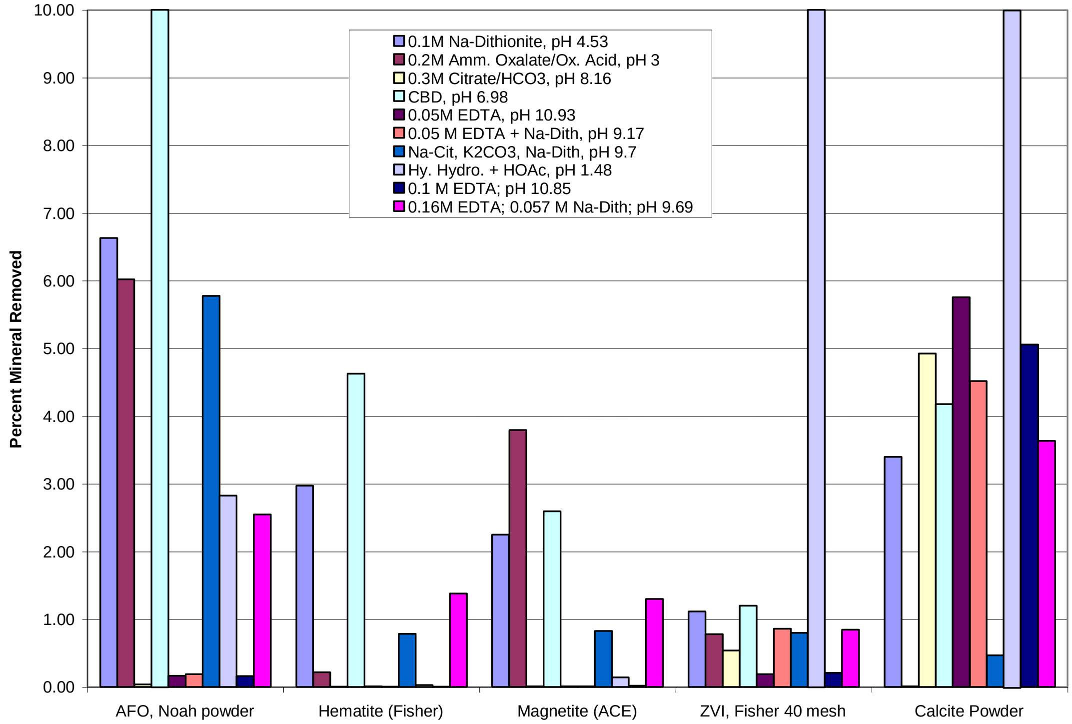


Figure 19. Results of Rejuvenation Batch Tests

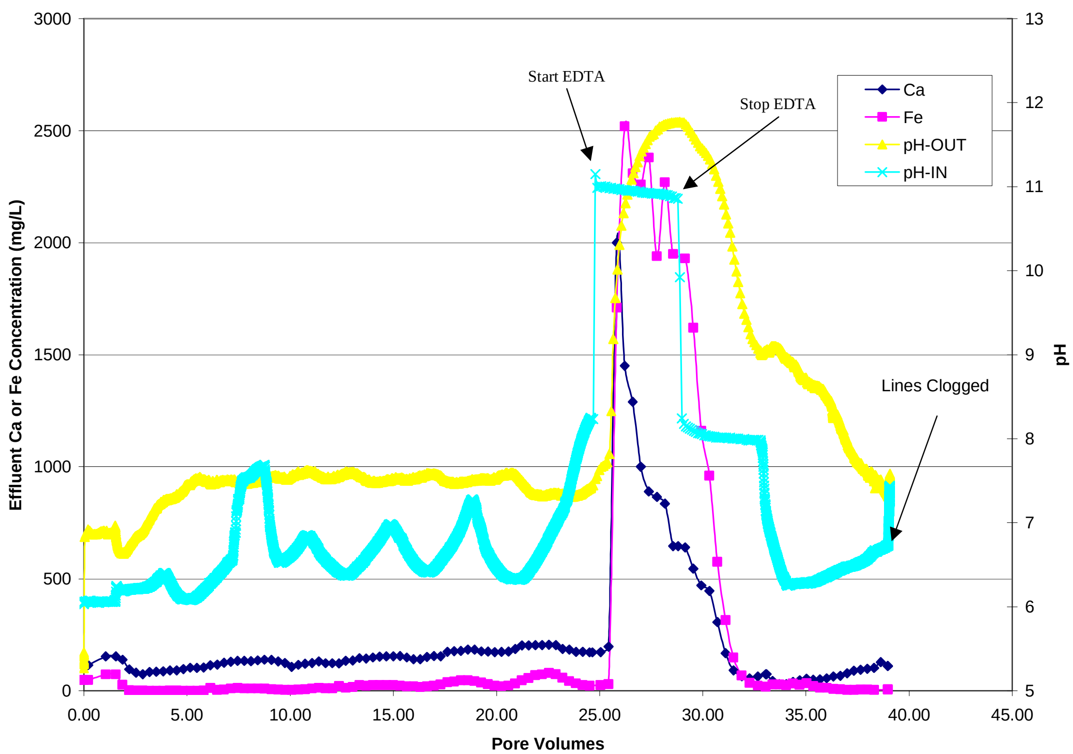


Figure 20. Results of Rejuvenation Column Test Using EDTA

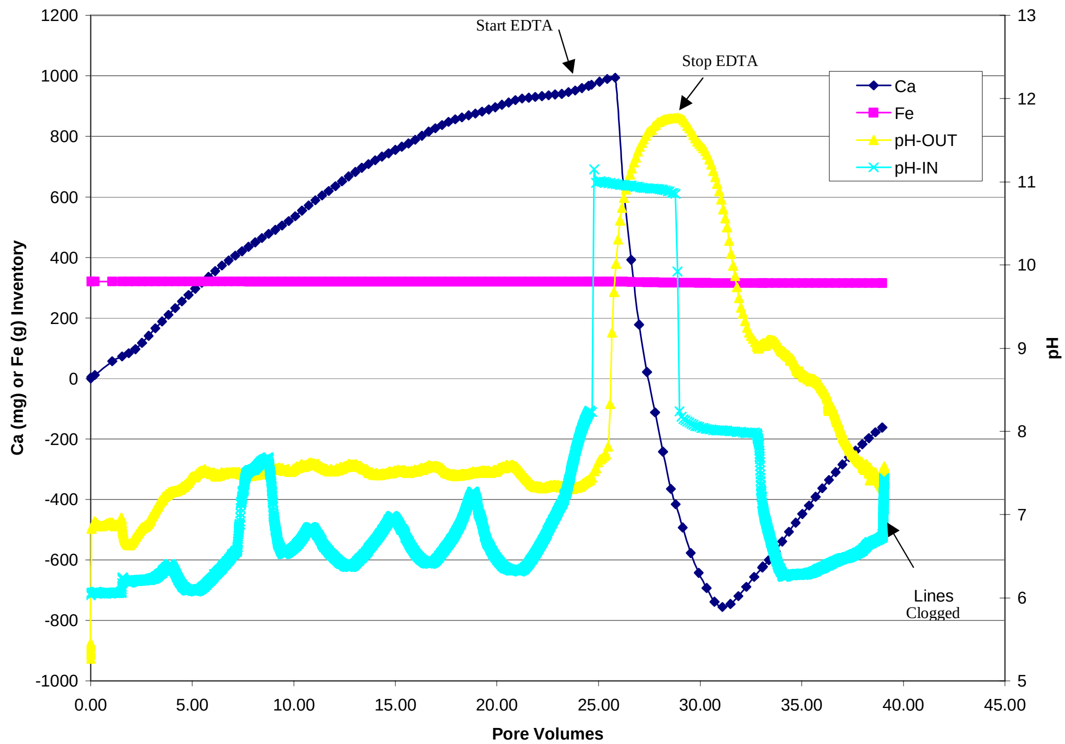


Figure 21. Chemical Inventory in Preliminary Column Test

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Appendix A

Environmental Sciences Laboratory Notes

End of current text

Monticello PeRT Rejuvenation MPERT01-09-01

4/30/03 Pack a 2" diameter column with fresh ZVI/gravel mix like that used in the ZVI/gravel zone @ PeRT wall in Monticello. It is a mix of ~ 2500 lbs -4/+20 iron to 9 cubic yards of gravel. Net weight of fill is 1602.5g

Prepare 20L RIM3 synthetic water by adding chemical solids to Milli-Q water

	1L (g)	20L (g)
$NaHCO_3$	0.55	11.0
$CaSO_4 \cdot 2H_2O$	0.7725	15.45
$MgSO_4 \cdot 7H_2O$	0.54	10.8
$CaCl_2 \cdot 2H_2O$	0.1576	3.15
K_2SO_4	0.025	0.5

320 g ZVI (assuming ~20% by weight)

1600 Place carboy on stir plate. Entrain CO_2 @ ~60cc/min. Monitor pH data logger initial pH = 6.89
1630 CO_2 flow ↓ to 20 mL/min
pH and ORP probes calibrated prior to monitoring. pH used 7 and 10 buffer.
ORP used zobell @ +230.

5/1/03 0745 Check pH of source tank. pH = 5.908. DC CO_2 flow. alk = 279 mg/L as $CaCO_3$
0850 pH now @ 5.94

Note that data logger channels are:
1 ORP inlet
2 ORP outlet
3 pH inlet
4 pH outlet

File: APR30_03 is monitoring 20L source tank of influent c̄ CO_2 entrained pH only

Slope-intercept for ORP probe calibration (from factory) = intercept -389.76, slope 222.6

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Monticello PeRT Rejuvination MPERT 01-09-02

5/1/03 0915 Start flow to column @ 4ml/min

1123 First outflow. Collect in 50ml cent tube. That is 129 minutes till first programmed collect on fraction collector.

Fraction collector is set @ 234 minute drain, 6 minute collect.

Note outflow pH has not increased as expected.

1441 Change pump heads to size 16. Flow set @ 0.7ml minute. Will reprogram frac collector to 35 minute collects, 205 minute drain, 176 minutes left on drain.

flow changed @ [redacted] on data logger pH in 6.071 pH out 6.904

1130 * Flow starts to outflow sensors @ 11:30 [redacted] May 01–03

1150 Start drain to beaker.

1339 first collect on fraction collector 6" = 24ml rate = 4ml/min

PV = 512 ml (128 minutes x 4ml/minute)

1535 Start CO_2 flow @ 10 ml/min [redacted]

5/2/03 0847 pH inlet at 6.23. Turned off CO_2 gas (although it was barely flowing if at all). [redacted] MAY 01–03

0852 Stopped data logger. Started new file

pH IN Intercept = 13.5801
Slope = −3.7123

0930 [redacted] file (with time column)
Lost all data from 0852 – 0930
Had to restart [illegible]

pH OUT Intercept = 13.1649
Slope = −3.7520

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MPERT 01-09-03

5/2/03 1930 pH inlet is rising 6.395. Started 10 ml/min CO_2
Time = 9.833 hours
2019 Increased CO_2 to 20 ml/min

5/3/03 1028 Log time = 24.917 hrs. pH in was 6.004. Turned CO_2 off

5/4/03 1151 Log time = 50.333 hrs. pH in was 6.556. Turned CO_2 to 10 ml/min
Attached Aquarium pump with Aeration stone to add O_2 to source tank
ORP has drifted down slightly from about 200 to 179 mV

5/5/03 0701 pH in up to 7.675. Turned off air. Turned CO_2 on at 20 ml/min
Log time = 69.5 hours

1224 pH_{in} is 6.792. D/C CO_2 (log time = 74.917 hours)

1615 pH_{in} is 6.538 (logtime 78.667)

5/6/03 0632 Log = 93.000 pH in = 6.796 CO_2 turned on 10 ml/min

5/7/03 0643 Log = 117.25 hr. pH in = 6.375 CO_2 D/C

0 17:17 Stopped datalogger MAY02_03
17:20 Start MAY07_03 (0 hours)

5/8/03 0637 (logger 13.250 hrs) pH in at 6.896, turned CO_2 on 10 ml/min
Some tubes on fraction collector are not filling all the way. Some are only about ½ full. Lots of Fe staining (red) in lines.

5/9/03 0600 Turned CO_2 off. 100 ml Conc HNO_3 put in Tubes 31-54
(logger 36.607)

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MPERT 01-09-04

5/10/03 0748 CO_2 started 10 mL/min
0906 Added 100 µL HNO_3 conc to tubes 50 – 74
0906 Last tube collected was #5[illegible] . Logger 63.750 hours

5/11/03 1213 D/C CO_2 Log time = [illegible] ([illegible]-03) Last tube collected = #60

5/12/03 0619 Last Tube collected was [illegible] Log time = 109.000
Added another 100 µL conc HNO_3 to tubes 50-74 (total 200 µL)
Added 200 µL conc HNO_3 to [illegible] [illegible]-9[illegible]

0640 Started filling tube #65 Log time = 109.333
0653 Made 2L of 0.1 M EDTA (41.62 g/L) 83.24 g per 2L

0712 Ended Tube #65 collect. Log Time = 109.833

0717 Stopped File MAY07_03
0718 Started File MAY12_03 (1000 hours)

5/13/03 0821 Start flow @ 10 mL/min of 0.1 M EDTA Log time @ 25.000 + Change collect times
to 18 min. drain / 2 min collect to get 20 mL split.

0839 First collect (tube 72) after start of EDTA Soln is clear. 0.2 mL HNO_3 in test tubes

0859 tube 73 off - soln is clear

0919-21 tube 74 off. soln is layered. bottom 1/3rd green, middle 1/3rd tan, top 1/3rd orange
0939-41 75 as above
0959-1001 76 as above
1019-[illegible] 77 [illegible]

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MPERT 01-09-05

5/12/03 1039-41 tube 78 off [illegible]

1059-1101 79 off No acid in test tube

5/13/03 1105 Change outlet ORP probe. Check new probe prior to installation. [illegible] = +227

1119-21 tube 80 off Note that tubes without acid are very pale orange with dark orange thin layer at top. Cloudy orange [illegible] throughout tube

Prepare new 20L of R1A3 [illegible] dissolved chemical soln to MQ H_2O

50g/L	$NaHCO_3$	230
1.5g/L	$CaSO_4 \cdot 2H_2O$	10300
200g/L	$MgSO_4 \cdot 7H_2O$	54
92.72g/L	$CaCl_2 \cdot 2H_2O$	5
100g/L	K_2SO_4	34
	MQ H_2O	9387
		20,000

1153 Switch to new source tank c R1A3 file time = 28.583 Six minutes left on drain between tubes 81 an 82.

1159 Start tube 82 collect. file time 28.667

1400 Column appears to be running well. Samples are lightening in color

1420 Start CO_2 flow to source tank @ ~10 ml/min

1520 ↓ flow to 0.7 ml/min. Reprogram frac collector to 205 min drain/35 min collect

add acid to [illegible]

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MPERT 01-09-06

5/13/03 1655 (33.583 file time) Columns running well, will leave CO_2 @ 10ml/min.

5/14/03 0723 Completed TUBE 96. File time = 48.083

1123 complete tube 97 file time - 52.083

acidify tubes 79-92 (not acidified @ time of collection) to rerun Fe, Cu, use 0.5ml conc HNO_3
add addtl HNO_3 to tubes 74-78 (pH was ~7 prior to addition) all now pH<2

1502 Stop file collect MAY14-03 file time 55.750, restart MAY14-03 since clock time @ 1502
during RJV098 collect (20 minutes left to collect)

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Ca (source tank) = 219 mg/L (measured)
= 220 mg/L (calculated)

MPERT 01-09-07

Column Rejuvenation (ml) (ml/min)

Outflow/tube	Vol (ml)	Cum Vol	Rate	PV 1=512	Color	Ca (mg/L)	Fe (mg/L)
1st outflow	25	25	4	0.05	Red	115	47.5
drain	516	541	4	1.06			
RJV001	24	565	4	1.10	Red	153	72.6
drain	224	789	4	1.54			
drain	18	807	0.7	1.58			
drain	102	909	0.7	1.78			
RJV002	23	932	0.7	1.82	Red	139	26.0
drain	144	1076	0.7	2.10			
RJV003	23	1099	0.7	2.15	Clear	96	1.48
drain	144	1243	0.7	2.43			
RJV004	23	1266	0.7	2.47		80	0.91
drain	144	1410	0.7	2.75			
RJV005	23	1433	0.7	2.80		74	0.52
drain	144	1577	0.7	3.08			
RJV006	23	1600	0.7	3.13		84	0.43
drain	144	1744	0.7	3.41			
RJV007	23	1767	0.7	3.45		85	0.21
drain	144	1911	0.7	3.73			
RJV008	23	1934	0.7	3.78		87	0.23
drain	144	2078	0.7	4.06			
RJV009	23	2101	0.7	4.10		90	0.78
drain	144	2245	0.7	4.38			
RJV010	23	2268	0.7	4.43		91	0.99
drain	144	2412	0.7	4.71			
RJV011	23	2435	0.7	4.76		97	0.10
drain	144	2579	0.7	5.04			
RJV012	23	2602	0.7	5.08		103	0.12
drain	144	2746	0.7	5.36			
RJV013	23	2769	0.7	5.41		102	0.42
drain	144	2913	0.7	5.69			
RJV014	23	2936	0.7	5.73		104	0.85

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Column Rejuvination (ml) (ml/min) (ml)

MPERT01-09-08

	Outflow	1 Vol (ml)	2 Cum Vol	3 Rate	4 PV1=512	5 Color	Cu (mg/L)	7 Fe (mg/L)	8	9	10	11	12	13
1	drain	144	3080	0.7	6.02									
2	RJV015	23	3103	0.7	6.06	Red	114	12.3						
3	drain	144	3247	0.7	6.34									
4	RJV016	23	3270	0.7	6.39		117	3.77						
5	drain	144	3414	0.7	6.67									
6	RJV017	23	3437	0.7	6.71		125	5.42						
7	drain	144	3581	0.7	6.99									
8	RJV018	23	3604	0.7	7.04		129	9.6						
9	drain	144	3748	0.7	7.32									
10	RJV019	23	3771	0.7	7.37		133	11.4						
11	drain	144	3915	0.7	7.65									
12	RJV020	23	3938	0.7	7.69		133	10.3						
13	drain	144	4082	0.7	7.97									
14	RJV021	23	4105	0.7	8.02		132	10.0						
15	drain	144	4249	0.7	8.30									
16	RJV022	23	4272	0.7	8.34		136	10.2						
17	~~RJV 02~~ drain	144	4416	0.7	8.63									
18	RJV023	23	4439	0.7	8.67		139	9.5						
19	drain	144	4583	0.7	8.95									
20	RJV024	24	4607	0.7	9.00		138	6.7						
21	drain	144	4751	0.7	9.28									
22	RJV025	24	4775	0.7	9.33		131	4.78						
23	drain	144	4919	0.7	9.61									
24	RJV026	22	4941	0.6	9.65	pale yellow	124	4.00						
25	drain	144	5085	0.7	9.93									
26	RJV027	25	5110	0.7	9.98		107	3.72						
27	drain	144	5254	0.7	10.26									
28	RJV028	21	5275	0.6	10.30		116	4.15						
29	drain	144	5419	0.7	10.58									
30	RJV029	23	5442	0.7	10.63		120	6.60						
31	drain	144	5586	0.7	10.91									

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MPERT01-09-09

Column Rejuvenation

	Outflow/tube	1 Vol (ml)	2 CumVol (ml)	3 Rate (ml/min)	4 PV 1=512	5 Color	6 Ca (mg/L)	7 Fe (mg/L)	8	9	10	11	12	13
1	RJV030	23	5609	0.7	10.96	pale yellow	124	10.0						
2	drain	144	5753	0.7	11.24									
3	RJV031	22	5775	0.6	11.28		131	12.4						
4	drain	144	5919	0.7	11.56									
5	RJV032	23	5942	0.7	11.61		123	10.5						
6	drain	144	6086	0.7	11.89									
7	RJV 033	23	6109	0.7	11.93		123	10.5						
8	drain	144	6253	0.7	12.21									
9	RJV 034	16	6269	0.5	12.24	rust flocs	122	21.1						
10	drain	144	6413	0.7	12.53									
11	RJV 035	24	6437	0.7	12.57	pale yellow	134	12.6						
12	drain	144	6581	0.7	12.85									
13	RJV 036	26	6607	0.7	12.90		135	16.5						
14	drain	144	6751	0.7	13.19									
15	RJV 037	17	6768	0.5	13.22	rust flocs	146	25.4						
16	drain	144	6912	0.7	13.50									
17	RJV 038	16	6928	0.5	13.53		144	22.3						
18	drain	144	7072	0.7	13.81									
19	RJV 039	24	7096	0.7	13.86		149	25.4						
20	drain	144	7240	0.7	14.14									
21	RJV 040	23	7263	0.7	14.19		152	25.2						
22	drain	144	7407	0.7	14.47									
23	RJV 041	21	7428	0.6	14.51		153	25.2						
24	drain	144	7572	0.7	14.79									
25	RJV 042	23	7595	0.7	14.83		154	25.2						
26	drain	144	7739	0.7	15.12									
27	RJV 043	24	7763	0.7	15.16		155	22.3						
28	drain	144	7907	0.7	15.44									
29	RJV 044	24	7931	0.7	15.49		149	19.0						
30	drain	144	8075	0.7	15.77									
31	RJV 045	15	8090	0.4	15.80	rust flocs	140	20.4						

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MPERT01-09-10

Column Rejuvenation

outflow/tube		Vol (ml)	Cum Vol (ml)	Rate (ml/min)	PV (1=51.2)	Color	La (mg/L)	Fe (mg/L)	9	10	11	12	13
drain	1	144	8234	0.7	16.08	clear							
RJV 046	2	17	8251	0.5	16.12		140	16.1					
drain	3	144	8395	0.7	16.40								
RJV 047	4	22	8417	0.6	16.44		151	18.9					
drain	5	144	8561	0.7	16.72								
RJV 048	6	24	8585	0.7	16.77		155	22.3					
drain	7	~~144~~ 144	8729	0.7	17.05								
RJV 049	8	~~144~~ 25	8754	0.7	17.10		154	28.2					
drain	9	144	8898	0.7	17.38								
RJV 050	10	23	8921	0.7	17.42		174 ~~210~~	38.0					
drain	11	144	9065	0.7	17.71								
RJV 051	12	21	9086	0.6	17.75		177	40.8					
drain	13	144	9230	0.7	18.03								
RJV 052	14	22	9252	0.6	18.07		178	46.5					
drain	15	144	9396	0.7	18.35								
RJV 053	16	23	9419	0.7	18.40		184	46.5					
drain	17	144	9563	0.7	18.68								
RJV 054	18	23	9586	0.7	18.72		183	42.8					
drain	19	144	9730	0.7	19.00								
RJV 055	20	25	9755	0.7	19.05		176	36.6					
drain	21	144	9899	0.7	19.33								
RJV 056	22	23	9922	0.7	19.38		175	28.9					
drain	23	144	10066	0.7	19.66								
RJV 057	24	17	10083	0.5	19.69		172	21.5					
drain	25	144	10227	0.7	19.97								
RJV 058	26	22	10249	0.6	20.02		173	20.5					
drain	27	144	10393	0.7	20.30								
RJV 059	28	22	10415	0.6	20.34		175	22.7					
drain	29	144	10559	0.7	20.62								
RJV 060	30	24	10583	0.7	20.67		186	32.0					
drain	31	144	10727	0.7	20.95								

EFFICIENCY LINE® 22-210

(5)

Column Rejuvenation

MPERT01-09-11

#	Outflow/tube	Vol (mL)	Cum Vol (mL)	Rate (mL/min)	AV (1=512)	Color	Ca (mg/L)	Fe (mg/L)
1	RJV 061	28	10755	0.8	21.01	clear	202	46.6
2	drain	144	10899	0.7	21.29			
3	RJV 062	25	10924	0.7	21.34		202	56.6
4	drain	144	11068	0.7	21.62			
5	RJV 063	24	11092	0.7	21.66		203	69.0
6	drain	144	11236	0.7	21.95			
7	RJV 064	20	11256	0.6	21.98		204	73.2
8	drain	144	11400	0.7	22.27			
9	RJV 065	23	11423	0.7	22.31		205	79.2
10	drain	144	11567	0.7	22.59			
11	RJV 066	24	11591	0.7	22.64		204	73.6
12	drain	144	11735	0.7	22.92			
13	RJV 067	25	11760	0.7	22.97		187	57.4
14	drain	144	11904	0.7	23.25			
15	RJV 068	21	11925	0.6	23.29		184	42.4
16	drain	144	12069	0.7	23.57			
17	RJV 069	23	12092	0.7	23.62		173	33.0
18	drain	144	12236	0.7	23.90			
19	RJV 070	21	12257	0.6	23.94		174	24.6
20	drain	144	12401	0.7	24.22			
21	RJV 071	23	12424	0.7	24.27		171	21.6
22	drain	73	12497	0.7	24.41			
23	drain	180	12677	10.0	24.76		~~172~~	~~25.4~~
24	RJV 072	20	12697	10.0	24.80		172	25.4
25	drain	180	12877	10.0	25.15			
26	RJV 073	19	12896	9.5	25.19		197	29.1
27	drain	180	13076	10.0	25.54			
28	RJV 074	19	13095	9.5	25.58	tinged green	2000	1710
29	drain	180	13275	10.0	25.93	brown		
30	RJV 075	20	13295	10.0	25.97	orange (top)	1450	2520
31	drain	180	13475	10.0	26.32			

Only 105 min, Δ to EDTA, 10 mL

max 18° | pileTime

2" | 25.333+ | @08:39

25.667+ | @08:59

Clump white ppt @ bottom

clump | 26.333+ | @9:39

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MPERT01-09-12

Column Rejuvenation

#	outflow/tube	Vol (mL)	Cum Vol (mL)	Rate (mL/min)	PV (1=512)	Color	Ca (mg/L)	Fe (mg/L)	Notes
1	RJV 076	20	13495	10.0	26.36	beyond	1290	2310	clump white ppt.
2	drain	180	13675	10.0	26.71				
3	RJV 077	20	13695	10.0	26.75		1000	2260	Clump white ppt
4	drain	180	13875	10.0	27.10				
5	RJV 078	19	13894	9.5	27.14		890	2380	Clump white ppt
6	drain	180	14074	10.0	27.49				
7	RJV 079	19	14093	9.5	27.53	cloudy orange rust ppt	865	1940	@1059 - 27.667 + filetime 3/c acid in tubes
8	drain	180	14273	10.0	27.88				
9	RJV 080	20	14293	10.0	27.92		835	2270	Change ORP outlet probe cloudy orange
10	drain	180	14473	10.0	28.27				
11	RJV 081	19	14492	9.5	28.30		645	1950	@1139 - 28.333
12	drain	180	14672	10.0	28.66				Change back to R1M3 @ 6" left on drain tube @28.58
13	RJV 082	19	14691	9.5	28.69		640	1930	
14	drain	180	14871	10.0	29.04				
15	RJV 083	20	14891	10.0	29.08		545	1620	
16	drain	180	15071	10.0	29.44				
17	RJV 084	19	15090	9.5	29.47		470	1160	
18	drain	180	15270	10.0	29.82				
19	RJV 085	19	15289	9.5	29.86		446	960	
20	drain	180	15469	10.0	30.21				
21	RJV 086	20	15489	10.0	30.25		306	575	
22	drain	180	15669	10.0	30.60				
23	RJV087	19	15688	9.5	30.64	clearing	168	315	
24	drain	180	15868	10.0	30.99	pale orange			
25	RJV088	19	15887	9.5	31.03		91	128	
26	drain	180	16067	10.0	31.38				
27	RJV 089	16	16083	8.0	31.41		645	68	
28	drain	180	16263	10.0	31.76				
29	RJV 090	19	16282	9.5	31.80		55.9	35.5	
30	drain	180	16462	10.0	32.15				
31	RJV 091	19	16481	9.5	32.19	clear	63.5	22.8	

AMPAD EFFICIENCY LINE® 22-210

MPERT01-09-13

Column Rejuvenation

outflow/tube	Vol (mL)	Cum Vol (mL)	rate mL/min	PV (1=512)	Color	Ca (mg/L)	Fe (mg/L)	8	9	10	11	12	13
drain 1	180	16661	10.0	32.54									
RJV 092 2	19	16688	9.5	32.59	clear	73.5	16.9		last collect @ ↑ flow				
drain 3	144	16824	0.7	32.86				filtime=	Δ collect time 20s drain /35 collect ↓flow 0.7 mL/min				
RJV 093 4	23	16847	0.7	32.90		44	27.4	32,000	resume acid addition				
drain 5	144	16991	0.7	33.19					0.2 mL HNO_3 in each tube				
RJV 094 6	23	17014	0.7	33.23		29.2	27.8						
drain 7	144	17158	0.7	33.51									
RJV 095 8	23	17181	0.7	33.56		29.3	25.9						
drain 9	144	17,325	0.7	33.84									
RJV 096 10	25	17350	0.7	33.89		39.7	31.6						
drain 11	144	17494	0.7	34.17									
RJV 097 12	23	17517	0.7	34.21		46.2	26.6						
drain 13	144	17661	0.7	34.49		53.5	33.3						
RJV 098 14	25	17686	0.7	34.54		55,750	6/12	stop @ 15:02, start 5/14 @ 15:02 ~~MAY 15~~ MAY14_0					
drain 15	144	17830	0.7	34.82									
RJV 099 16	19	17849	0.5	34.86		49.0	21.0						
drain 17	144	17993	0.77	35.14									
RJV 100 18	21	18014	0.6	35.18		51.0	13.9						
drain 19	144	18158	0.6 5m	35.46									
RJV 101 20	18	18176	0.5	35.50		55.5	12.4						
drain 21	144	18320	0.7 5m	35.78									
RJV 102 22	22	18342	0.6	35.82		64.0	7.4						
drain 23	144	18486	0.7	36.11									
RJV 103 24	25	18511	0.7	36.15		66.5	6.5						
drain 25	144	18655	0.7	36.44									
RJV 104 26	26	18681	0.7	36.49		78.0	3.95						
drain 27	144	18825	0.7	36.77									
RJV 105 28	25	18850	0.7	36.82		89.0	3.80						
drain 29	144	18994	0.7	37.10									
RJV 106 30	25	19019	0.7	37.15		94.0	4.50						
drain 31	144	19163	0.7	37.43									

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MPERT01-09-14

AMPAD EFFICIENCY LINE® 22-210

Column Rejuvenation Rate

outflow/tube	Vol (ml)	Cum vol(ml)	(ml/min)	PV (1=512)	Color	Ca (mg/L)	Fe (mg/L)	
RJV 107	15	19178	0.4	37.46	clear	98.5	4.75	
drain	82	19260	0.4	37.62				
RJV 108	15	19275	0.4	37.65		102.0	3.40	
drain	82	193[illegible]	0.4	37.81				
RJV 109	28	19385	0.8	37.86	rust ppt.	127.5	33.5	
drain	164	19549	0.8	38.18				
RJV 110	16	19565	0.4	38.21		110.0	4.45	
drain	82	19647	0.4	38.37				
RJV 111	3	19650	0.09	38.38		110.0	5.93	shut down - Column tubing
drain	18	19668	0.09	38.41				plugged.
RJV 112	3	19671	0.09	38.42				
drain	18	19689	0.09	38.46				
RJV 113	2	19691	0.06	38.46				
drain	12	19703	0.06	38.48				
RJV 114	1	19704	0.03	38.48				
drain	6	19710	0.03	38.50				
RJV 115	1	19711	0.03					
drain	6	19717	0.03	38.51				
RJV 116	1	19718	0.03					
drain	6	19724	0.03	38.52				
RJV 117	1	19725	0.03					
drain	6	19731	0.03	38.53				
RJV 118	1	19732	0.03					
drain	6	19738	0.03	38.54				
RJV 119	1	19739	0.03					
drain	6	19745	0.03	38.56				
RJV 120	<1		Ø					
drain	—							
RJV 121	<1							
drain	—							
RJV 122	<1							

EFFICIENCY LINE® 22-210

Rejuvenation Batch Tests

MPERT 01-10-01

5/4/2/03 ODL 19:41 Made 500 mL of NaOAc Buffer (Jackson recipe)
41 g NaOAc and 13.5 mL glacial Ac. Acid in 500 mL

20:00 pH of NaOAc Buffer = 4.95 (Should be 5 - close enough)
Testing to see if NaOAc Buffer ~~removes calcite from ZVI~~ w/o removing Fe

	Tube #	Cast/ZVI (g)	Calcite Powder (g)	NaOAc Buffer	Start Time		Stop Time		Time Shake (HR)	Ca mg/L	Fe mg/L	Final pH
RJV-B1	1	0	50 mg	50 mL	2016 4/2/03		4/3/03	10:22	~14	352*	1.01	5.01
RJV-B2	2	2.0	0	↓	↓		4/3/03	10:22	~14	102	2650	5.10
RJV-B3	3	2.0	0				4/3/03	16:54	~20	92	3270	5.14
RJV-B4	4	2.0	0				4/4/03	11:38	~39	76	6020	5.36

*Dissolved 17 mg (of 50) ~~dis~~

5/4/3/03 Tubes # 2, 3, 4 (those w/ gran ZVI) had pressured up and leaked slightly
Removed # 1, and 2 Centrifuged @ 3820 rpm for 22 mins. Decanted ~15 mL and Added 100 µL conc HNO_3
Appears to be a small amount of powder in Tube 1 (why didn't it pressure up?)
Must be H_2 that is causing P buildup.

pH of Conc. Glacial Acetic Acid = 0.25. Does not fizz when powdered calcite added

16:54 Tubes 3 and 4 pressured up and leaked - released pressure
Centrifuged tube 3 20 min @ 3820 rpm. Preserved (after decanting) with 100 µL HNO_3

1731 Made EDTA Solution 100 mg EDTA in 50 mL DI (~0.005 M). Looks like
RJV-B5 it dissolved immediately. pH = 10.57 Added 100 mg powdered $CaCO_3$.
Placed on stir bar 1737. Cloudy (i.e. $CaCO_3$ has not dissolved)

5/4/4/03 1138 Tube #4 had pressured up and leaked again
Centrifuged Tube #4, EDTA + $CaCO_3$, and HOAc + Calcite 20 min @ 3820 RPM

RJV-B5 EDTA + Calcite: There is undissolved powder in the EDTA pH = [illegible] Ca = 175 mg/L Fe = 0.4

RJV-B6 HOAc + Calcite: " " " " " " HOAc pH = 0.28 Ca = 50 mg/L Fe = 1.01

MPERT 01-10-02

5/5/03 0701 Tubes 2, 3, 4 (w/ grav ZVI), after centrifugation have turned red

RJV-B1 * NaOAc Buffer (50 mL) had 352 mg/L Ca

$0.050 L \times \frac{352 mg}{L} = 17.6 mg$

$17.6 mg\ Ca \times \frac{100 mg\ CaCO_3}{40 mg\ Ca} = 44 mg\ CaCO_3$ $\left(\frac{44}{50} = \underline{88\%} \text{ dissolved}\right)$

RJV-B5 EDTA (50 mL) had 175 mg/L Ca

$0.050 L \times \frac{175 mg}{L} = 8.75 mg\ Ca$

$8.75 mg\ Ca \times \frac{100 mg\ CaCO_3}{40 mg\ Ca} = 21.9 mg\ CaCO_3$ $\left(\frac{21.9}{100} = 21.9\%\right)$ Dissolved

5/7/03 0645 Made Solution of EDTA, tetra sodium salt Baker I 693-7

FW = 416.2 $(NaOCOCH_2)_2NCH_2CH_2N(CH_2COONa)_2 \cdot 2H_2O$

0.25 M = 0.25 × 416.2 = 104 g/L

0.10 M = 41.62 g/L

MADE 1 L of 0.10 M. Solution has yellow cast. pH = 10.85

	0.1M EDTA	gr AV/ZVI	START* Time	START** pH	Conc HCl added (mL)	End Time	Final pH	Ca (mg/L)	Fe (mg/L)	[illegible]
RJV B7	50 mL	2 g	[illegible] 0753	10.85	0	[illegible] 1640	11.02	145	84	9
RJV B8	50 mL	2 g	0753	9.05	270	"	9.70	242	940	"
RJV B9	50 mL	2 g	0753	6.88	550	"	8.25	142	1165	"

* End over End

** Solution – no grav/ZVI

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MPERT 01-10-03

5/7/03 1640 Removed RJV B7 - B9 from shaker. Centrifuged 20 m at 3780 RPm
No pressuring (ie no leakage, no swelling caps)

5/8/03 0725 Prepared new leach tests:

	0.1M EDTA	Material (1g each)	Start Time	Stop Time	Shake Time (hr)	Final pH	Ca (mg/L)	Fe (mg/L)
RJV B10	50 mL	$CaCO_3$ Powder	5/8/03 0742	5/9/03 01516	7.5	11.11	5820	0.36
RJV B11	↓	ZVI -6 +10 (Mont)	↓	↓	↓	11.13	1.67	80
RJV B12	↓	~~Fe_2O_3~~ Hematite Fisher	↓	↓	↓	10.76	2.38	1.21
RJV B13	50 mL	Magnetite ACE	↓	↓	↓	10.85	15.4	4.88

ALL tubes had residual solids after treatment.
1516 D/C Samples from shaker. Centrifuged 3780 RPM 22 mins

0.1 M NaOAc FW = 82.03 (ALDRich 241245) 8.2 g/L made 1L, pH = 7.32

5/9/03 Analyzed Ca and Fe.

(different concentrations)
5/10/03 0735 Made new batches with EDTA + 1g Calcite powder + 1g ZVI -6 +10 (Mont). End over End

	50 mL	1g Calcite	1g ZVI	Start Time	Stop Time	Shake Time (Hr)	Final pH	Ca (mg/L)	Fe (mg/L)
RJV B14	0.1 M EDTA	↓	↓	5/10/03 0800	5/11/03 1213	28	11.11	3450	5.20
RJV B15	0.05M EDTA	↓	↓	↓	↓	↓	11.06	1970	4.10
RJV B16	0.025M EDTA	↓	↓	↓	↓	↓	10.90	930	2.50
RJV B17	0.1 NaOAc*	↓	↓	↓	↓	↓	9.64	10.4	0.69

*pH 7.32 (no HOAc)

5/11/03 1215 D/C shaker. Centrifuged 40 min @ 3780 RPm

Phase II – Rejuvenation Extractions

MPERT 01-10-04 ~~P.T~~

9/30/03 Set up. Precision Model 25 Temperature controlled shaker bath. Using 50 mL-glass erlenmeyer flasks. Bath will hold up to 16 flasks. Powdered NOAH AFO (DRIED) in MORTAR/PESTLE. This (DRIED NOAH AFO) WAS MADE 9/18/00 BY DRYING NOAH AFO SLURRY ON BREAD PANS. MADE SOLUTION OF 0.2M Ammonium oxalate and 0.2M oxalic acid. Mixed these together (see ESL Proc.) to yield pH 3 (400 mL Am-Ox + 300 mL Ox Acid). Call this Amm. Oxalate-pH3. Set temperature bath to 25°C (distilled H_2O – SAYS not to use DEIONIZED H_2O). EDTA (0.1 M) Solution was made 5/7/03 from Baker EDTA Tetrasodium Salt Dihydrate. pH = 10.71; cond = 18,470 µS/cm

Amm Oxalate-pH3 cond = 20,300 µS/cm

Flask	Sample No. (40mL)	Liquid (40mL)	Solid (0.5 g)	pH initial	pH final	Cond initial (µS/cm)	Cond final (µS/cm)	Ca (mg/L)	Fe (mg/L)	Eff. Color	Shake Time	Te…
1	RE-1	~~0.1 M EDTA~~ Na Dithionite	NOAH AFO Powder	~~10.74~~	5.85	~~18,470~~	16,130	21.0	434	clear	2 hr	[illegible]
2	2	↓	Hematite Powder	4.53	4.83	15,600	15,960	0.40	260	lgt susp. pink	↓	↓
3	3		MAGNETITE powder	↓	4.11	↓	15,960	2.12	204	Clear		
4	4		Fisher 40 mesh ZVI		3.75		15,910	0.26	140	Clear		
5	5	↓	CALCITE Powder	↓	4.22	↓	16,070	170	0.50	Clear		
6	6	0.2M Amm. Oxalate - pH3 (in dark)	NOAH AFO Powder	3	3.18	20,300	20,100	<0.1	394	green/yel.		
7	7		Hematite Powder		3.05		20,100	0.31	~~<0.1~~ 19.1	pink		
8	8		magnetite powder		3.13		20,100	0.45	~~19.1~~ 344	lgt. green		
9	9		Fisher 40 mesh ZVI		3.12		20,200	0.18	98	"		
10	10	↓	Calcite Powder	↓	3.14	↓	20,200	0.50	0.48	clear	↓	↓

STARTED SHAKE 10/1/03 @ 0644 * Shaker bath keeps them in the dark

Stopped 10/1/03 @ 0844 Shaken at 60 RPM

Solid MATERIALS

(17) NOAH AFO Powder – see above

(29) Hematite Powder – Fisher Fe_2O_3 Ferric Oxide Red-Anhydrous I116-3, XRD confirmed hematite

(37) MAGNETITE Powder – ACF A-310, magnetic ferric oxide, Black; XRD confirmed as magnetite

(44) Fisher 40 mesh ZVI – Fisher Iron metal, Filings About 40 mesh, I57-500

(59) CALCITE powder – Aldrich 23,921-6 $CaCO_3$; confirmed as calcite by XRD

Made 0.1 M Sodium Dithionite Cond = 15,600 µS/cm, pH = 4.53

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MPERT 01-10-05 P.2

10/1/03

0844 Stopped shaker bath. Decant into 50mL plastic centrifuge tubes.
Centrifuged 20 m @ 3500 RPM

Analyzed for Ca and Fe by AA

EFFICIENCY LINE® 22-210

Rejuvenation Tests

MPERT 01-10-06

10/2/03

0813 Prepared 0.3M Na-citrate (pH = 8.40); 1M $NaHCO_3$ (pH = 7.95)

Mixture of 200mL 0.3m Na-citrate + [illegible] $NaHCO_3$ (pH = 8.16)

Mixture of 200mL 0.3m Na-citrate + 25mL 1m $NaHCO_3$ + 3.917g Na Dithionite (pH = 6.98)

Fizzes when dithionite is added (0.1M [illegible])

Flask	Sample No.	Liquid (40mL)	Ratio	Solid*	pH^i	pH^f	Ca (mg/L)	Fe (mg/L)	Shake Time (hr)	Controlled Temp.
1	RE-11	0.3m Na-citrate + 1m $NaHCO_3$	(40mL) (5mL)	NOAA AFO [illegible]	[illegible]	8.49	63.0	[illegible]	[illegible]	25°C
2	-12	↓		Hematite Powder	↓	8.41	2.08	0.58	↓	↓
3	-13			Magne[illegible]		8.44	16.4	1.45		
4	-14			Fisher 40mesh ZVI		8.57	1.44	68		
5	-15			Cal[illegible]		8.68	246.5	0.15		
6	-16	Same as RE-11 - 15 but + 3.917g Na-Dithionite		NOAA AFO Powder	6.98	7.44	62.8	1050		
7	-17	↓		Hematite Powder	↓	7.19	2.41	405		
8	-18			Magnetite Powder		7.08	13.0	235		
9	-19			Fisher 40mesh ZVI		7.08	1.49	150		
10	-20			Calcite Powder		7.13	209	0.40		

* See previous day chart for product designations

0841 Start shaking in T-controlled bath 60 RPM

1041 Stopped shaker. Decanted into 50mL plastic centrifuge tubes. Centrifuged 20min @ 3500 RPM

RE-16 AFO w/ dithionite turned brown (Fe being reduced); however, hematite RE-2 does not appear to have been reduced.

MPERT 01-10-07

10/3/03

Made 0.05 M EDTA Tetrasodium salt solution (20.81 g/L) pH = 10.92

Made mixture of 0.05M EDTA 50% and 0.1 M Na-Dithion. 50% pH = 6.97

Flask	Sample No.	Liquid (40mL)	Solids*	[illegible]	[illegible]	Ca mg/L	Fe mg/L	Shake [illegible]	Controlled [illegible]
1	RE-21	0.05M EDTA (Tetra)	NOAH AFO Powder	10.93	10.61	52.5	11.2	2	25°C
2	-22	↓	Hematite Powder	↓	10.79	1.88	0.66	↓	↓
3	-23	↓	Magnetite Powder	↓	10.82	7.9	1.22	↓	↓
4	-24	↓	Fisher 40 ZVI	↓	[illegible]	1.45	24.0	↓	↓
5	-25	↓	Calcite Powder	↓	10.92	288	0.14	↓	↓
6	-26	200 mL 0.05 EDTA + 65mL 0.1 M Na-Dith	NOAH AFO Powder	9.17	9.30	4.3	12.5	↓	↓
7	-27	↓	Hematite Powder	↓	9.25	1.76	0.64	↓	↓
8	-28	↓	magnetite Powder	↓	9.33	5.8	1.45	↓	↓
9	-29	↓	Fisher 40 ZVI	↓	9.37	1.16	107.5	↓	↓
10	-30	↓	Calcite Powder	↓	9.36	226	<0.1	↓	↓

Started shaking (60 RPM) 0704 10/6/03. Stopped 0904 (2Hr). Decanted Centri. @ 3500 RPM, 20 min Decanted

10/09/03 0839 Titration of 0.1 M EDTA (Tetra) w/ 0.1 M Na Dithionite (Start w/ 200 mL of EDTA)

Added	Vol Na Dith (mL)	pH	Add.	Cum	pH	Add	Cum	pH
0	0	10.74	5	20	10.13	10	90	9.36
1	1	10.70	10	30	9.97	10	100	9.28
2	3	10.60	10	40	9.84	10	110	9.20
2	5	10.53	10	50	9.73	20	130	9.02
5	10	10.36	10	60	9.63	20	150	8.83
5	15	10.24	10	70	9.54	20	170	8.59
			10	80	9.45	20	190	8.26
						10	200	8.07

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MPERT - 01 - 10 - 08

10/6/03 Made 200 mL 0.05 EDTA (Tetra-Na) + 65 mL 0.1M Na-Dithionite (pH = 9.17)
This solution is based on the titration (See MPERT-01-10-07) to achieve approx. pH 9. The thought is that since EDTA (pH 10.93) is effective at removing Ca but also removes some Fe; perhaps by adding a reductant (Na-Dith) the proportion of Fe corrosion would be reduced.

10/7/03 Made solutions for next tests:
Soln 10-7-1 1M Hydroxylamine Hydrochloride in 25% Acetic acid (See Landa 1982)
pH = 1.48
Soln 10-7-2 200 mL 0.3M Na Citrate, 25 mL 1M K_2CO_3, 3.917 g Na-Dithionite
pH (before Na Dith) = [illegible]
pH (After Na Dith) = 9.70

Start Shaker @ 15:35 10/7/03
Stop Shaker @ 17:35 10/7/03

Flask	Sample No	Liquid (40 mL)	Solid*	pH^i	pH^f	Ca (mg/L)	Fe (mg/L)	Shake Time	controlled T °C	
1	RE-31	200 mL 0.3M Na Citrate 25 mL 1M K_2CO_3 3.917 g Na-Dithionite	NoAH AFO Powder	9.70	8.58	36.6	378	2 hr	25	
2	-32	↓	Hematite Powder	↓	8.56	1.46	69	↓	↓	
3	-33	↓	Magnetite Powder	↓	8.63	4.38	75	↓	↓	
4	-34	↓	Fisher 40 mesh ZVI	↓	[illegible]	0.85	100	↓	↓	
5	-35	↓	Calcite Powder	↓	8.44	23.4	0.75	↓	↓	
6	-36	1M Hydroxylamine hydrochloride in 25% Acetic Acid	NoAH AFO Powder	1.48	1.52	46.8	185	↓	↓	
7	-37	↓	Hematite Powder	↓	1.32	0.96	2.51	↓	↓	
8	-38	↓	Magnetite Powder	↓	1.33	3.37	13.3	↓	↓	
9	-39	↓	Fisher 40 mesh ZVI	↓	2.20	0.33	2160	↓	↓	
10	-40	↓	Calcite Powder	↓	2.67	5620	1.33	↓	↓	← Foamed - nearly overflowed

MPERT-01-10-09

10-9-03

Results to date suggest that EDTA is good at removing calcite but not good at removing Fe-oxide corrosion products. Na-Citrate + Dithionite appears to be good at removing Fe oxides. High pH appears to minimize ZVI removal.

Therefore we will try mixing Na-Citrate EDTA and Dithionite.

10:03 Start with 200 mL EDTA (1M) pH = [illegible]
Added 4g Na-Dith, pH = 9.13
Added 100 mL EDTA (1M), pH = [illegible]
Added 100 mL EDTA (0.1M), pH = 9.58
Added 1g EDTA, pH = [illegible]
Added 9g EDTA, pH = 9.69

Solution Composition:
400 mL EDTA, 41.62 g/L = 16.648 g
+ 10 g = 26.648 g EDTA
$\frac{26.648\,g}{.4\,L} = 66.62\,g/L \times \frac{mol}{416.2\,g} = 0.16\,M$ EDTA
$\frac{4\,g\,Dith}{.4\,L} \times \frac{mol}{174.1\,g} = 0.057\,M$ Dith

FLASK	Sample No	Liquid (40 mL)	Solid*	pH^i	pH^f	Ca mg/L	Fe mg/L	Shake Time	Controlled T °C
1	RE-41	0.1M EDTA (Tetra Na)	NOAH AFO Powder	10.95	10.66	59.5	10.8	2 hr	25
2	-42	↓	Hematite Powder	↓	10.80	2.15	0.53	↓	↓
3	-43	↓	Magnetite Powder	↓	10.85	9.0	1.76	↓	↓
4	-44	↓	Fisher 40 mesh ZVI	↓	10.97	1.6	26.6	↓	↓
5	-45	↓	Calcite Powder	↓	10.88	253	0.34	↓	↓
6	-46	0.16M EDTA (Tet. Na) 0.057 M Dith.	NOAH AFO Powder	9.69	9.21	37	167	↓	↓
7	-47	↓	Hematite Powder	↓	9.19	2.04	121	↓	↓
8	-48	↓	Magnetite Powder	↓	9.16	8.7	118	↓	↓
9	-49	↓	Fisher 40 mesh ZVI	↓	9.16	1.9	106	↓	↓
10	-50	↓	Calcite Powder	↓	9.20	182	0.53	↓	↓

Started shaker 12:41 10/9/03
Stopped " 14:41 10/9/03

EPAPRB drilling MPERT02-01-01 1

0745 6/19/03 Offset between PE5 + PE6, attempt to sample virgin material not sampled 2/02.
- Push w/ open tube to 9' - easy push
- Collapses to ~6' = DTW
- Push closed tube to 12' easy push
  - Pin released early during push
  - Pull + [illegible]

Push to 11.5 w/ closed tube — becomes difficult @ 11.5'
Pull pin [illegible] 11.5'.
Pushed to 15.5' — easy push

0850 Bedrock @ 14 ft
Collected PE5' samples ~12.1' to 14'.
Hole PE5' is 0.5' east of PE5.

0900 Offset rig ~1' north of original sample transect
Start PE4
0-3.5', discard soil backfill + dry iron
3.5-6.5' 1' recovery easy push with ZVI; collapse to 5.5'
~~6.5-9.5~~ closed tube
6-10' 6-inch recovery easy push
Closed pin push to 10' Pull pin @ 10/11
Push 10 to [illegible] [illegible], v easy @ ~13-14'
Bedrock @ ~13.8' gray/black mudstone

0945 Set up on ~~PE3~~ PE2
0-3.5 backfill to ~3' dry ZVI ~3-3.5'
3.5-6.5' Open tube push poor recovery ZVI + pea gravel mix
Rename hole PE-2'
3.5-6.5 ~~9.5~~ Closed tube push — Not difficult push.
6.5-7.5 [illegible] Pull pin to collect samples, Pull tools.
- Pin released [illegible]

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8/19/03

Continue PE2 – thread problems w/ top cap

1025 Resume

~~3.5–6.5 closed tube push to~~ abort too dense to push

1115 PE3 – 0–3.5' backfill to 3' dry ZVI 3–3.5

3.5–4.0 ~~open tube~~ discard

6.5–9.5 discard top 6" sample

9–12.5 discard top 6" sample

3 attempts to clean hole + drive w/ closed tube >12' not successful,

~~Ins~~ Insert 2.25 in probe rod to 7' then drive – no sampling tool.

1345 7–14' Recovered 4'

Saving sample from 12.5 to 14' ~~#6,7~~ 6,7,8

1400 Resume at PE2 2.25" rods w/o sampler

Drive to 14'

1500 Move to PE1 2.25" rod from ~4' to TD

Refusal @ ~9–10' w/ ~3' of sample in rod.

Retained single samples 7.5 to ~8' 6" compact/moist

ZVI/gravel

1630 Move to PE9 0-3.5 backfill discard

3.5–6.5 core [illegible]

6.5–9.5 sample

[illegible]

13.5–14 [illegible] sample

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MPERT02-01-03

8/20/03 Set up on PE-2~~1~~0 ~1' E of PE-9 Push to 6.5 discard

Sample 6.5-9.5

no sample 9.5-12.5

back to 9.5-~~12.5~~-14 BR@ 13.5

8/20/03 Setup on PE-13 (~6" So of original flag) push to 3.5 discard

Sample 3.5-6.5 per Paul M. 0-3

6.5-11 Samples 4-8

11-14 no recovery

11-14 trip back down hole Samples 9-11 Sample 9 short by 3"

1040 Set up on PE-12 (6" So of original flag) push to 3.5 ZVI @ 3'

0→3.5 discard

3.5→7 Samples 1-5

7-11 sampled

11-13 7-9 Block @ 13

1245 Setup on PE 11 (6" So of original flag) push to 3.5 discard

0→3.5 discard

3.5-6.5 ZVI @ 5 3 samples 1st day

6.5-10 5 samples #8 short sample

Trip back down - Stop @ 9' can't go further

Move 6" South PE 22 (offset per P. Mushovic)

attempt to go to 10' to duplicate PE11, refusal @ 9

D/C attempt.

Move 6" east (1' south, 8" east of original PE11 flag) PE23

0-3.5 discard

3.5-8 5 samples

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4

MPERT02-01-04

8/20/03 PE13 cont 12- 13.5 4 samples #13 @ 4" just tag bedrock @ 13.5

PE20 move 2' east of flag 0-3.5 discard
3.5-7 3 samples
into sand pack from TW14

PE24 move 24" south of PE20 0-3.5 discard
3.5-16.5 1-5 dug @ top ~2" fill discarded
6.5 10 6-10 6-9
10 - 13 11-16 10-16 16 ~2" tag BR ~1/2"

1625 PE19 as marked on map 0-3.5 discard
3.5-13 continuous coring
samples 1-7 orange @ top black @ bottom

1600 PE17 as marked on map 0-3.5 discard
3.5-13 ~~11 12~~ samples

8/21/03 PE16 as marked on map 0-3.5 discard
3.5-13 continuous push 15 SAMPLES

PE10 6" south of original mark 3.5-14 Continuous push 11 Samples

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MPERT02-01-05

8/21/03 PE14 0-3.5 discard
3.5-14 continuous push 6' core recovered 9 samples
6" south of original point 1st foot of core (top, samples 1,2) look like sandpack

PE15 6" south of original point
0-3.5 discard
3.5-14 continuous push 5' core recovery samples 1-8
some fine sorted sand 1st 2 samples

PE18 as marked on map (should be 6" inside ZVI) use continuous push,
no sample sleeves
0/3.5 discard
3.5-14 18 samples

PE7 as marked on map 0-3.5 discard
3.5-13.2 continuous core ~ 4' core recovered
8 samples

PE8 6" north of as marked on map. 9 samples

145 PEA1 Measure 0.5' W of ramp then 4' South then 3.8' W
set geoprobe @ 70°/60°

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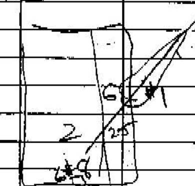
MPERT02-01-06

8/21/03 PEA1 cont. Continuous push for 12' recover 7.5 feet.

Bags 1-3 ZV1 3 ~~colds~~ contact c̄ G/ZV1 Short sample
4,5,6,7 G/ZV1
8 contact soil/G/ZV1



Renumber 1 = contact soil/G
2,3,4,5 G/ZV1
6,7,8 ZV1

send sampler c̄ sleeve @ 12'–16'

PEA2 core sample with sleeves. Take samples starting @ from Ground surface.
0.6' west RZM7, 4.6' South then 3.8' West

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MPERT02-01-07 7

8/22 Move to new location PEA ~~2~~ 3. Hole is 5.5' N of R1M7 60° angle
Effort is test of new dual well sampling tubes
Will push 1st 4' with 2" barrel.
put new runner assembly ~~dry~~ drive to 8' Only 1' recovery into Gravel
switch to 2" core c 1" tip. drive to 13' 4 samples
1 G/ZVI contact
2-4 ZVI

Move to PEA4 hole is 6' south, 1.5' east of RIM5 58° angle
continuous push from surface c 2" pipe, ~~[illegible]~~ to 11'6"
8 samples 1 = ~~soil~~
2,3 = soil/G interface
4-6 G
7,8 ZVI

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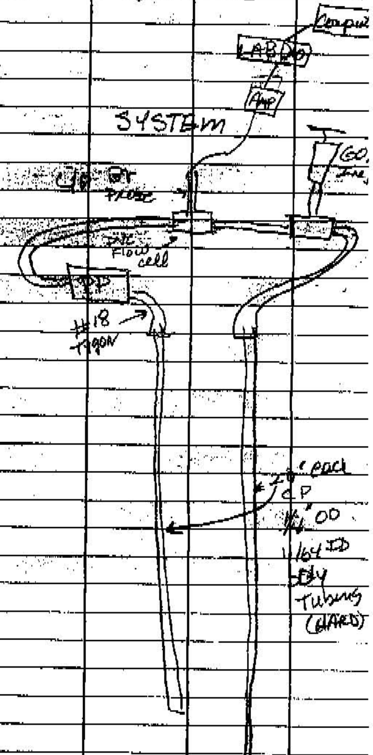
Monticello EAA - PHASE II
Borehole Dilution Tests MPERT02-02-01

8-13-03 Worked all day developing apparatus for tests. Got electrical interference from computer + mV meter w/ Orion data collect. Went to Vernier data collect system = no interference.

8-14-03 Calibration: File = ~~calibration Br1~~. Br probe #2 (Cole-Palmer)

Br Conc (in DI)	mV
0	+133
1	+133
10	+91
100	+31
1000	-25



First Trial
0835 LAB TEST of system File = "inLAB_2", 100 mL/min
Circulated tap water ~130 mV, fairly steady for 16 min
At ~~16~~ 18 min injected 60 mL of 10,000 mg/L Br
Ends of Tubes are separated by 5". Upflow, 1" PVC casing in 4" column. No sand - only H_2O.

~52 min - Removed outflow tube (to start dilution). Conc decreasing, apparently mixing was limited w/ water outside of pipe
70.6 min - Added TAP WATER (mV went down - hot tap water?)
91.8 min - added " "
~118 min - Added mQ
~165 - went Dry. Added mQ
~169 - start recirculation

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MPERT02-02-02

11:24 Calibration: File = Calibrate_Br2

Log Time (min)		Value (mV)
0 – 11	milli-Q	~170 (dropping)
11 – 17	1 mg/L Br	128
17 – 21	10 mg/L Br	90
21 – 24	100 mg/L Br	29
24 – 27.5	1000 mg/L Br	–26
27.5 – 30	10000 mg/L Br	–80
~30	10000 mg/L Br (E)	–81
30–33	10000 mg/L Br (F)	–81
	10000 mg/L Br (G)	–81
33 – 36	1000 mg/L	–28
36 – 41	MQ	+137
41 – 45	Cold TAP H_2O	+140
45 – 48	Hot TAP H_2O (cold)	+151

$(mV) = -55.2(\log Br) + 140.6$

$R^2 = 0.999$

12:22 2nd Trial: MQ, same set up as 1st Trial but up flow instead of down flow
File = INLAB 3 Probe #2 ~100 mL/min pump rate
Circulating (Log time 0 – 62 min; constant @ 138 mV)

Inject 60 mL of 10,000 mg/L Br @ 62 min. – as exact as possible
64.744 min = FIRST Arrival 2.44 min ≈ 244 mL of Dead Space (6" separation)
66.2 min = –40 mV Bottomed Out, (~2000 mg/L ?)

100 mins – removed outflow (start purging)
pushed inflow to bottom.

[illegible] mins – Added 2L MQ

MPERT 02-02-03

143 mins removed probe; Calibrate w/ 10 mg/L Br. 86 mV (not bad)
150 mins Back on Line. Went back to value before calibn. so appears to be functioning fine.

165 mins Added 3 1 L mQ Brought system to 114 mV (~8 ppm)
203 mins Added 3 L mQ

16:00 Check 100 mg/L Br calibration = 28.6 mV (good)

Start new Test (3rd Lab Trial) File = INLAB_4

14 min Inject 60 mL 10,000 mg/L (Probe came out (forgot to shut pump off))
45.3 min Removed Outlet Pushed Inlet to bottom - Start flush.

8/15/05 Tried an OMNI glass column for injection. The injection did not go as plug flow - there must be a preferential flow path through the middle. Need a smaller diameter

Tried using a coil of #15 Tygon

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MPERT02-02-04 (4)

8/18/03 0932 Start R5-M10 - BH dilution test. Water in surface casing - oil film.

CALIBRATION Probe #2 File = CALIBRATE_BR3

mg/L Br		mV		mg/L Br		mV	
0	nQ	140		1000	site water	-34	temp. slightly different
1	↓	125	stds kept on	10,000	"	-86	
10		81					
100		25	blue ice				
1000		-29					
10000		-82					
1000		-32					

$(mV) = -52.4 \log(Br) + 128.8$

$R^2 = 0.9986$

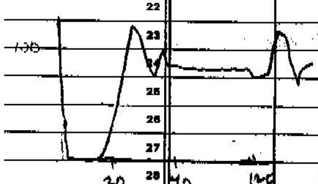
Inlet positioned at 14.4', outlet at 11.4' - ie testing top 3' of screen

Made site water standard. Water very grey (not filtered)

File = R5M10a Pump Rate 230 mL/min. Using syringe injector

~10:00 INJECT @ 10.7 mins. Contained red food color.
60 mL of 10,000 mg/L Br

112 mins Pushed in-tube to 16 ft (from 14.4)
We left the sampling tube in so will need to re do this one.



130 mins Pulled sampling tube out.
145 mins. Steady signal ~ -15 mV. Shut down.

Flushed tubing w/ DI to Decon

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MPERT02-02-05

(ie Top 3' of Screen)

13:30 R2/m10 Inlet 13', Outlet 10'1 230 mL/min File = R2M10a
Inject 60 mL 10,000 mg/L Br w/ Food color.
21.2 mins Injection of Br.

15:06 94.8 mins stopped -96 mV constant

Well R5mq9a Inject at 15.1 mins 15:31 60 mL 10,000 mg/L Br + red Food color
~~250~~ 230 mL/min, Top at 9.6' Bottom at 12.6' ie
Top 3' of screen. File = R5mq9a
61.7 mins Shut down 27 mV steady

16:25 Well R2mq File R2mq9a. Inj. 60 mL of 10,000 mg/L Br + red food color
Top at 9.6' Bottom at 12.6'. ie top 3' of screen.
Start Inj @ 20.0 min (16:45)

8-19-03 Calibration of Probe #2 [illegible]

Br (mg/L) DI	mV
0	139
1	124
10	78
100	21
1000	-34
10000	-85
[illegible]	-35

(mV) = -53 (Log Br) + 126.8
R^2 = 0.999

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MPERT 02-02-06

(6)

Well R5M8

0825 Start circulating. Start Data logger 0825. File = R5M8a. Probe #2

Log time 33.5 min 0859 — Inject 120 ml of 10,000 mg/L Br. + Red Food color

Injection at 12.9 ft, Outlet @ 7.9 ft (i.e. full 5' of screen)

~~1410~~ 1205 logtime 241.383 DC experiment

Well R2M8 probe #2 with Vernier. tubing @ 7.6' and 12.6' pump rate @ 230 ml/min

1250 Inject 120 ml @ 12.6' (with red food coloring) 10,000 mg/L Br

log time 9.5

1510 DC experiment logtime 148.480

Well R5M7

1515 Start circulating Start datalogger file R5M7a, Probe #2

1530 Inject 120 ml of 10,000 mg/L Br c̄ Red food color

Inject @ 13.11', outlet @ 8.11'

~~1530~~ logtime 12.999 inject.

1713 Stopped logtime ~ 118 min

Well R2M7a Probe #2, Injection 120 ml 10,000 mg/L Br + Food color

1723 Started circulating — Inlet at screen ~~top~~ bottom

1729 " data logger — Outlet at " top

[illegible] (log time = 8.0 min) (i.e. flow over entire screen)

1925 Shut down (log time ≈ 115 min)

MPERT02-02-07 (9)

8/20/03 Cal Probe 2 Calibrate_Br5

0920

	MV
MQ=0	145
1	130
10	80
100	20
1000	-33
10000	-82

0945 Start circulation R5M1 file = R5M1a. Start called 0947

1005 inject Logtime 18.115 inject 120ml 10,000mg/L Br c Red food color

pump set @ 230 ml/min (actual probably ~75ml)

1600 D/c Data collect Logtime 373

restart immediately to R5M1b @ 1602

1800 D/c data collect Logtime 117.496

8/21/03 Cal probe #2 Calibrate_Br6

	MV
MQ=0	146
1	~~176~~ 118
10	~~118~~ 71
100	~~71~~ 18
1000	~~18~~ -35
10000	-85

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Br Tracer

MPERT02-02-08

(8)

8/21/03 Start circulation R2M1 @8:57 file R2M1 start collected 0858

0907 Logtime 14.399 inject 120 ml 10,000 mg/L Br Red food color

pump set @ 230 ml min

1503 370.550 Logtime D/C R2M1 1505 Restart as R2M1 B.

1710 124.214 shutdown rain

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MPERT02-02-089 sm

(9)

8-27-03 CALIBRATION

[CALIBRATION-ORB] [CALIBRATION-BRB]

~11:00	BR	PROBE 2 (Output 1) 2R7)	PROBE 3 Output 2	PROBE 4 Output 3	PROBE 5 Output 4
	0	129	97	123	119
	1	129	103	160	161
	10	90	73	125	125
	100	37	24	58	58
	1000	-14	-30	27	25
	10000	-59	-77	-56	-56

(mV) = -48(Br) + 132.6 ; $R^2 = 0.9979$

(mV) = -46.3(Br) + 111.2 ; $R^2 = .9908$

~~(mV) = -55.2(Br) + 140.6~~ ~~$R^2 = 0.995$~~ → (mV) = -55.43(Br) + 168.8 ; $R^2 = 0.9928$

→ (mV) = -55.65(Br) + 169.4 ; $R^2 = 0.9934$

PROBE #1 is leaking fill soln.

Honda generator stopped. Running off Schlossu's power.

Raining

15:00 Stopped raining

15:19 Set up for 1st 4 tests. Joe went for electrical cords.

File = AUG27_1

Channel	well	Probe
~~4~~ 2	R5 M10	2
~~2~~ 1	R5 M9	3
3	R5 M8	4
4	R5 M7	5

~16:07 started circulating. The injector on R5M10 was left open so 60 ml went in.

17:13 (240 log time) exp. stopped

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8-28-03 0746 Set up for 4 wells. File = Aug 28-1 (Logger Pro file)

Channel	Well	Probe
1	R5 m9	2
2	R5 m8	3
3	R5 m7	4
4	R5 m6	5

0750 Started pumps ~~Log time 0.5~~.

0812 (Log time 12.5 at end of injection) Injected 120 mL of 10,000 mg/L Br into each well. Took about 2.5 mins. Started with R5 m9, then R5 m8, R5 [illegible] m6.

Pumps set at 220 mL/min. Channels 1&2 record data from 1 pump (2 heads per pump). Used 25' cable to connect Br probes to data acquisition module (Vernier) via electrode amplifiers.

R5 m6 appears to be getting lighter (less red - more pink) in color. Consistent with faster release [illegible]

12:24 (Log time 264 mins). Stopped experiment

13:14 (Log time 0) Started new test File = Aug 28-2 (Logger Pro file)

Channel	Well	Probe
1	R2 m9	2
2	R2 M8	3
3	R2 m7	4
4	R2 m6	5

13:31 (Log time 17.5). Injected 120 mL 10,000 mg/L Br (w/ red color) into each well. Started pumps at 1:31 (17.5)

R2 M8 and R2 M6 did not get nearly as red as the others. Consistent w/ less Br signals. Never mind! It just took longer.

14:08 (Los time 54) Probe 2 (channel 1) ran low on fill soln. Gave erratic signal. Refilled all probes

17:44 CALIBRATION BRQ

BR	Probe 2	3	4	5
0	148	9074	194	211
1	133	84	165	163
10	95	63	127	125
100	37	16	56	55
1000	-16	-34	-5.4	-5.6
10000	-63	-81	-59	-61

Probe	Equation	
#3	(mV) = -42.7(Br) + 95	$R^2 = 0.9836$
#2	(mV) = -50.3(Br) + 137.8	$R^2 = 0.9965$
#4	(mV) = -58.04(Br) + 172.8	$R^2 = 0.9933$
#5	(mV) = -57.96(Br) + 171	$R^2 = 0.9936$

8/29/03 Set up for 4 tests.

0814 (13.4 Los time) Injected 120 mL 10,000 mg/L Br (red) into each

0815 I had the valve turned wrong on channel 2. Line broke - repaired.

	Channel	Well	Probe
pink -	1	R5M5	2
deep orange -	2	R5M4	3
orange -	3	R5M3	4
some orange -	4	R5M2	5

File = aug29_1 (Logger Pro file)

R5M4 Color is deep orange (Fe?). R5M3 is also orange. R5M2 also but not as deep orange.

10:55 Stopped Test. (Los time 174)

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MPERT02-02-12 (12)

1125 New TEST

Channel	Well	Probe
1	R2 M5	2
2	R2 M4	3
3	R2 M3	4
4	R2 M2	5

File = aug29_2 (Logger Pro file)

11:33 (Log 58.3) Inject 120 mL 10,000 mg/L Br (red) into each well
There was some air going into R2M2. Subdued signal may be due to air bubbles causing high Br to go up the well.

14:53 (Log 208). Stopped.

CALIBRATION ~~BR10~~ CAL_BR10

Br	Probe 2	PROBE 3	PROBE 4	PROBE 5
0	124	66	174	195
1	125	68	144	151
10	87	55	119	120
100	33	13	51	52
1000	-19	-39	-5	3
10000	-69	-87	-64	-62

PROBE	Equation	R^2
2	(mV) = -49.4 (Br) + 130.2	R^2 = 0.9971
3	(mV) = -40.4 (Br) + 82.8	R^2 = 0.9665 *
4	(mV) = -54 (Br) + 157	R^2 = 0.9847
5	(mV) = -54.3 (Br) + 161.4	R^2 = 0.9888

* Use previous day's calibration!

EFFICIENCY LINE® 22-210

MPERT02-03-01

DP-1

Mont Peit Well Br⁻ tracer test: MEASUREments with Docoohole Probe

8/19/03	Cal Br probe #3				Hand-held meter 25' cord.					
0830	Br (mg/L)	DI	0850 mV	0920 mV	0950 mV	1344 mV	15:20 mV	1630 mV	1753 mV	
	MQ =		~~mV~~ 175	160	156	126			126	c. (mV) = -43.05 (Log Br) + 130.2 R^2 = 0.9883
	1		148	144	136	126			121	
	10		~~117~~	~~110~~	~~100~~	93		91	95	
	100		72	59	54	48	47	53	~~5~~1	
	1000		24	5	3.8	-1.8			0.5	
	10000		-18	-41	-42	-50			-47	
	1000	Site H_2O				b. (mV) = -44.68 (Log Br) + 132.4 R^2 = 0.9947				
						a. (mV) = -46.22 Log (Br) + 140.8 R^2 = 0.997				

Readings from Wells

DATE	Time	Well	Depth	mV	Br (mg/L)
8/19/03	0950	~~R2M109~~	10	185	0
		R5M9	12.5	250	0
			8	86	17
			7	90	14
	1003	R2M9	9	101	8
			11	268	0
			13	384	0
			14.5 (Bot)	554	0
	10:09	R5M10	7	19	~~25~~
			8	78	25
			9	76	28
			10	178	0
			12	182	0
			14	253	0
	10:14	R2M10	7	106	7
			8	103	8
			9	[illegible]	[illegible]
			10	216	0

Data Invalid! Interference

EFFICIENCY LINE® 22-210

DP-2

MPERT02-03-02

Date	Time	Well	Depth	mV	
8/19/03	14:02	R5M8	7	40	
			8	24	
			9	13	
			10	210	
			12	400	
			13	400	
	15:20	R2M8	7	40	
			8	40	Data invalid! Interference
			9	31	
			10	200↑	
			12	300↑	
			13	320↑	
	15:23	R5M8	7	60	
			8	54	
			9	39	
			10	196	
			12	340↑	
			13	375↑	

16:42 Tape the hand held Br Probe (#3) to the downhole Tygon pumping on ~~pt~~ R5M7 test. The probe (#3) read ~250 mV whereas the pumping probe (#2) read ~ -3 mV. There is an interference. Removed the metal rod that #2 was attached to and place electrical tape over the BNC connector. Reading now 28 mV for #3. (Still ~0.0 mV on #2.)

EFFICIENCY LINE® 22-210

DP-3

MPERT02-03-03

	Date	time	Well	Depth	mV
1	Date	time	Well	Depth	mV
2	8/19/03	17:27	R5 M7	7 ft	32
3				8	31
4				9	21
5				10	15.5
6				10.5	57
7		17:34	R5 M8	7 ft	42
8				8	40
9				9	35
10				10	59
11				11 –	65
12					
13		17:39	R2 M8	7	47
14				8	47
15				9	40
16				10	80 +
17				11	10.5 +
18				12	117 +
19					
20		17:44	R5 M7	7	31
21				8	31
22				9	32
23				10	69 +
24				11 –	100 +
25					
26					
27					
28					
29					
30					
31					

	Date	Time	Well	Depth	mV	11	12
1	Date	Time	Well	Depth	mV		
2	8/19/03	18:08	R5M8	7	39		
3		Screen		8	36		
4		7.9'-12.9'		9	29	mean = 48mV	
5		INT time =		10	58	(11.2 mg/L Br)	
6		8/19/03 08:59		11	57		
7		(9.2 hrs)		12	62		
8		since INJ	Bottom	13	23		
9							
10		18:12	R2m8	7	47		
11		Screen 7.6-12.6		8	58		
12		Inj @		9	52		
13		8/19/03 1250		10	105	mean = 91mV	
14		Time from Inj = 5.4		11	122	(12.6 mg/L Br)	
15				12	118		
16			Bottom	13	137		
17							
18		18:16	R5m7	7	31	242 mg/L Br	
19		Screen 8.1-13.1		8	33		
20		Inj @ 8/19/03		9	38		
21		1530		10	79	mean = 84mV	
22		Time from Inj =		11	103	(18 mg/L Br)	
23		2.76		12	122		
24				13	130		
25				13.5 Bottom			
26							
27		18:21	R5m9	7	58		
28		screen		8	51		
29		Inj @ 8/19/03		9	40		
30		1237		10	86	mean = 72.5 mV	
31		[illegible]		11	83		
		Time from Inj = 26.8		12	88		
				13	87	14.5	Bottom

EFFICIENCY LINE® 22-210

DP-4

MPERT 02-03-04

Date	Time	Well	Depth	mV		mV (Repeat)	
8/19/03	18:25	R2m9	7	92		92	
screen 9.6 – 14.6			8	85		86	
Circulation 9.6 – 12.6			9	75		83	
Inj. time:			10	139	drift		no
8/18/03 16:25			11	143	"		Good
			12	223	"		
			13	237	"		
			14	285	"		
			14.7 Bot	158			
	18:31	R2m10	7	80			
screen 10–15'			8	76			
Circulation 10–13'			9	61			
			10	90		97	
Inj. time =			11	93	mean =	~~87~~ mV	
8/18/03 13:30			12	109			
Time since Inj =			13	95			
29 hrs			14	111			
			15	110			
			15.5 Bot	102			
	18:34	R5M10	7	69			
screen = 11.4 – 16.4			8	68			
Circulation = 11.4 – 14.4			9	63			
			10	84			
Inj. time =			11	66			
8/18/03 10:00			12	66	Mean = 73 mV		
			13	77			
Time Since Inj =			14	83			
	20.3		15	103			
			16	123			

EFFICIENCY LINE® 22-210

a. (mV) = -45.02 (Br) + 143 R^2 = 0.9885

b. (mV) = -45.35 (Br) + 145.6 R^2 = 0.9908

c. (mV) = -44.7 (Br) + 148 R^2 = 0.9833

MPERT 02-03-05

DP-5

	1	2			5	6 Date	7 Time	8 well	9 depth	10 mV	11	12	13
8/20/03	CAL Br	PROBE #3				8/20/03	9:00	R2 M9	7 ft	93			
	Br (mg/L)	mV 8:15	mV 1345	mV 1720					8 ft	88			
8:	MQ	146	150	148					9	83			
	1	134	137	137					10	168			
	10	106	110	117					11	148			
	100	61	58	62					12	210			
	1000	3.8	8.5	10					13	236			
	10000	-40	-39	-33					14	281			
Date	Time	Well	Depth	mV		8/20/03	9:10	R5 M7	7	38			
8/20/03	8:36	R2-M10	7 ft	85					8	38			
			8	79					9	40			
			9	64					10	105			
			10	93					11	117			
			11	91					12	136			
			12	101					13	152			
			13	89									
			14	98		8/20/03	9:19	R2 M7	7	71			
			15	99					8	67			
									9	75			
8/20/03	8:44	R5 M10	7 ft	69					10	153			
			8	69					11	167			
			9	62					12	198			
			10	95					13	242			
			11	85									
			12	84		8/20/03	9:28	R5 M8	7	52			
			13	92					8	51			
			14	103					9	50			
			15	129					10	79			
			16	146					11	82.			
									12	91			
									13	63.			

EFFICIENCY LINE® 22-210

DP-6

MPERT02-03-06

	1 time	2 well	3 depth	4 mV	5	6	7 time	8 well	9 depth	10 mV	11	12	13
✓8/20/03	9:38	R2 M8	7 (ft)	87		✓8/20/03	11:40	R5M10	7	71			
			8	88					8	68			
			9	90					9	62			
			10	146					10	89			
			11	174					11	83			
			12	183					12	81			
			13 -	205					13	92			
									14	97			
✓8/20/[illegible]	9:42	R5 M9	7	62					15	113			
			8	53					16	123			
			9	42									
			10	84		✓8/20/03	11:55	~~R5M9~~	7	48			
			11	92				R5M7	8	50			
			12	100					9	52			
			13	101					10	110			
			14	122					11	122			
									12	138			
✓8/20/03	11:20	R2M10	7	73					13	150			
			8	67					14	?			
			9	51.									
			10	81.		✓8/20/03	12:[illegible]	R2M7	7	66			
			11	78					8	64			
			12	86					9	72			
			13	66					10	148			
			14	89					11	162			
			15	84					12	195			
									13	[illegible]			

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MPERT 02-03-07

DP-7

Date	1 Time	2 Well	3 Depth	4 mV	5	6	7 Date	8 Time	9 Well	10 Depth	11 mV	12	13
8/20/03	1230	R2M8	7	100			8/20/03	1530	R2M10	7	60		
✓			8	103			✓			8	46		
			9	100						9	32		
			10	155						10	172		
			11	185						11	173		
			12	200						12	199		
										13	197		
8/20/03	1252	R5M8	7	61						14	209		
✓			8	61						15	230		
			9	56									
			10	98			8/20/03	1600	R5M10	7	66		
			11	105			✓			8	62		
			12	119						9	54		
			13	97						10	126		
										11	119		
8/20/03	1307	~~R5M9~~	7	78						12	112		
✓		R5M9	8	68						13	123		
			9	58						14	140		
			10	103						15	130		
			11	107						16	150		
			12	116									
			13	123			8/20/03	1620	~~R5M9~~	7	75		
			14	152			✓		R5M9	8	66		
										9	58		
8/20/03	1318	R2M9	7	110						10	107		
✓			8	104						11	106		
			9	101						12	117		
			10	177						13	126		
			11	[illegible]						14	150		
			12	211									
			13	[illegible]									
			14	300									

EFFICIENCY LINE® 22-210

MPERT02-03-08

DP-8

Date	Time	Well	Depth	mV	5	6	Date	Time	Well	Depth	mV	12	13
8/20/03	1635	R2M9	7	114			8/20/03	1745	R2M7	7	77		
✓			8	107			✓			8	77		
			9	104						9	88		
			10	172						10	161		
			11	152						11	170		
			12	213						12	192		
			13	243						13	255		
			14	288									
8/20/03	1650	R2M8	7	119									
✓			8	121									
			9	119									
			10	166									
			11	192									
			[illegible]	209									
[illegible]	1705	R5M8	[illegible]	82									
✓			8	81									
			9	[illegible]									
			10	112									
			11	[illegible]									
			12	141									
			13	[illegible]									
8/20/03	1730	~~R5M9~~ R5M7	7	58									
✓			8	57									
			9	[illegible]									
			10	100									
			11	107									
			12	114									
			13	[illegible]									
			14	[illegible]									

EFFICIENCY LINE® 22-210

MPERT02-03-09

DP-9

2 $(mV) = \cancel{-31.371}\ -37.6\,(Br) + \cancel{103.13}\ 137 \quad R^2 = \cancel{0.9368}\ .871$ *used

3 $(mV) = -39.96\,(Br) + 158.26 \quad R^2 = 0.9854$

4 $(mV) = -42.7\,(Br) + 141 \quad R^2 = 0.9785$

5 $\cancel{mV = -56.9\,(Br) + 137.4 \quad R^2 = 0.967}$

	1	2	3	4	5
8/21/03	CAL Br PROBE #3				
	Br (mg/l)	mV 805	mV 1030	mV 1330	mV 1615
	MQ	131	155	124	125
	1	127	152	129	124
	10	110	131	111	113
	100	67	74	63	70
	1000	22	35	8	30
	10000	-17	0.7	-33	-19
Date	Time	Well	Depth	mV	
8/21/03	825	~~R5M10~~	7	45	
		R5M1	8	47	
			9	46	
			10	49	
			11	129	
			12	118	
			13	161	
			14	138	
			15	168	
	850	R2M10	7	87	
			8	73	
			9	61	
			10	83	
			11	94	
			12	103	
			13	85	
			14	94	
			15	88	

Date	Time	Well	Depth	mV
8/21/03	910	R5M10	7	93
			8	88
			9	80
			10	100
			11	92
			12	88
			13	92
			14	94
			15	103
			16	104
8/21/03	925	R5M9	7	73
			8	74
			9	68
			10	105
			11	98
			12	97
			13	100
			14	106
8/21/03	940	R5M8	7	97
			8	95
			9	73
			10	84
			11	77
			12	81
			13	50

EFFICIENCY LINE® 22-210

MPERT02-03-10 DP-10

Date	Time	Well	Depth	mV	5	6	Date	Time	Well	Depth	mV	12	13
8/21/03	1010	R5M1	7	40			8/21/03	1345	R5M1	7	29		
			8	40						8	27		
			9	40						9	27		
			10	42						10	39		
			11	103						11	151		
			12	92						12	140		
			13	110						13	158		
			14	119						14	171		
			15	138						15	204		
8/21/03	1045	~~[illegible]~~	7	82			8/21/03	1405	R2M10	7	113		
		R5M7	8	78						8	98		
			9	82						9	88		
			10	118						10	126		
			11	133						11	127		
			12	137						12	135		
			13	181						13	124		
										14	130		
8/21/03	1055	R2M7	7	81						15	126		
			8	88									
			9	103			8/21/03	1430	R5M10	7	92		
			10	139						8	85		
			11	149						9	77		
			12	172						10	98		
			13	193						11	92		
										12	94		
										13	104		
										14	110		
										15	122		
										16	136		

EFFICIENCY LINE® 22-210

MPERT02-03-11 DP-11

Date		1 Time	2 Well	3 Depth	4 mV	5	6	7 Date	8 Time	9 Well	10 Depth	11 mV	12	13
8/21/03	1	1450	RSM9	7	78			8/21/03	1600	~~RSM10~~	7	42		
	2			8	69					RSM1	8	42		
	3			9	60						9	42		
	4			10	86						10	43		
	5			11	84						11	110		
	6			12	84						12	100		
	7			13	98						13	107		
	8			14	107									
	9													
8/21/03	10	1510	RSM8	7	81									
	11			8	81									
	12			9	78									
	13			10	91									
	14			11	89									
	15			12	94									
	16			13	69									
	17													
8/21/03	18	1530	RSM7	7	78									
	19			8	81									
	20			9	83									
	21			10	134									
	22			11	145									
	23			12	186									
	24			13	214									
	25													
8/21/03	26	1545	R2M7	7	85									
	27			8	86									
	28			9	93									
	29			10	145									
	30			11	154									
	31			12	175									
				13	218									

EFFICIENCY LINE® 22-210

DP-12

MPERT02-03-12

$(mV) = -41.3(Br) + 140.8 \quad R^2 = 0.9936$

used this one

	1	2	3	4	5	6	7 Date	8 Time	9 Well	10 Depth	11 mV	12	13
8/22/03	CAL Br Probe #3			(mV) = -3[illegible]55(Br) + [illegible]			8/22/03	855	R2M10	7	63		
	Br (mg/l)	mV 805	mV 1445		$R^2 = 0.9967$					8	61		
	MQ	138	107							9	55		
	1	136	106							10	122		
	10	106	79							11	132		
	100	61	40							12	153		
	1000	11	1.5							13	144		
	10000	-23	-33							14	159		
										15	162		
Date	Time	Well	Depth	mV									
8/22/03	825	R2M1	7	52			8/22/03	905	R5M10	7	53		
			8	58						8	49		
			9	51						9	46		
			10	58						10	104		
			11	74						11	103		
			12	226						12	104		
			13	201						13	120		
			14	232						14	133		
			15	230						15	155		
										16	172		
8/22/03	845	R5M1	7	15									
			8	15			8/22/03	920	R5M9	7	56		
			9	11						8	51		
			10	20						9	44		
			11	225						10	115		
			12	242						11	120		
			13	265						12	130		
			14	272						13	150		
			15	305						14	175		

MPERT02-03-13 DP-13

Date	Time	Well	Depth	mV			Date	Time	Well	Depth	mV		
8/22/03	940	R5M8	7	60			CONT		R2M1	15	176		
			8	72									
			9	62			8/22/03	1035	R5M1	7	32		
			10	107						8	31		
			11	124						9	31		
			12	150						10	33		
			13	125						11	162		
										12	158		
8/22/03	1000	R5M7	7	71						13	176		
			8	71						14	199		
			9	74						15	235		
			10	138									
			11	163									
			12	195									
			13	212									
8/22/03	1010	R2M7	7	55									
			8	62									
			9	79									
			10	167									
			11	180									
			12	208									
			13	275									
8/22/03	1025	R2M1	7	32									
			8	30									
			9	27									
			10	46									
			11	164									
			12	156									
			13	141									
			14	184									

AMPAD EFFICIENCY LINE® 22-210

DP-14

MAERT02-03-14

8-27-03 CAL Probe #3

Br (mg/L)	mV 10:43
0	106
1	120
10	94
100	48
1000	-3.9
10000	-50

$(mV) = -43.79(Br) + 129.2 \quad R^2 = 0.9887$

note: B. Schlosser has been out yesterday and today slug testing northern wells

Date	Time	Well	Depth	mV	Probe
8-27-03	10:58	R5 M10	5'	54	3
			6	53	
Screen 11.4-16.4			7	51	
DTW = 4.9'			8	48	
			9	48	
			10	126	
			11	126	
			12	127	
			13	145	
			14	153	
			15	162	
			16	185	

Date	Time	Well	Depth	mV
8-27-03	11:14	R2 M10	5	73
Screen 10.4-15.4			6	72
DTW = 4.85			7	71
			8	70
			9	71
			10	140
			11	151
			12	165
			13	165
			14	155
			15	150

AMPAD EFFICIENCY LINE® 22-210

MPERT 02-03-15

DP-15

DATE	Time	Well	Depth	mV
8/27/03	11:25	R5m9	5	62
			6	63
Screen 9.6 - 14.6			7	63
DTW =			8	63
			9	63
			10	123
			11	126
			12	134
			13	136
			14	145
8/27/03	11:35	R2m9	5	108
			6	114
Screen 9.7 - 14.7			7	115
			8	118
			9	124
			10	184
			11	165
			12	209
			13	233
			14	272

[illegible]	Time	Well	Depth	mV
8/27/03	11:45	R5m8	5	92
Screen 7.9 - 12.9			6	94
			7	96
			8	95
			9	106
			10	157
			11	164
			12	177
			13	104
8/27/03	11:52	R5m7	5	83
			6	83
Screen	8.1 - 13.1		7	83
			8	83
			9	81
			10	128
			11	134
			12	153
			13	170

EFFICIENCY LINE® 22-210

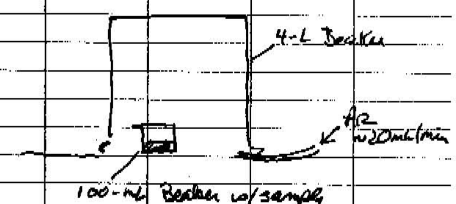
Monticello PRB MPERT02-04-01

Fissiom Track Analysis

9/15/03 CALLED Mike De Pangher. (Spectrum Petrographics). Mike out for the week. Talked to Bob (partner). They can probably cut the sections (or grind them) to fit 3/4" Triage tubes. Radioactivity in samples probably not an issue. Mike will call me Monday.

9/16/03 12:44 Placed 50% of sample PE 4-7 w/ Acetone in 100mL glass beaker. Inverted a 4L glass beaker and placed over it. Evacuating large beaker with Ar during drying. All under fume hood.

13:55 Added PE 5-10 and PE 6-9 to drying pan.



9/17/03 0738 Only PE 4-7 was dry. Argon ran out last night. This really doesn't work.

0740 Put small splits (~1g) of each sample PE 5-10, 6-9 and 4-7 on glass cover glasses. Added acetone to dilute H_2O that may be present. Let evaporate with fume hood fan on.

0818 Evaporation complete. Samples are dry.
Samples have a dull gray appearance. While wet, at least one sample had a distinctive H_2S odor. ZVI grains have disintegrated cf. original material (i.e. more fines); there are still many large laths and curls of ZVI however. Under a binoc scope the grains appear very corroded (dull gray color, sooty appearance). Also, there are occasional red brown rust spots on the surfaces

MPERT 02-04-02

10/20/03 Received polished thin sections back from Spectrum Petrographic
Samples were dried by flushing with acetone and then evaporating the acetone

Polished thin sections

Spectrum #	ESL #	Site	media	U (mg/kg)	R40 (Day ppm on)
OTA 001	PE 3-7	MONT ARB	ZVI/some GR	95.5	2160
002	PE 7-8	↓	G/Z	1210	11,000
003	PE 8-9	↓	G/Z	1640	7000
004	PE 11-8	↓	Z	2.1	nd
005	PE 17-11	↓	G/Z	345	3000
006	PE 18-17	↓	Z	5.6	nd
007	PEAFO 1-4	Fry Canyon	AFO	257.0	3000
008	PEAFO A2-6	↓	AFO	19.0	1000
009	PEZVI 1-2	↓	FILL/ZVI pellet	N/A	nd
010	PEZVI 2-6	↓	ZVI (Pellets)	1.1	nd
011	PE BC 1-4	↓	Pellet Bone char.	503.0	9000
012	PE BC 2-5	↓	Pellet Bone char.	144.0	7500

Irradiation dose is about
0.75 × 10^{16} n/cm^2
(for 1 hour of irradiation)

Notes: (1) U values were not known when selecting samples for fission tracking

11/26/03 Received samples back from USGS. M. Reed conducted rad survey.
Max counts on outside of cardboard box was 200 urem/hr. They were irradiated for 1 hour on lazy susan.

12/1/03 M. Reed survey of cardboard box. Max about 100 urem/hr
Opened box. Samples read up to 3 mRem/hr. Placed back in rad material storage at 1000.

Sarah Morris

From:	Stan Morrison
nt:	Wednesday, September 24, 2003 9:48 AM
:	Sarah Morris
Subject:	FW: Release of samples

-----Original Message-----

From:	Michael Hurshman
Sent:	Wednesday, September 24, 2003 9:06 AM
To:	Stan Morrison
Subject:	Release of samples

Stan, based on our surveys of the individual samples, they can be released without radiological controls. The surveys indicated values lower than our release limits.

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*****************************************************************************
*****  I N T E R F E R E N C E   C O R R E C T E D   R E P O R T       *****
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	Nuclide Name	Nuclide Id Confidence	Wt mean Activity (uCi/gram)	Wt mean Activity Uncertainty
	NA-24 15hr	0.431	2.081531E+003	6.078844E+001
?	CR-51 27da	0.992	4.208311E-002	4.664678E-003
	FE-59 44.5da	0.825	3.113260E-002	1.509375E-003
	AS-76 26hr	0.704	5.399611E+001	7.290850E-001
?	~~RH-105~~	0.543	7.799364E-001	8.573441E-002
	SB-122 2.7da	0.870	3.997373E-002	9.793491E-003
X	~~I-124~~	0.527		
	SB-124 60da	0.319	7.157738E-004	1.085697E-003
	~~TE-132~~	0.877	2.349579E-002	2.500721E-003
	~~CS-134~~	0.758	1.158076E-002	8.032226E-004

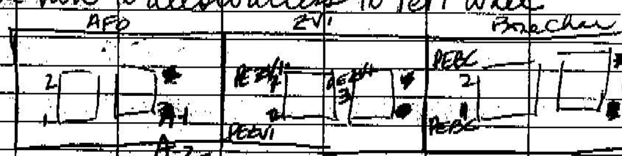
? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 1.000 sigma

Fry Canyon FCY01-02-01 8

8/22/03 1330 Arrive @ site. [illegible] here. Move van to allow access to Perf well

1530 Set up in barrier for drilling



PE-AFO-1

push to 4.5' discard
core to [illegible]" - bedrock 11.5'
5 samples 30" recovery
1,2 muddy
3-5 AFO gravel
3'3.5", 3"

PE-AFO-2

push to 4' discard
core to 11'

8/23/03 PE AFO-A1

push to 4' discard
push to 8.5' 3 samples
1 fill
2 fill } no sleeve
3 AFO
8.5 - 14' TOBR 4-9 al

PEAFO A2

push to 4.5' discard
4.5 - 9' discard 30"
1-3 [illegible]
4 [illegible]
22" recovery
9-13
4 samples 5-[illegible]

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FCY01-02-02 9

8/23/03 Move to ZVI Barrier

PE-ZVI-1 push to 4.5 fill discard
4.5-10' 3 samples 1 fill
2 fill ZVI contact
3 ZVI
4-6 ZVI
7 ZVI, plug B

PE-ZVI-2 push to 6 discard
6-11' @BR
1,2 fill
3 fill/ZVI contact
4-7 ZVI plug@end of 7

PE-BC-1 push to 6 discard
6-11 to BR 5 samples
1,2 fill
3 fill/BC contact
4,5 BC plug@end of 5

PE-BC-2 (w 10° angle) push to 6 discard
6-11 to BR - loose plug
1-3 fill
4 fill/BC contact
5 BC

EFFICIENCY LINE® 22-210

FCY01-02-03 10

8/23/07 Move to ZVI for 3rd hole

PE-ZVI-3 (Sample) push to 7 discard
7-11' present bentonite, al
abandon - no sample

move hole to between boxes @ front (Vertical Boring)

No angle push to 6 discard
6-9.7' 5 samples
1 fill
2 fill / ZVI contact
3-5 ZVI no plug

EFFICIENCY LINE® 22-210

Fry Canyon 8/22/03 - 8/23/03

FCY01-02-04

AFO Borings

PEAFO1

AFOT1
11" Left

AFOT3
39.25" Left

PEAFOA1
55°

AFOT2
16" Straight Back
19" Right

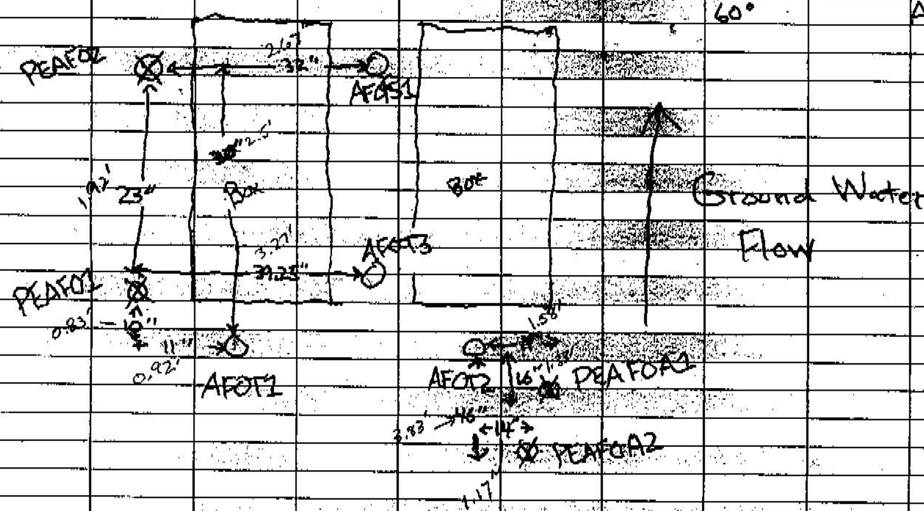
PEAFO2

AFOFS1
32" Left

AFOT1
30" Straight Forward

PEAFOA2
60°

AFOT2
46" Straight Back
14" Right



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Fry Canyon 8/23/03 FCY01-02-05

ZVI Borings

PEZVI1

ZVIFS1
39.25 Left

ZVIT1
26" Straight Forward

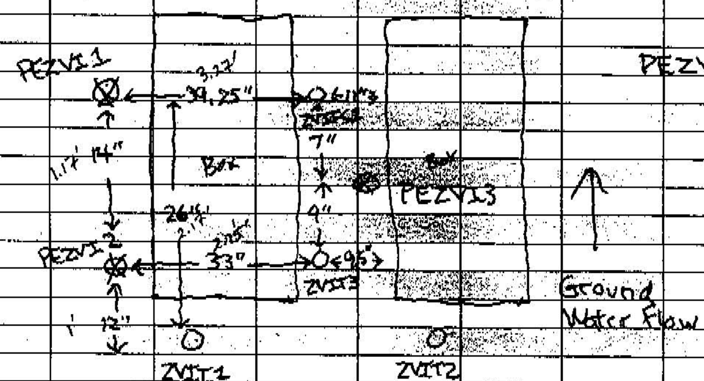
10" Left
0.83'

PEZVI2

ZVIT3
33" Left

ZVIT1
12" Straight Forward

10" Left



PEZVI3

ZVIT3
9" Straight Forward
9.5" Right

ZVIFS1
7" Straight Back
11" Right

Fry Canyon 8/23/03

FCY01-02-06

BC Borings

PEBC1

PO4FS1
31.5" Left

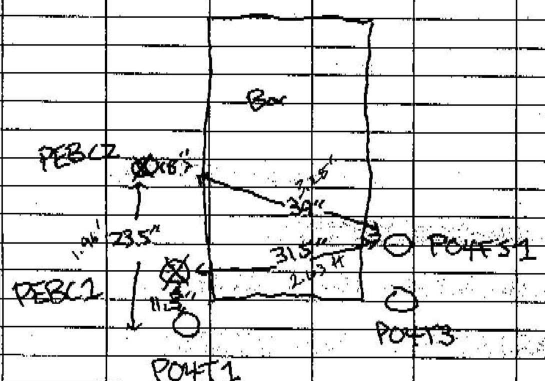
PO4T1
11.5" Straight Forward

PEBC2

PO4FS1
39" Left

PO4T1
23.5" Straight Forward

8" Left



Reactivity Tests P1

REACT001-01-01

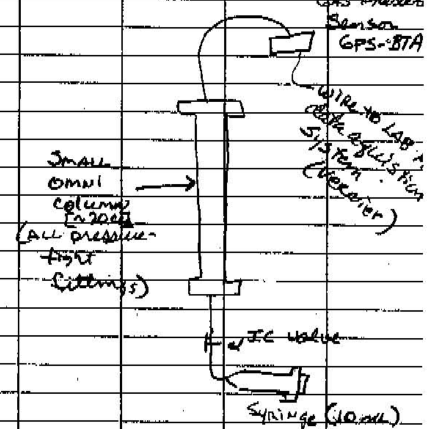
1/21/03 Runs #1 through #35 were made 12/30/02 → today.

Vol = 7 26 ml, Includes column and all tubing measured by injecting water into the system

0850 Pressure tested: Held at 30 psi for 30 min.

1/29/03 Continue tests (on angle cores)

All reactivity models have been calculated



3/26/03 Many runs have been made on Monticello samples.
They are filed in F: Home / Morrison / Reactivity Tests

Preparing solutions to treat ZVI to improve reactivity.
Under a microscope it is apparent that when treated with 5% HCl, a fresh ZVI sample (Peerless -10 from large sack in yard) has a short (~3 min) lag period with only a small amount of H_2 release. As time goes on the H_2 release increases substantially; however, there are portions of a single grain that have far less H_2 release than other portions. Is this due to an oxide coating; and can we remove the oxide coating?

0930 Prepared 0.1m (0.2N) Oxalic Acid solution 12.6 g of $H_2C_2O_4 \cdot 2H_2O$ crystals in 1L

0950 Prepared 0.2N H_2SO_4 (5.56 ml conc (36N) H_2SO_4 in 1 L)

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Reactivity Tests P.2

REACT001-01-02

3/26/03 10:32 20 mL of 0.2N Acetic Acid w/ 1g Peerless -8+20
20 mL of 0.2N H_2SO_4 "
20 mL of 0.2N Oxalic Acid "
20 mL of 10% HCl "

Placed in open 30 mL cent. tubes. Agitating back and forth.
After 10 mins capped and agitated end over end

1452 Removed from stir bar. HCl had major pressure buildup and smelled. Others did not build up pressure.

Effluent color

Oxalic	v. light gray green
H_2SO_4	gray green (darker) than oxalic
HCl	
Acetic	gray green, slightly brown?

1632 Decanted acids. Washed once with acetone. Transferred to tared cover glasses. Some solids lost.

DRIED Wgts (initially 1g each)

		Reactivity file
Oxalic	0.98g	Treat 1
H_2SO_4	0.86g	Treat 2
HCl	0.54g	Treat 3
Acetic	0.87g	Treat 4

Ran reactivity tests (see computer files)

4/11/03 Prepare the following in glass, round-bottom, screw top 30ml Centrifuge tubes

		Probe (File
Peerless -8 ~~+100~~ mesh ZVI	10g	1
Fisher iron Metal ~40mesh	10g	2
Mont RPMA 4-1	10g	3
Mont RPMA 4-3	10g	4

1515 Attach to Lab Pro Data logger set for q2 min collects x 96 hrs. Add 10ml MQ water

4/14/03 Switched probes (and caps) in #1 and #2 (to check if there is a problem with #1)
07:20 (Time = 64.2 hours on file)

1236 (69.367 hours) tapped and shook on Vial 1 (Peerless -8+20) to mix.
1249 Shook and tapped other 3 (69.600 hrs)

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EPA Reactivity

p4
REACT001-01-04

10/20/03 Obtain ~~200g~~ 100g fresh Cercona ZVI (foamed iron pellets). This is the ZVI that was used in the Fry Canyon PERT wall
Sieve to determine size fractions.

Sieve	Opening		Mass(g)
10	2mm	+10	61.5
18	1mm	✓ -10/+18	37.4
35	500mic	✓ -18/+35	0.8
140	106mic	-35/+140	0.3
200	75mic	-140/+200	<0.1
		-200	<0.1
			100

Obtain 100g split PE-ZVI-3-4. Spent ZVI from Fry Canyon Drilling 8/03.

	Mass(g)
+10	55.2
-10/+18	30.3
-18/+35	8.3
-35/+140	4.1
-140/+200	0.5
-200	1.6
	100.0

Retain splits of each fraction
Perform pressure tests on

		Run
Cercona:	-10/+18	171
	-18/+35	172
PE ZVI-3-4:	-10/+18	170
	-200	169

End of current text

Appendix B

Descriptions of Alluvium Samples from Monticello PRB

Core PEA1

Continuous push to 12 ft.

A sample of sticky gray clay was found in this core at a location that should be about 3 ft below grade and within 3 ft of the gravel/ZVI zone. (Tim has this sample that Paul collected)

Sample PEA1-1 (uppermost sample; the upper 3.5 ft or so of core was discarded): This sample was labeled soil/G in the field. It is a very small sample (about 50 mL) composed mostly of dark brown to almost black gravel with thick coatings of sticky, gray, mud (about 2 percent mud). Probably mostly alluvium.

Samples below this are gravel/ZVI and ZVI.

Core PEA2

The upper 7 ft of soil were discarded.

Samples PEA2 5-7: Loose silty sand, red brown. “Soil.”

Samples PEA2 8-10: Sticky gray clay (this was labeled “sluff” in field notes).

Samples below this are gravel/ZVI

Core PEA3

No alluvium was recovered.

Core PEA4

Continuous push from 0 to 11.5 ft.

Sample PEA4 –1: Loose soil

Sample PEA 4-2: Gravel. Dark brown. Contains piece of fabric (indicates boring penetrated the top, not the side, of the gravel/ZVI zone). No obvious clay.

Samples below this are gravel/ZVI (samples 3-6) and ZVI (samples 7 and 8).

Summary

Sticky gray clay was encountered in 2 of the 4 borings near or at the contact of alluvium with gravel/ZVI zone. It was not encountered in the other 2 borings but sample collection may have been inadequate. This evidence suggests there could be an impermeable clay zone at the contact, but the evidence is inconclusive.

End of current text

Appendix C

Results of Chemical Analysis of Monticello Cores
(see Figure 1 for locations)

Sample	Zone	Sample Date	Core Interval start ft	Core Interval end ft	Bottom Sample Depth ft	Radioactivity (dry) dpm	Moisture Content (wgt%)	Ca mg/kg	Fe mg/kg	U mg/kg
PE 2-7	G	8/19/2003	6.5	9.5	7.5	540	7.55	8250	141000	46.50
PE 2-10	G	8/19/2003	9.5	11.5	10.2	1620	6.61	15200	115000	255.00
PE 2-13	G	8/19/2003	11.5	12.5	12.0	3240	6.32	21700	116000	435.00
PE 2-14	G	8/19/2003	11.5	12.5	12.5	3780	8.04	30700	196000	359.00
PE 3-1	Z	8/19/2003	7	9.5	7.8	1080	16.01	10800	668000	78.50
PE 3-3	Z	8/19/2003	7	9.5	9.5	nd	21.85	28300	686000	11.50
PE 3-4	Z	8/19/2003	9	12.5	10.8	nd	18.33	38500	663000	62.70
PE 3-5	Z	8/19/2003	9	12.5	12.5	4860	19.26	32800	652000	186.00
PE 3-7	Z	8/19/2003	12.5	14	13.5	2160	7.74	16500	659000	95.50
PE 4-1	Z	8/19/2003	6	10	10.0	nd	19.29	19300	708000	2.00
PE 4-2	Z	8/19/2003	10	14	10.7	nd	18.71	16400	705000	0.10
PE 4-4	Z	8/19/2003	10	14	12.0	nd	21.44	24600	700000	0.19
PE 4-7	Z	8/19/2003	10	14	14.0	nd	20.29	50100	614000	0.15
PE 5-2	Z	8/18/2003	6.5	9.5	7.7	nd	19.32	19800	724000	2.00
PE 5-3	Z	8/18/2003	6.5	9.5	8.3	nd	16.37	21600	751000	3.20
PE 5-5	Z	8/18/2003	6.5	9.5	9.5	nd	17.45	26300	731000	0.58
PE 5-10	Z	8/19/2003	12.1	15.5	14.7	nd	21.80	35300	723000	0.02
PE 6-1	Z	8/18/2003	6.5	9.5	7.5	nd	17.31	18700	723000	0.02
PE 6-2	Z	8/18/2003	6.5	9.5	8.5	nd	18.66	24100	759000	0.02
PE 6-3	Z	8/18/2003	6.5	9.5	9.5	nd	18.07	16000	778000	0.02
PE 6-9	Z	8/18/2003	9.5	13	13.0	nd	19.77	33600	708000	0.02
PE 7-5	G	8/21/2003	3.5	13.2	9.6	3000	9.42	19800	236000	822.00
PE 7-6	G	8/21/2003	3.5	13.2	10.8	3000	9.05	19200	184000	392.00
PE 7-7	G	8/21/2003	3.5	13.2	12.0	10500	9.60	28800	227000	792.00
PE 7-8	G	8/21/2003	3.5	13.2	13.2	11000	57.28	34800	252000	1210.00
PE 8-4	G	8/21/2003	3.5	13	7.3	500	6.08	9100	181000	94.70
PE 8-7	G	8/21/2003	3.5	13	10.2	3500	9.04	29200	117000	563.00
PE 8-8	G	8/21/2003	3.5	13	11.1	7500	9.86	40000	132000	990.00
PE 8-9	G	8/21/2003	3.5	13	12.1	7000	11.49	23900	162000	1640.00
PE 9-3	G	8/19/2003	6.5	9.5	8.8	38500	20.52	27700	681000	1400.00
PE 9-4	G	8/19/2003	6.5	9.5	9.5	18500	11.66	38700	636000	968.00
PE 9-6	G	8/19/2003	9.5	13.5	11.1	7500	13.48	26600	220000	2020.00
PE 9-7	G	8/19/2003	9.5	13.5	11.9	6000	10.75	41500	208000	3330.00
PE 9-8	G	8/19/2003	9.5	13.5	12.7	13500	10.21	49600	161000	4630.00
PE 9-9	G	8/19/2003	9.5	13.5	13.5	18500	9.95	58700	365000	4100.00
PE 10-5	G	8/21/2003	3.5	14	8.3	1500	8.28	21700	192000	184.00
PE 10-6	G	8/21/2003	3.5	14	9.2	2500	9.85	41800	295000	354.00
PE 10-7	G	8/21/2003	3.5	14	10.2	2500	9.56	37300	261000	567.00
PE 10-9	G	8/21/2003	3.5	14	12.1	3500	12.37	68800	272000	515.00
PE 11-5	Z	8/20/2003	6.5	10	7.9	nd	21.88	42500	661000	11.60
PE 11-6	Z	8/20/2003	6.5	10	8.6	nd	21.61	46200	653000	2.70
PE 11-7	Z	8/20/2003	6.5	10	9.3	nd	23.18	43200	672000	7.90

Sample	Zone	Sample Date	Core Interval start ft	Core Interval end ft	Bottom Sample Depth ft	Radioactivity (dry) dpm	Moisture Content (wgt%)	Ca mg/kg	Fe mg/kg	U mg/kg
PE 11-8	Z	8/20/2003	6.5	10	10.0	nd	21.26	32900	711000	2.10
PE 12-5	Z	8/20/2003	3	7	7.0	nd	16.30	13600	746000	0.05
PE 12-6	Z	8/20/2003	7	11	11.0	nd	20.30	9320	754000	0.03
PE 12-7	Z	8/20/2003	11	13	11.7	nd	16.95	9000	763000	0.04
PE 12-9	Z	8/20/2003	11	13	13.0	nd	20.55	23700	664000	0.06
PE 13-5	Z	8/20/2003	6.5	11	8.3	nd	93.60	10000	702000	0.05
PE 13-8	Z	8/20/2003	6.5	11	11.0	nd	18.30	7310	747000	0.20
PE 13-9	Z	8/20/2003	11	14	12.0	nd	15.57	17000	759000	0.05
PE 13-10	Z	8/20/2003	11	14	13.0	nd	13.69	3080	766000	0.03
PE 13-11	Z	8/20/2003	11	14	14.0	nd	13.50	11500	770000	0.04
PE 14-4	G	8/21/2003	3.5	14	8.2	1000	9.07	13100	205000	274.00
PE 14-6	G	8/21/2003	3.5	14	10.5	4000	9.00	48000	212000	751.00
PE 14-7	G	8/21/2003	3.5	14	11.7	4000	10.34	58700	212000	931.00
PE 14-8	G	8/21/2003	3.5	14	12.8	1500	10.59	43400	222000	179.00
PE 15-3	G	8/21/2003	3.5	14	7.4	8500	11.50	7090	659000	289.00
PE 15-5	G	8/21/2003	3.5	14	10.1	2500	10.12	39800	280000	545.00
PE 15-6	G	8/21/2003	3.5	14	11.4	3500	9.23	42000	223000	483.00
PE 15-7	G	8/21/2003	3.5	14	12.7	2500	9.94	42500	209000	134.00
PE 16-8	G	8/21/2003	3.5	13.5	8.8	2000	9.46	24200	213000	117.00
PE 16-12	G	8/21/2003	3.5	13.5	11.5	3500	9.38	46800	236000	484.00
PE 16-13	G	8/21/2003	3.5	13.5	12.2	2500	9.16	43400	214000	135.00
PE 16-14	G	8/21/2003	3.5	13.5	12.8	6000	11.67	45100	261000	427.00
PE 17-5	G	8/20/2003	3.5	13.5	8.0	1000	8.41	15600	201000	151.00
PE 17-6	G	8/20/2003	3.5	13.5	9.0	500	8.01	19700	289000	91.90
PE 17-8	G	8/20/2003	3.5	13.5	10.8	6000	9.00	30200	215000	1190.00
PE 17-11	G	8/20/2003	3.5	13.5	13.5	3000	10.43	27900	104000	345.00
PE 18-4	Z	8/21/2003	3.5	14	5.8	500	14.01	6440	735000	10.00
PE 18-7	Z	8/21/2003	3.5	14	7.6	nd	13.95	19100	723000	0.47
PE 18-10	Z	8/21/2003	3.5	14	9.3	nd	17.06	17400	741000	3.00
PE 18-12	Z	8/21/2003	3.5	14	10.5	nd	16.50	24100	715000	5.10
PE 18-17	Z	8/21/2003	3.5	14	13.4	nd	16.36	30400	719000	5.60
PE 19-4	G	8/20/2003	3.5	13	8.9	4500	9.78	23700	244000	745.00
PE 19-5	G	8/20/2003	3.5	13	10.3	5500	13.19	28100	258000	747.00
PE 19-6	G	8/20/2003	3.5	13	11.6	2000	10.31	29000	187000	266.00
PE 19-7	G	8/20/2003	3.5	13	13.0	nd	10.46	31000	256000	34.50
PE 21-6	Z	8/20/2003	9.5	14	10.6	nd	12.04	5710	800000	0.09
PE 21-7	Z	8/20/2003	9.5	14	11.8	nd	13.99	26800	711000	0.23
PE 21-8	Z	8/20/2003	9.5	14	12.9	nd	13.46	9400	740000	0.25
PE 21-9	Z	8/20/2003	9.5	14	14.0	nd	16.89	16800	772000	1.30
PE 23-6	Z	8/20/2003	8	12	9.0	nd	18.95	18400	768000	0.20
PE 23-7	Z	8/20/2003	8	12	10.0	nd	20.42	14300	763000	0.43
PE 23-8	Z	8/20/2003	8	12	11.0	nd	21.55	16900	689000	0.44
PE 23-13	Z	8/20/2003	12	13.5	13.5	nd	20.49	38900	679000	11.80

Sample	Zone	Sample Date	Core Interval start ft	Core Interval end ft	Bottom Sample Depth ft	Radioactivity (dry) dpm	Moisture Content (wgt%)	Ca mg/kg	Fe mg/kg	U mg/kg
PE 24-8	Z	8/20/2003	6.5	10	8.6	nd	21.54	5350	606000	0.03
PE 24-11	Z	8/20/2003	10	13	10.5	nd	19.33	22500	721000	1.20
PE 24-12	Z	8/20/2003	10	13	11.0	nd	21.74	20700	734000	0.41
PE 24-13	Z	8/20/2003	10	13	11.5	nd	19.14	26100	737000	4.90
PE 24-15	Z	8/20/2003	10	13	12.5	nd	17.76	79900	475000	6.50

Zones: G = gravel/ZVI, Z = ZVI. nd = not detected, dpm = disintegrations per minute

End of current text

Appendix D

Reactivity Values for All Samples

0.2 g samples except where noted	Run No.	Zone	Mesh Size	Reactivity No.	Water Table
Standards					
Cercona Pellets, -10/+18 fraction	171	na	pellets	**2.6**	na
Cercona Pellets, -18/+35 fraction	172	na	pellets	**3.2**	na
Connelly 1004	9	na	-8 +50	**4.5**	na
Fisher	12	na	~40	**7.0**	na
Fisher	117	na	~40	**9.8**	na
Fisher	209	na	~40	**7.0**	na
Fisher	13	na	-100	**38.0**	na
Peerless	32	na	-6 +10	**4.3**	na
Peerless	14	na	-8 +50	**3.2**	na
Peerless	7	na	-60 +100	**9.5**	na
Peerless	11	na	-8 +18	**7.0**	na
Peerless	16	na	-8 +20	**3.5**	na
Peerless	90	na	-8 +20	**6.1**	na
Peerless	91	na	-8 +20	**4.5**	na
Peerless	92	na	-8 +20	**5.0**	na
Peerless	100	na	-8 +20	**4.0**	na
Peerless	101	na	-8 +20	**3.7**	na
Peerless	102	na	-8 +20	**3.8**	na
180 mg Peerless, 20 mg powdered calcite	114	na	-8 +20	**4.8**	na
Peerless New WSR	51	na	-8 +50	**4.7**	na
Peerless Traditional	52	na	-8 +50	**4.1**	na
Peerless, grav/ZVI parent	24	na	-4 +20	**1.5**	na
160 mg Fisher, 40 mg powdered calcite	123	na	~40	**9.1**	na
180 mg Peerless, 20 mg powdered calcite	114	na	-8 +20	**4.8**	na
50 mg Fisher	121	na	~40	**7.6**	na
Hematite	22	na	powder	**0.0**	na
Siderite	23	na	-18	**0.3**	na
a Corrected for 100 percent ZVI (0.2 g)					
TREATED ZVI Standards					
Peerless, treated with 0.2 N Oxalic Acid	86	na	-8 +20	**3.5**	
Peerless, treated with 0.2 N H2SO4	87	na	-8 +20	**5.4**	
Peerless, treated with10 percent HCl	88	na	-8 +20	**4.4**	
Peerless, treated with 0.2 N acetic acid	89	na	-8 +20	**6.1**	
MONTICELLO					
Feb 2002 Angle Core Samples					
RPMA 1-4	49	ZVI	-8 +20	**4.1**	Above
RPMA 1-5	50	ZVI	-8 +20	**2.1**	Above
RPMA 2-1	46	ZVI	-8 +20	**3.9**	Above
RPMA 3-1	43	ZVI	-8 +20	**3.5**	Above
RPMA 4-1	40	ZVI	-8 +20	**3.8**	Above
RPMA 5-1	55	ZVI	-8 +20	**3.6**	Above
RPMA 1-6	53	ZVI	-8 +20	**2.4**	Below
RPMA 1-7	54	ZVI	-8 +20	**2.5**	Below
RPMA 2-2	47	ZVI	-8 +20	**2.5**	Below
RPMA 2-3	48	ZVI	-8 +20	**1.7**	Below
RPMA 3-2	44	ZVI	-8 +20	**2.3**	Below
RPMA 3-3	45	ZVI	-8 +20	**2.5**	Below
RPMA 4-2	41	ZVI	-8 +20	**1.2**	Below
RPMA 4-3	42	ZVI	-8 +20	**1.8**	Below
RPMA 5-2	56	ZVI	-8 +20	**1.7**	Below

0.2 g samples except where noted	Run No.	Zone	Mesh Size	Reactivity No.	Water Table
MONTICELLO					
Feb. 2002 Verticle Core Samples					
RPM 64-1	66	grav/ZVI	-4 +20	**2.8**	Above
RPM 64-1, 2nd HCl	67	grav/ZVI	-4 +20	**2.3**	Above
RPM 64-1, 3rd HCl	68	grav/ZVI	-4 +20	**0.4**	Above
RPM 11-7, mag/sonic coarse split	25	grav/ZVI	-4 +20	**2.0**	Below
RPM 11-7, mag/sonic coarse split, acid wash	26	grav/ZVI	-4 +20	**2.0**	Below
RPM 42-7	28	grav/ZVI	-4 +20	**2.0**	Below
RPM 48-4, as run 62 but 2nd HCl	63	grav/ZVI	-4 +20	**0.7**	Below
RPM 48-4, mag split, red powder	31	grav/ZVI	-4 +20	**0.6**	Below
RPM 48-4, mag split, red powder, dup	62	grav/ZVI	-4 +20	**1.1**	Below
RPM 53-4, 2nd HCl	65	grav/ZVI	-4 +20	**2.1**	Below
RPM 53-4, strange curve	64	grav/ZVI	-4 +20	**3.1**	Below
RPM 65-5, 2nd HCl	70	grav/ZVI	-4 +20	**1.7**	Below
RPM 65-5, 3rd HCl	71	grav/ZVI	-4 +20	**0.9**	Below
RPM 65-5, not good fit	69	grav/ZVI	-4 +20	**2.5**	Below
RPM 10-11	39	ZVI	-8 +20	**3.4**	Below
RPM 10-2	35	ZVI	-18	**3.5**	Below
RPM 10-2	36	ZVI	-8 +20	**2.7**	Below
RPM 10-2, coarse	33	ZVI	+10	**1.4**	Below
RPM 10-7	37	ZVI	-8 +20	**3.0**	Below
RPM 10-9	38	ZVI	-8 +20	**2.0**	Below
RPM 13-2	72	ZVI	-8 +20	**4.5**	Below
RPM 13-5	73	ZVI	-8 +20	**3.3**	Below
RPM 13-6	74	ZVI	-8 +20	**3.1**	Below
RPM 13-7	75	ZVI	-8 +20	**3.5**	Below
RPM 16-1	77	ZVI	-8 +20	**4.2**	Below
RPM 16-3	78	ZVI	-8 +20	**3.7**	Below
RPM 16-4	79	ZVI	-8 +20	**5.4**	Below
RPM 16-5	80	ZVI	-8 +20	**4.8**	Below
RPM 61.2	81	ZVI	-8 +20	**3.7**	Below
RPM 61-3	82	ZVI	-8 +20	**3.7**	Below
RPM 61-6	83	ZVI	-8 +20	**4.8**	
RPM 61-8	85	ZVI	-8 +20	**5.0**	
RPM 61-8, cemented lump	84	ZVI	-8 +20	**5.0**	
MONTICELLO					
August 2003, Samples					
PE 2-7, oven dried, rad. Fines.	174	grav/ZVI	-4 +20	**0.0**	
PE 2-7, oven dried, rad. Fines.	178	grav/ZVI	-4 +20	**0.1**	
PE 2-10, oven dried, rad. Fines.	179	grav/ZVI	-4 +20	**0.3**	
PE 2-13, oven dried, rad. Fines.	180	grav/ZVI	-4 +20	**0.2**	
PE 2-14, oven dried, rad. Fines.	181	grav/ZVI	-4 +20	**0.6**	
PE 3-1, oven dried, rad. Fines.	182	grav/ZVI	-4 +20	**2.9**	
PE 3-5, oven dried, rad. Fines.	183	grav/ZVI	-4 +20	**3.7**	
PE 3-7, oven dried, rad. Fines.	184	grav/ZVI	-4 +20	**3.9**	
PE 7-5, oven dried, rad. Fines.	185	grav/ZVI	-4 +20	**1.0**	
PE 7-6, oven dried, rad. Fines.	186	grav/ZVI	-4 +20	**1.0**	
PE 7-7, oven dried, rad. Fines.	187	grav/ZVI	-4 +20	**0.6**	
PE 7-8, oven dried, rad. Fines.	188	grav/ZVI	-4 +20	**1.2**	
PE 8-4, oven dried, rad. Fines.	189	grav/ZVI	-4 +20	**0.5**	
PE 8-7, oven dried, rad. Fines.	190	grav/ZVI	-4 +20	**0.5**	
PE 8-8, oven dried, rad. Fines.	191	grav/ZVI	-4 +20	**0.6**	
PE 8-9, oven dried, rad. Fines.	192	grav/ZVI	-4 +20	**0.9**	
PE 9-3, oven dried, rad. Fines.	193	grav/ZVI	-4 +20	**3.1**	
PE 9-4, oven dried, rad. Fines.	194	grav/ZVI	-4 +20	**2.6**	
PE 9-6, oven dried, rad. Fines.	195	grav/ZVI	-4 +20	**0.1**	
PE 9-7, oven dried, rad. Fines.	196	grav/ZVI	-4 +20	**0.5**	
PE 9-8, oven dried, rad. Fines.	197	grav/ZVI	-4 +20	**0.5**	

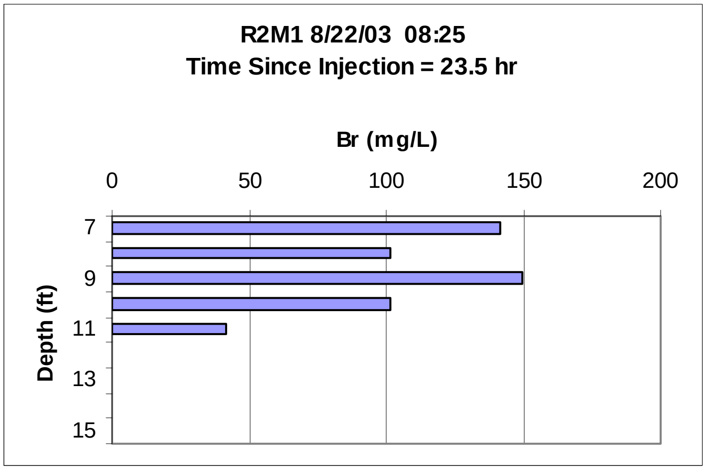
0.2 g samples except where noted	Run No.	Zone	Mesh Size	Reactivity No.	Water Table
PE 9-9, oven dried, rad. Fines.	198	grav/ZVI	-4 +20	**2.4**	
PE 10-5, oven dried, rad. Fines.	199	grav/ZVI	-4 +20	**0.8**	
PE 10-6, oven dried, rad. Fines.	200	grav/ZVI	-4 +20	**1.8**	
PE 10-7, oven dried, rad. Fines.	201	grav/ZVI	-4 +20	**1.0**	
PE 10-9, oven dried, rad. Fines.	202	grav/ZVI	-4 +20	**2.4**	
PE 14-4, oven dried, rad. Fines.	203	grav/ZVI	-4 +20	**0.1**	
PE 14-6, oven dried, rad. Fines.	204	grav/ZVI	-4 +20	**1.3**	
PE 14-7, oven dried, rad. Fines.	205	grav/ZVI	-4 +20	**1.3**	
PE 14-8, oven dried, rad. Fines.	206	grav/ZVI	-4 +20	**2.1**	
PE 15-3, oven dried, rad. Fines.	207	grav/ZVI	-4 +20	**0.6**	
PE 15-5, oven dried, rad. Fines.	208	grav/ZVI	-4 +20	**1.6**	
PE 15-6, oven dried, rad. Fines.	210	grav/ZVI	-4 +20	**0.6**	
PE 15-7, oven dried, rad. Fines.	211	grav/ZVI	-4 +20	**2.0**	
PE 16-12, oven dried, rad. Fines.	213	grav/ZVI	-4 +20	**2.0**	
PE 16-13, oven dried, rad. Fines.	214	grav/ZVI	-4 +20	**2.4**	
PE 16-14, oven dried, rad. Fines.	215	grav/ZVI	-4 +20	**2.1**	
PE 16-8, oven dried, rad. Fines.	212	grav/ZVI	-4 +20	**1.0**	
PE 17-11, oven dried, rad. Fines.	219	grav/ZVI	-4 +20	**0.2**	
PE 17-5, oven dried, rad. Fines.	216	grav/ZVI	-4 +20	**0.1**	
PE 17-6, oven dried, rad. Fines.	217	grav/ZVI	-4 +20	**1.0**	
PE 17-8, oven dried, rad. Fines.	218	grav/ZVI	-4 +20	**0.3**	
PE 18-4, oven dried, rad. Fines.	220	grav/ZVI	-4 +20	**2.6**	
PE 19-4, oven dried, rad. Fines.	221	grav/ZVI	-4 +20	**0.5**	
PE 19-5, oven dried, rad. Fines.	222	grav/ZVI	-4 +20	**0.4**	
PE 19-6, oven dried, rad. Fines.	227	grav/ZVI	-4 +20	**1.3**	
PE 19-7, oven dried, magnetic fraction	144	grav/ZVI	-4 +20	**2.7**	
PE 1-odd, oven dried	158	ZVI	-8 +20	**0.5**	
PE 3-3, oven dried	105	ZVI	-8 +20	**4.3**	
PE 3-4, oven dried	106	ZVI	-8 +20	**4.2**	
PE 4-1, oven dried	107	ZVI	-8 +20	**5.4**	
PE 4-2, oven dried	108	ZVI	-8 +20	**5.7**	
PE 4-4, oven dried	109	ZVI	-8 +20	**4.7**	
PE 4-7, acetone dried	98	ZVI	-8 +20	**4.7**	
PE 4-7, oven dried	97	ZVI	-8 +20	**3.6**	
PE 5-10, acetone dried	104	ZVI	-8 +20	**3.8**	
PE 5-10, oven dried	103	ZVI	-8 +20	**3.5**	
PE 5-2, oven dried	110	ZVI	-8 +20	**1.5**	
PE 5-3, oven dried	111	ZVI	-8 +20	**4.9**	
PE 5-5, oven dried	112	ZVI	-8 +20	**3.8**	
PE 6-1, oven dried	113	ZVI	-8 +20	**3.5**	
PE 6-2, oven dried	124	ZVI	-8 +20	**5.1**	
PE 6-3, oven dried	125	ZVI	-8 +20	**3.8**	
PE 6-9, acetone dried	96	ZVI	-8 +20	**5.5**	
PE 6-9, oven dried	94	ZVI	-8 +20	**4.2**	
PE 6-9, oven dried	95	ZVI	-8 +20	**3.6**	
PE 11-5, oven dried	126	ZVI	-8 +20	**3.6**	
PE 11-6, oven dried	127	ZVI	-8 +20	**3.6**	
PE 11-7, oven dried	128	ZVI	-8 +20	**3.6**	
PE 11-8, oven dried	129	ZVI	-8 +20	**4.0**	
PE 12-5, oven dried	131	ZVI	-8 +20	**2.4**	
PE 12-6, oven dried	132	ZVI	-8 +20	**3.5**	
PE 12-7, oven dried	133	ZVI	-8 +20	**3.5**	
PE 12-9, oven dried	134	ZVI	-8 +20	**2.0**	
PE 13-10, oven dried	138	ZVI	-8 +20	**3.0**	
PE 13-11, oven dried	139	ZVI	-8 +20	**2.8**	
PE 13-5, oven dried	135	ZVI	-8 +20	**2.1**	
PE 13-8, oven dried	136	ZVI	-8 +20	**2.3**	
PE 13-9, oven dried	137	ZVI	-8 +20	**1.1**	
PE 18-10, oven dried	141	ZVI	-8 +20	**3.9**	

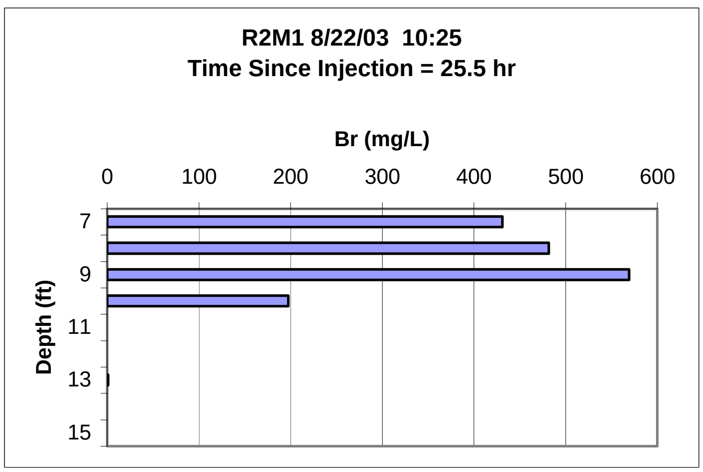
0.2 g samples except where noted	Run No.	Zone	Mesh Size	Reactivity No.	Water Table
PE 18-12, oven dried	142	ZVI	-8 +20	**3.7**	
PE 18-17, oven dried	143	ZVI	-8 +20	**3.4**	
PE 18-7, oven dried	140	ZVI	-8 +20	**2.9**	
PE 21-6, oven dried	145	ZVI	-8 +20	**3.5**	
PE 21-7, oven dried	146	ZVI	-8 +20	**3.0**	
PE 21-8, oven dried	147	ZVI	-8 +20	**3.5**	
PE 21-9, oven dried	148	ZVI	-8 +20	**4.4**	
PE 23-13, oven dried	152	ZVI	-8 +20	**3.4**	
PE 23-6, oven dried	149	ZVI	-8 +20	**4.4**	
PE 23-7, oven dried	150	ZVI	-8 +20	**3.8**	
PE 23-8, oven dried	151	ZVI	-8 +20	**3.0**	
PE 24-11, oven dried	154	ZVI	-8 +20	**4.4**	
PE 24-12, oven dried	155	ZVI	-8 +20	**3.9**	
PE 24-13, oven dried	156	ZVI	-8 +20	**5.0**	
PE 24-15, oven dried	157	ZVI	-8 +20	**6.5**	
PE 24-8, oven dried	153	ZVI	-8 +20	**3.7**	
Fry Canyon					
Aug. 2003 Samples					
PE ZVI 1-3, oven dried	159	ZVI	pellets	**0.8**	
PE ZVI 1-4, oven dried	160	ZVI	pellets	**1.0**	
PE ZVI 1-5, oven dried	161	ZVI	pellets	**1.0**	
PE ZVI 1-6, oven dried	162	ZVI	pellets	**1.7**	
PE ZVI 2-6, oven dried	163	ZVI	pellets	**2.3**	
PE ZVI 2-5, oven dried	164	ZVI	pellets	**0.8**	
PE ZVI 3-3, oven dried	166	ZVI	pellets	**0.2**	
PE ZVI 3-4, oven dried	167	ZVI	pellets	**1.2**	
PE ZVI 3-5, oven dried	168	ZVI	pellets	**1.9**	
PE ZVI 2-4, oven dried, rad.	228	ZVI	pellets	**2.2**	
PE ZVI 3-4, oven dried, -200 fraction	169	ZVI	pellets	**0.3**	
PE ZVI 3-4, oven dried, -10/+18 fraction	170	ZVI	pellets	**0.5**	
PE ZVI 3-4, oven dried, -10/+18 fraction	170	ZVI	pellets	**0.5**	
Summary Categories	**Mean**	**Sdev**	**Count**		
Peerless -8 +20 Standards	4.4	0.9	7.0		
Fisher ~40 Standards	7.9	1.6	3.0		
Mont. RPMA ZVI, above water table	3.5	0.7	6.0		
Mont. RPMA ZVI, below water table	2.1	0.5	9.0		
Mont. RPM ZVI, below water table	3.7	1.1	19.0		
Mont. PE G/Z, fines	1.3	1.0	47.0		
Mont. PE ZVI	3.7	1.1	49.0		
Fry Canyon PE ZVI - pellets	1.3	0.7	10.0		
Mont. Feb 2002 ZVI, Below water table	3.0	1.1	25.0		
Mont. Feb. 2002 G/Z, Below water table	1.7	0.8	11.0		
Mont. August 2003. ZVI Zone	3.7	1.1	49.0		
Mont. August 2003. G/Z Zone	1.3	1.0	47.0		

Appendix E

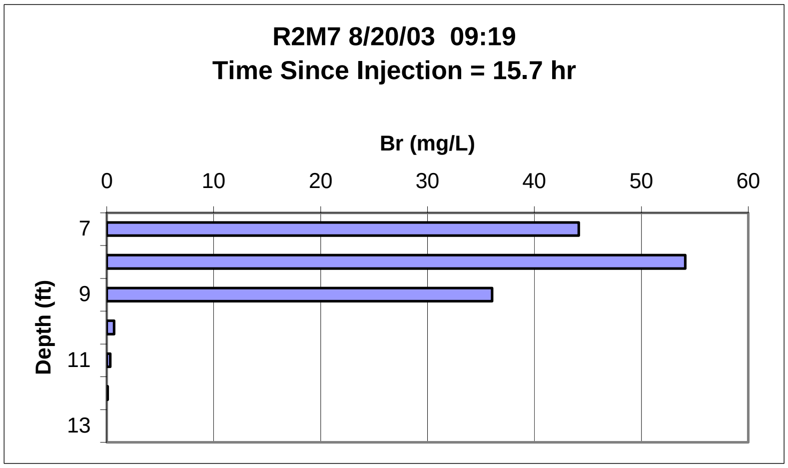
Bromide Concentration Vertical Profiles

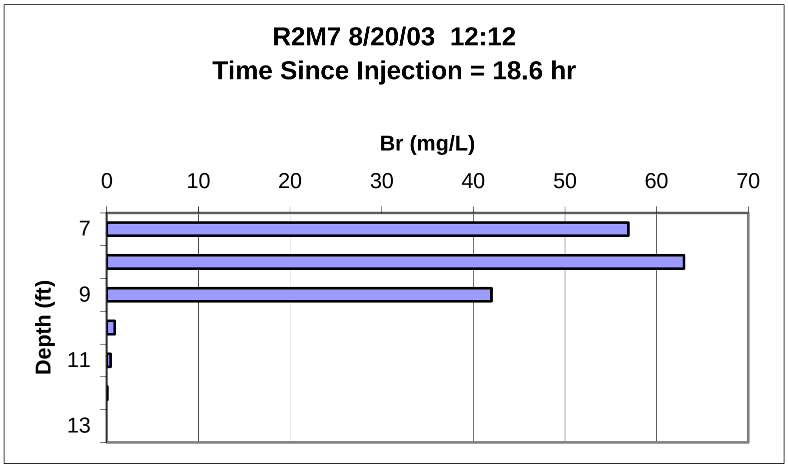
Well R2M1

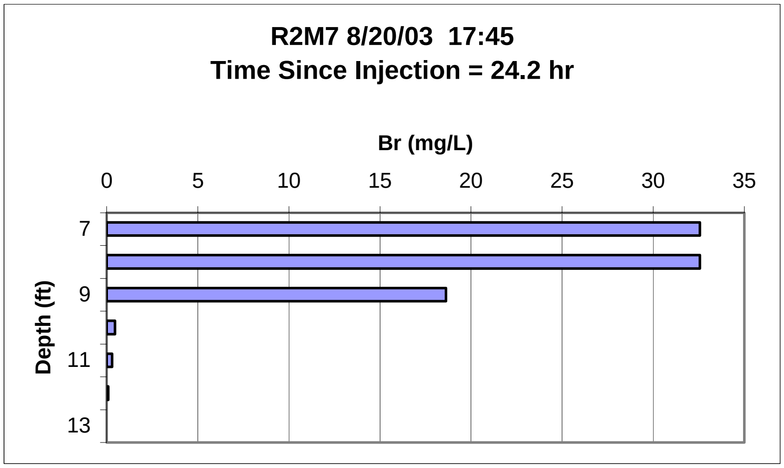

R2M1 8/22/03 08:25
Time Since Injection = 23.5 hr
Br (mg/L)
0
50
100
150
200
Depth (ft)
7
9
11
13
15


R2M1 8/22/03 10:25
Time Since Injection = 25.5 hr
Br (mg/L)
0
100
200
300
400
500
600
Depth (ft)
7
9
11
13
15

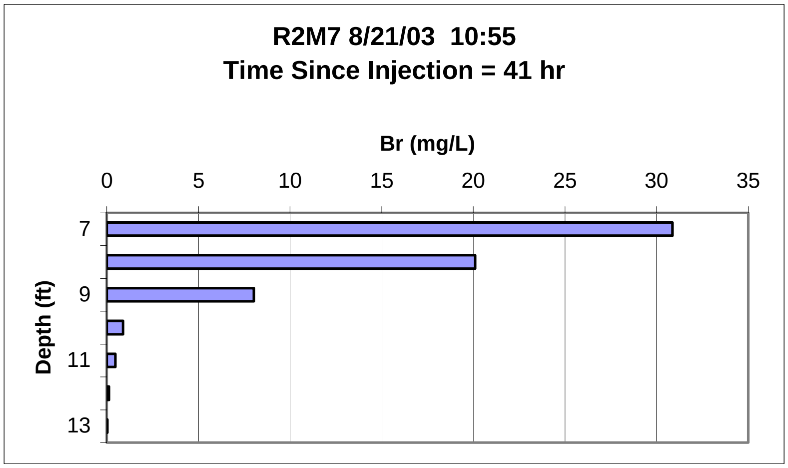
Well R2M7

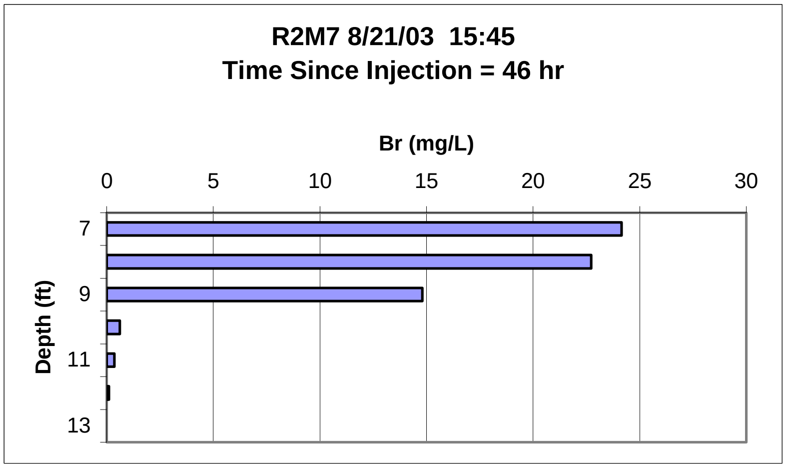

R2M7 8/20/03 09:19
Time Since Injection = 15.7 hr
Br (mg/L)
0
10
20
30
40
50
60
Depth (ft)
7
9
11
13

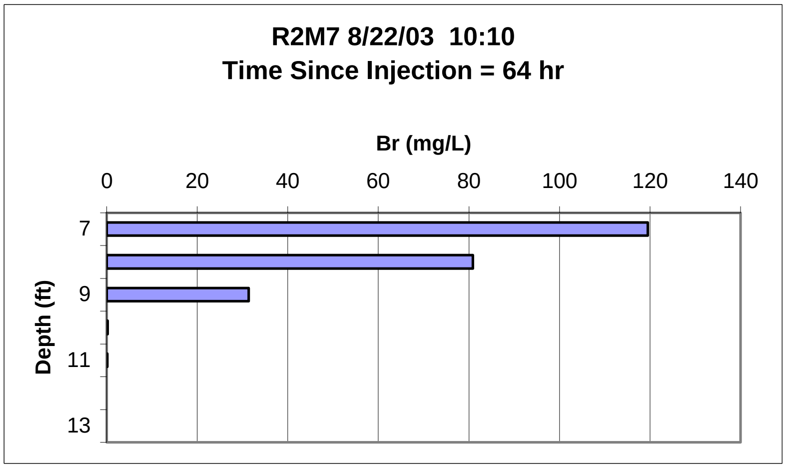

R2M7 8/20/03 12:12
Time Since Injection = 18.6 hr
Br (mg/L)
0
10
20
30
40
50
60
70
Depth (ft)
7
9
11
13


R2M7 8/20/03 17:45
Time Since Injection = 24.2 hr
Br (mg/L)
0
5
10
15
20
25
30
35
Depth (ft)
7
9
11
13

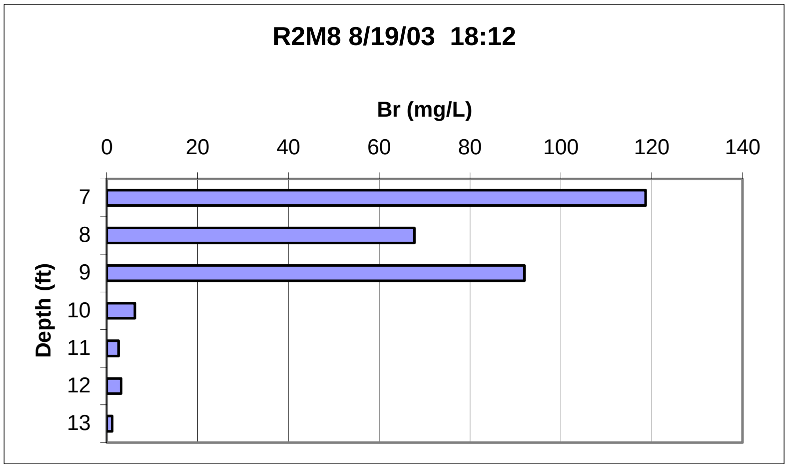
Well R2M7 (continued)

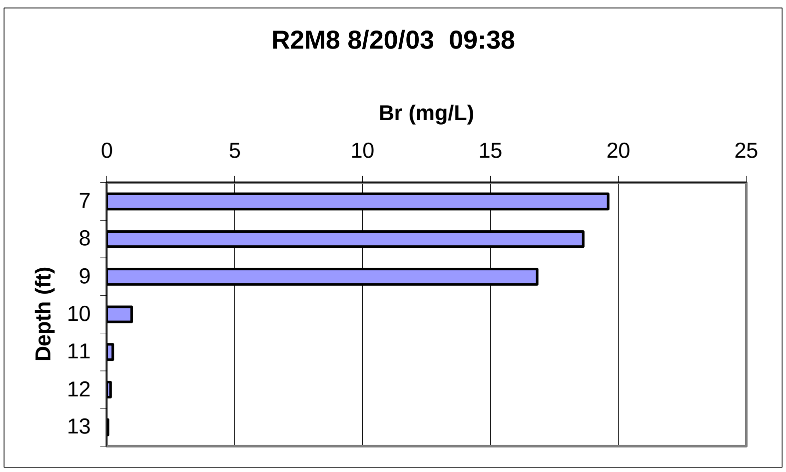


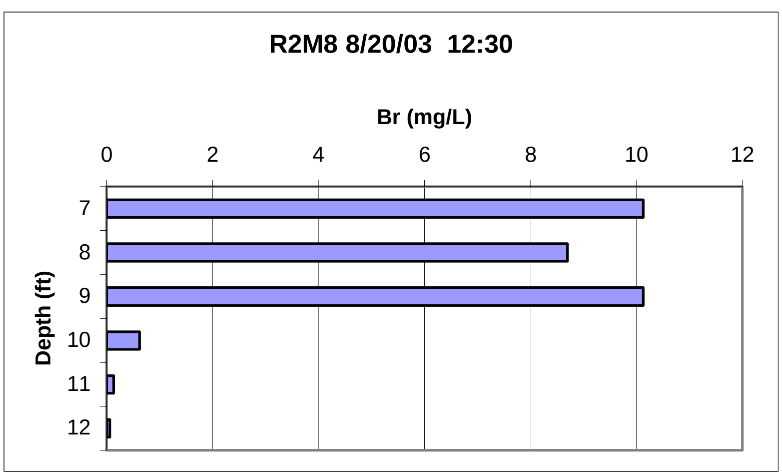




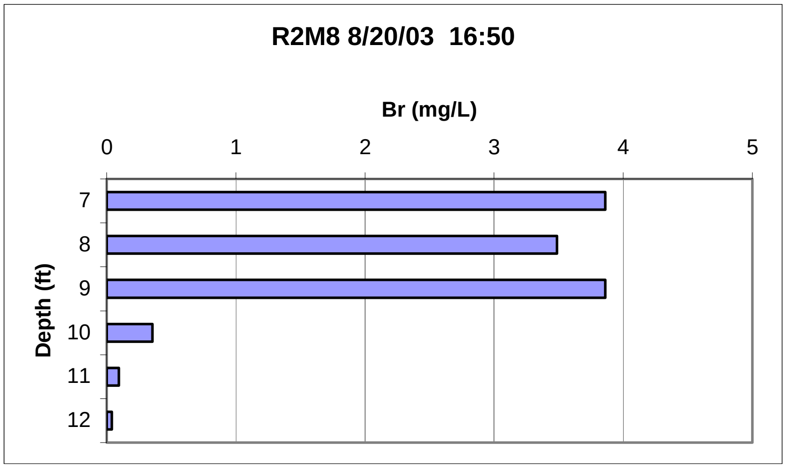
Well R2M8


R2M8 8/19/03 18:12
Br (mg/L)
0 20 40 60 80 100 120 140
Depth (ft)
7
8
9
10
11
12
13

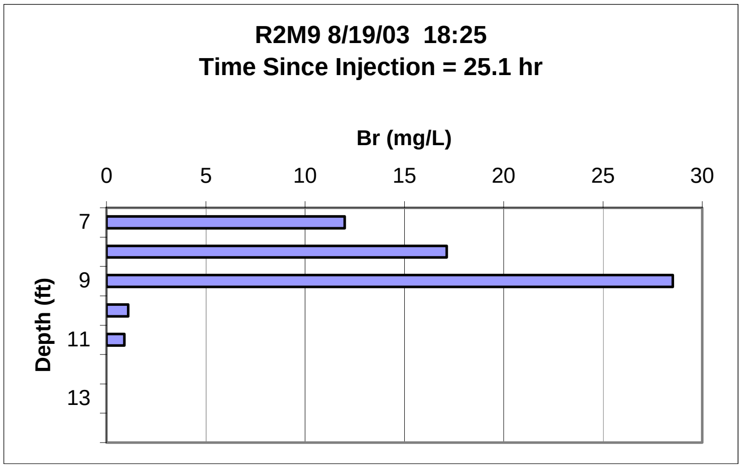

R2M8 8/20/03 09:38
Br (mg/L)
0 5 10 15 20 25
Depth (ft)
7
8
9
10
11
12
13


R2M8 8/20/03 12:30
Br (mg/L)
0 2 4 6 8 10 12
Depth (ft)
7
8
9
10
11
12

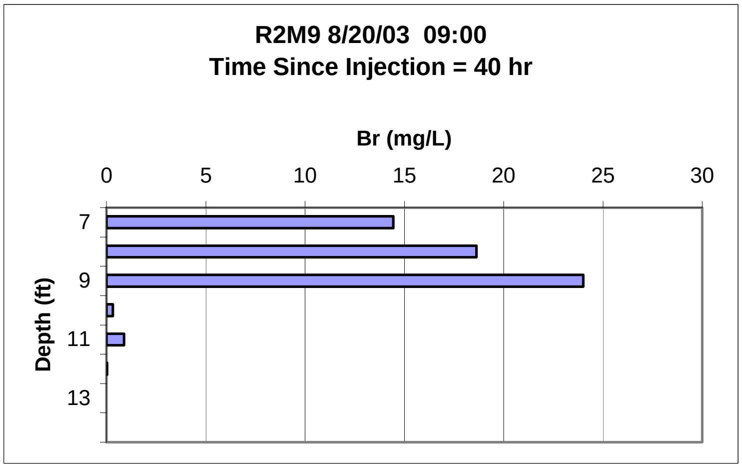
Well R2M8 (continued)



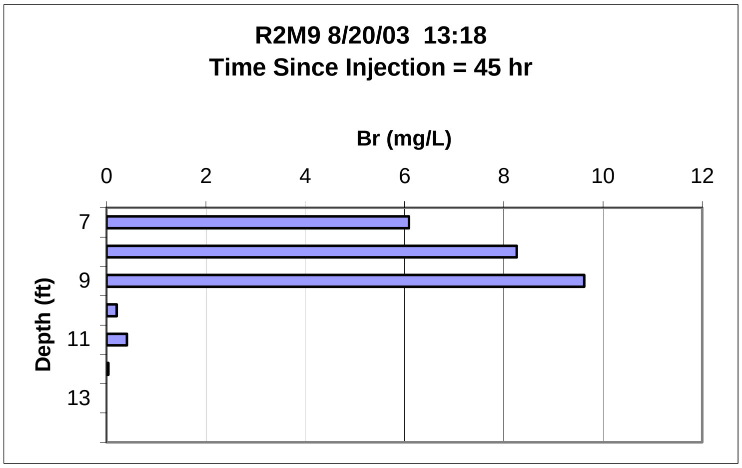
Well R2M9



R2M9 8/19/03 18:25
Time Since Injection = 25.1 hr
Br (mg/L)
0
5
10
15
20
25
30
7
9
11
13
Depth (ft)

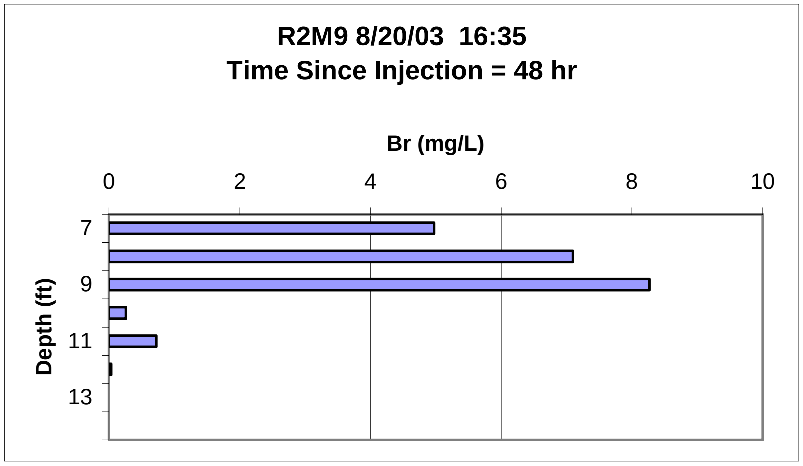


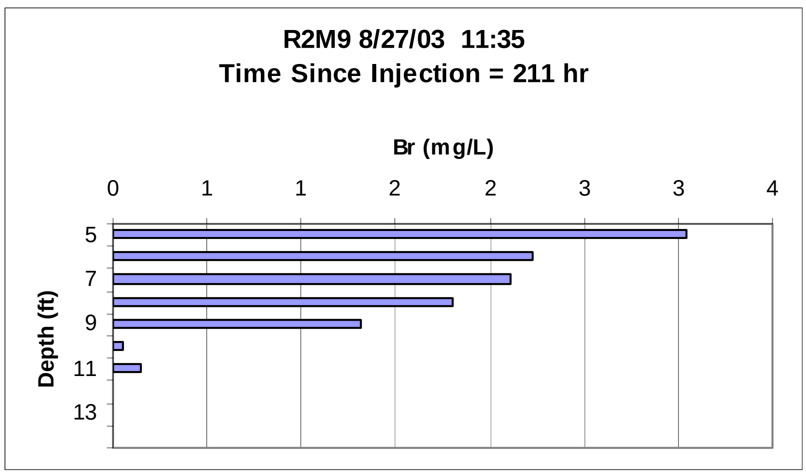
R2M9 8/20/03 09:00
Time Since Injection = 40 hr
Br (mg/L)
0
5
10
15
20
25
30
7
9
11
13
Depth (ft)



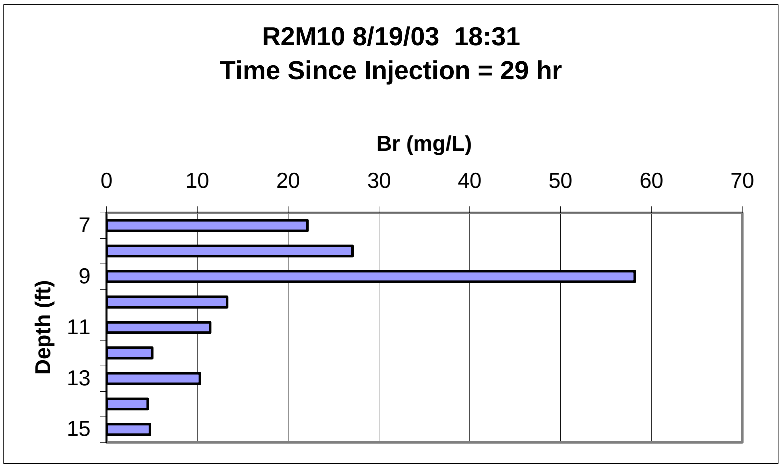
R2M9 8/20/03 13:18
Time Since Injection = 45 hr
Br (mg/L)
0
2
4
6
8
10
12
7
9
11
13
Depth (ft)

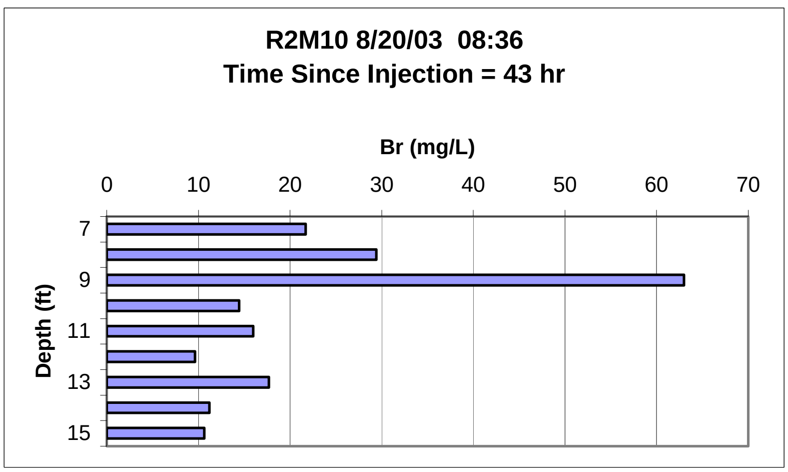
Well R2M9 (continued)

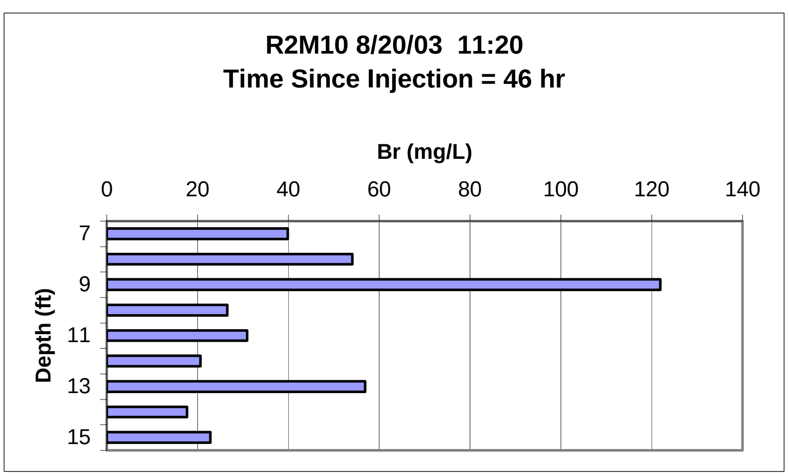




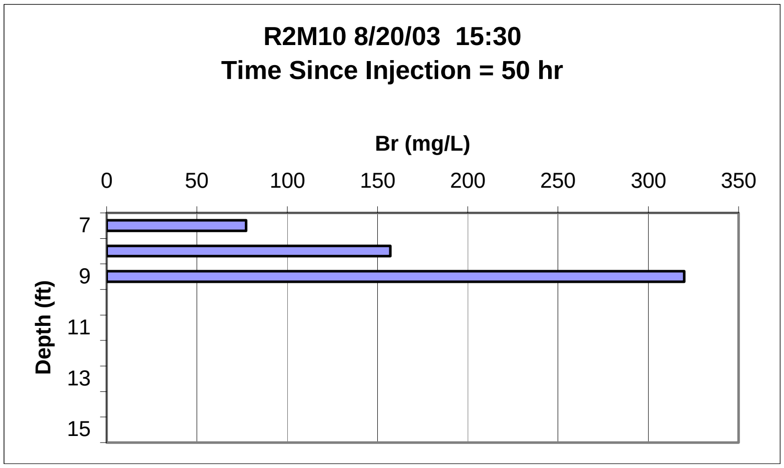
Well R2M10 (continued)

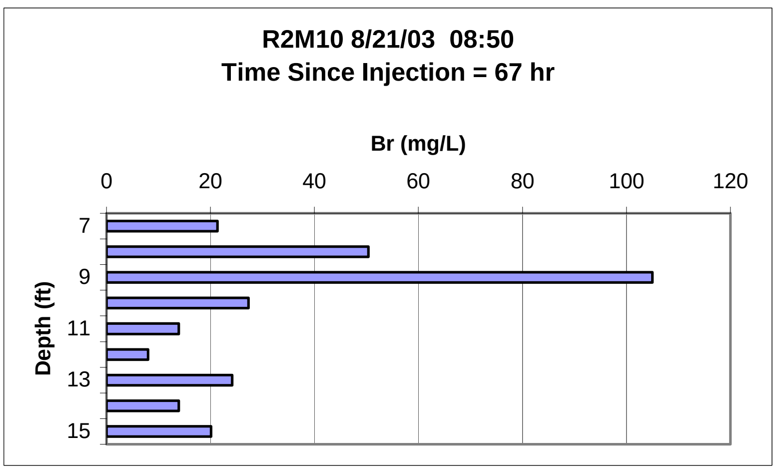


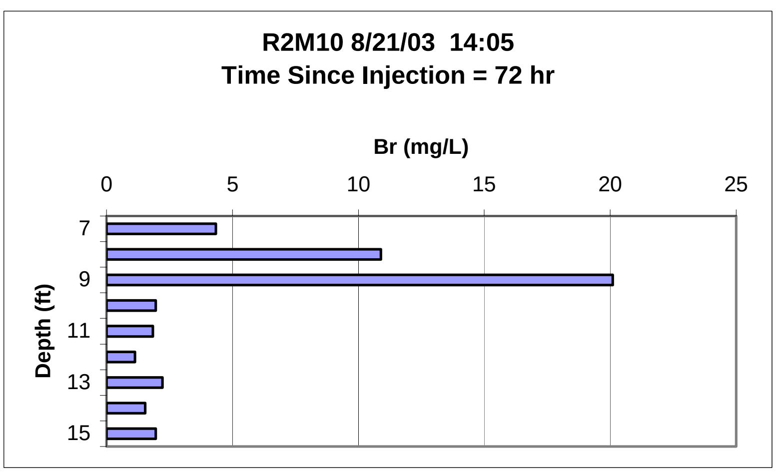




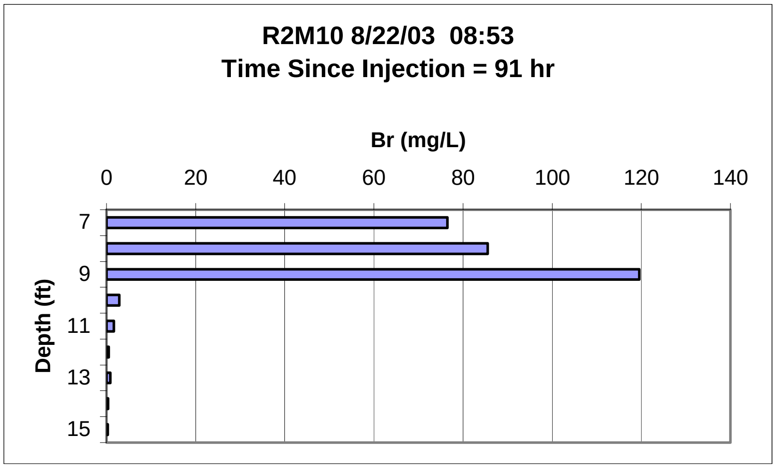
Well R2M10 (continued)

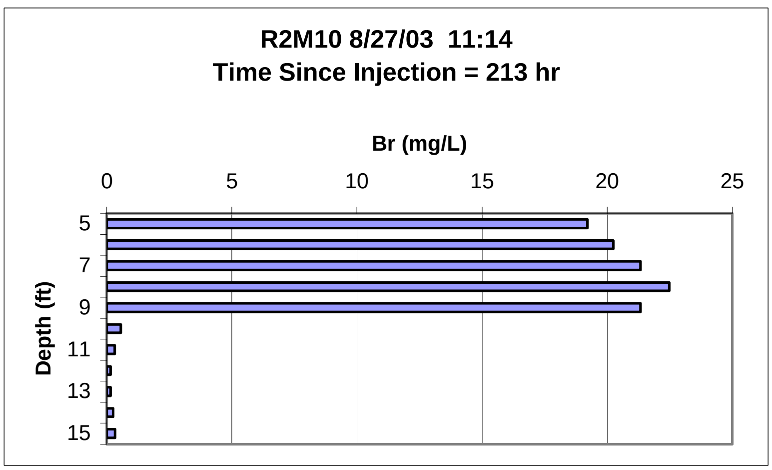




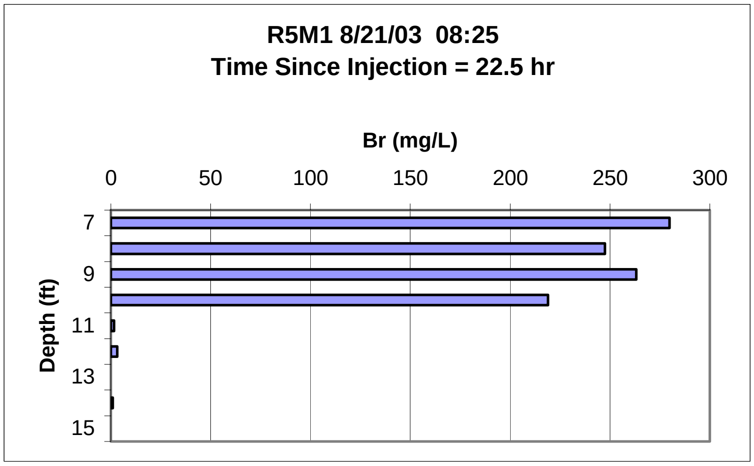


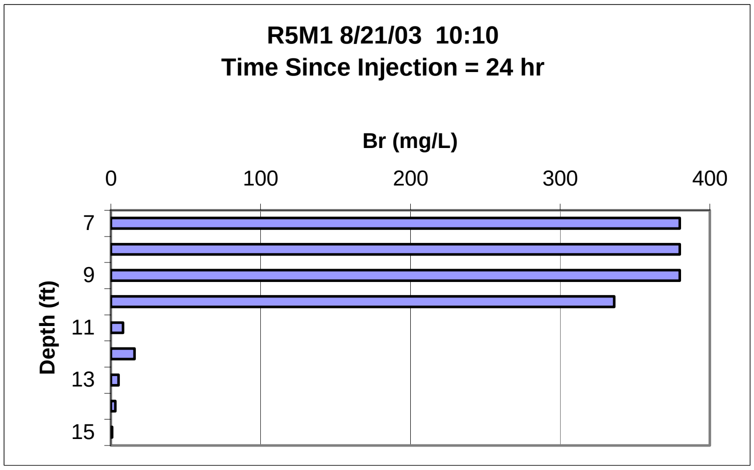
Well R2M10 (continued)

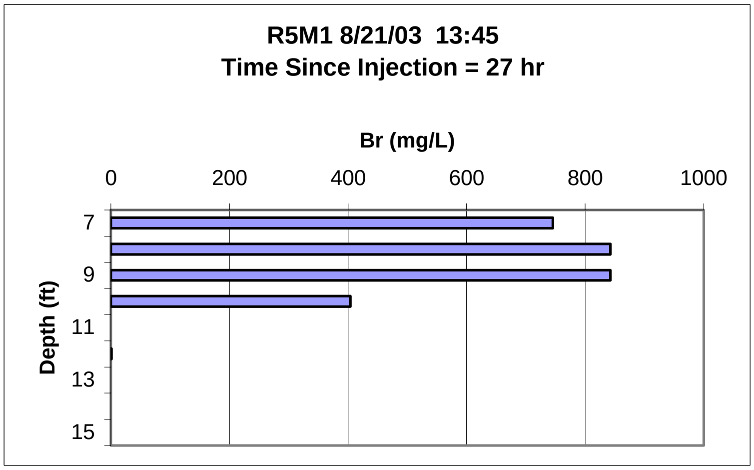




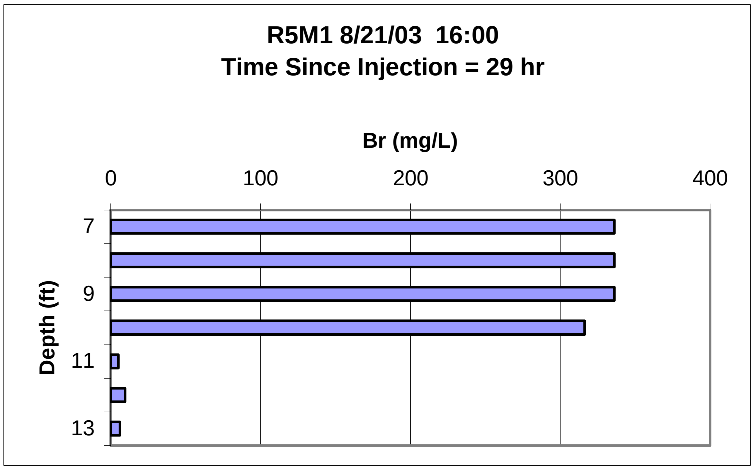
Well R5M1

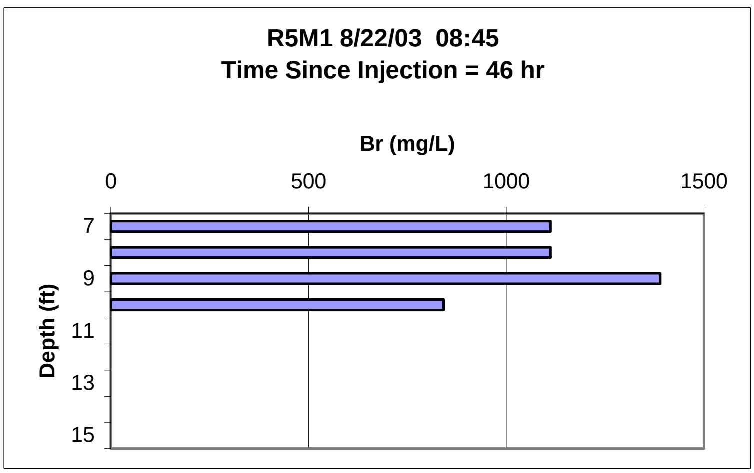

R5M1 8/21/03 08:25
Time Since Injection = 22.5 hr
Br (mg/L)
0
50
100
150
200
250
300
Depth (ft)
7
9
11
13
15

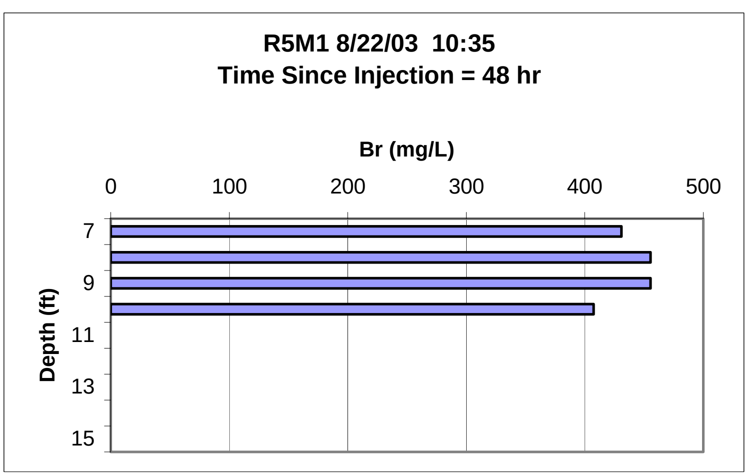

R5M1 8/21/03 10:10
Time Since Injection = 24 hr
Br (mg/L)
0
100
200
300
400
Depth (ft)
7
9
11
13
15


R5M1 8/21/03 13:45
Time Since Injection = 27 hr
Br (mg/L)
0
200
400
600
800
1000
Depth (ft)
7
9
11
13
15

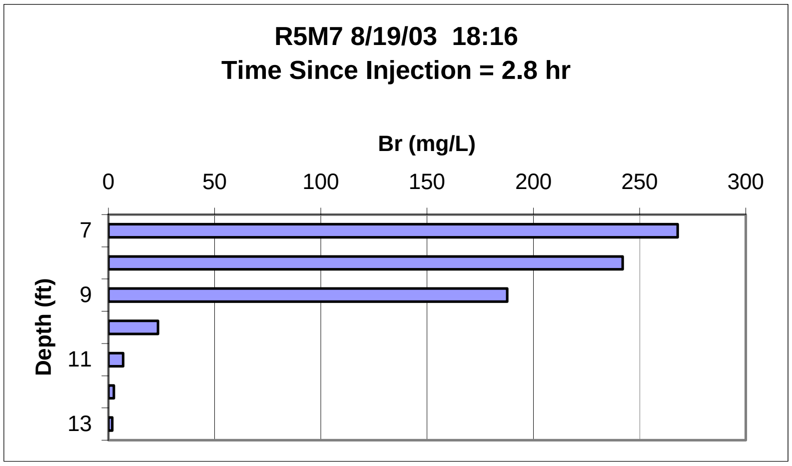
Well R5M1 (continued)



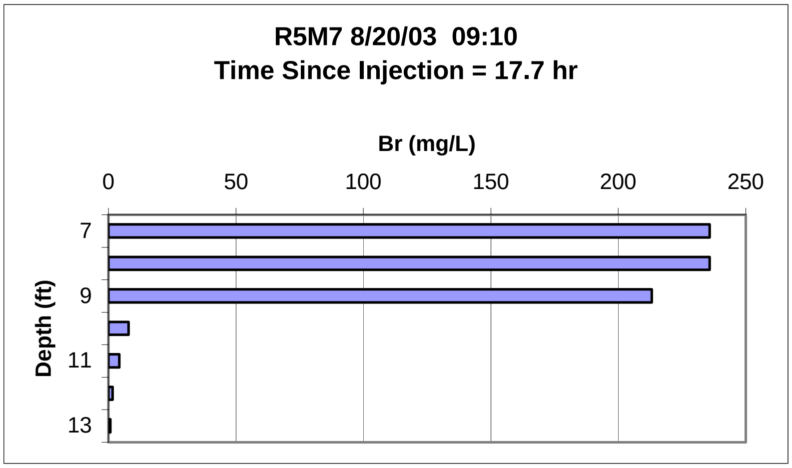




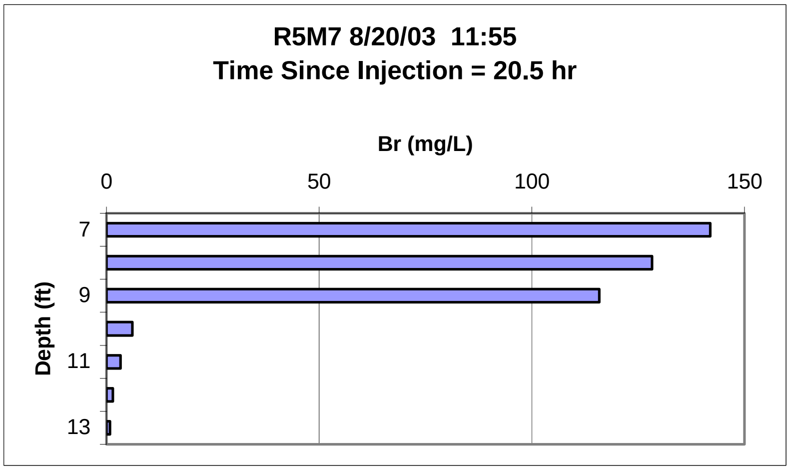
Well R5M7



R5M7 8/19/03 18:16
Time Since Injection = 2.8 hr
Br (mg/L)
0
50
100
150
200
250
300
Depth (ft)
7
9
11
13

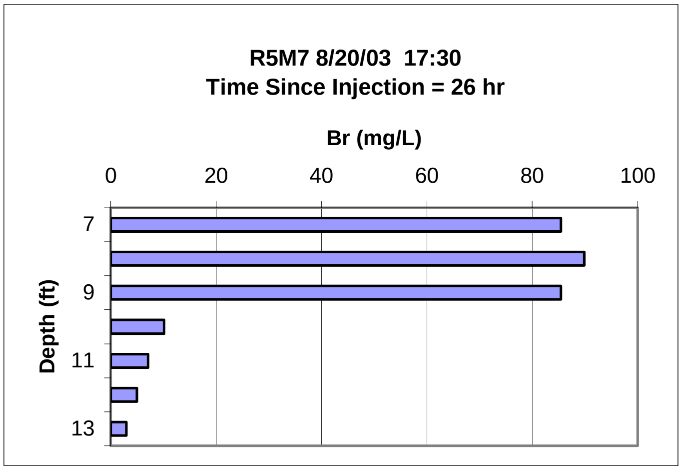


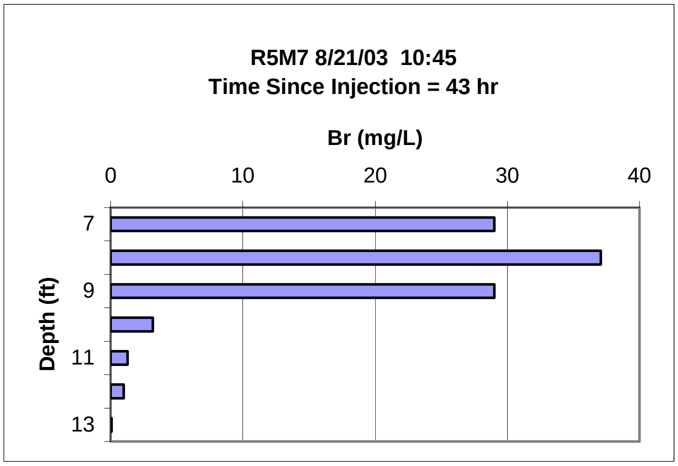
R5M7 8/20/03 09:10
Time Since Injection = 17.7 hr
Br (mg/L)
0
50
100
150
200
250
Depth (ft)
7
9
11
13

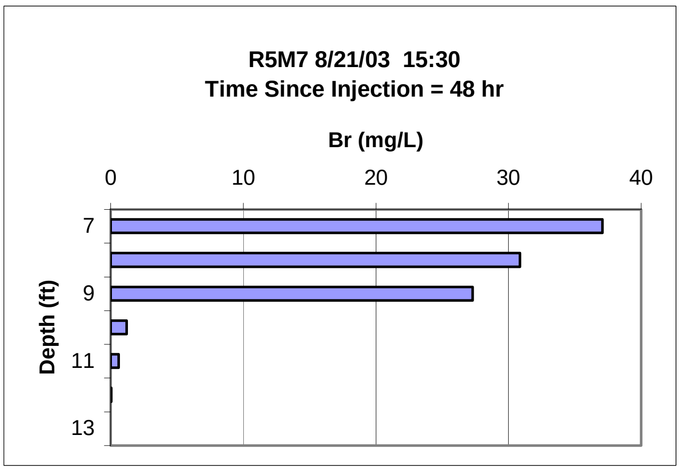


R5M7 8/20/03 11:55
Time Since Injection = 20.5 hr
Br (mg/L)
0
50
100
150
Depth (ft)
7
9
11
13

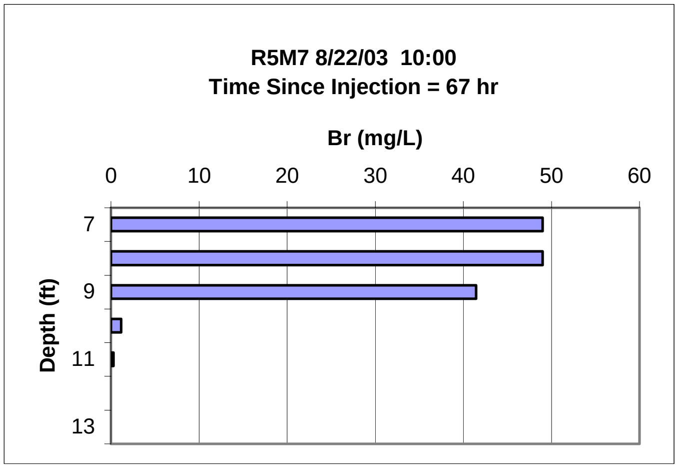
Well R5M7 (continued)

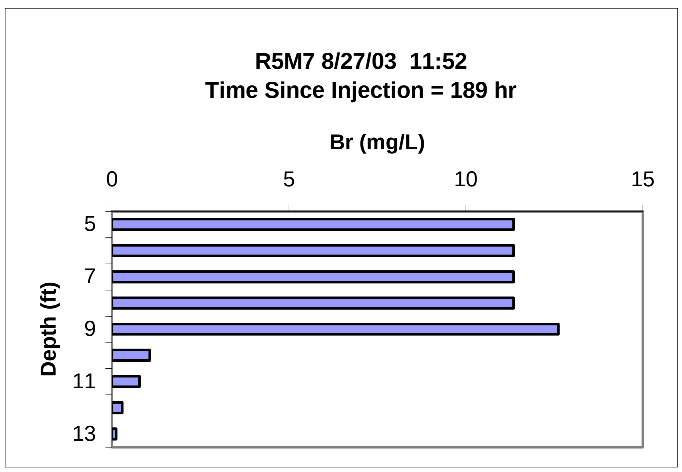




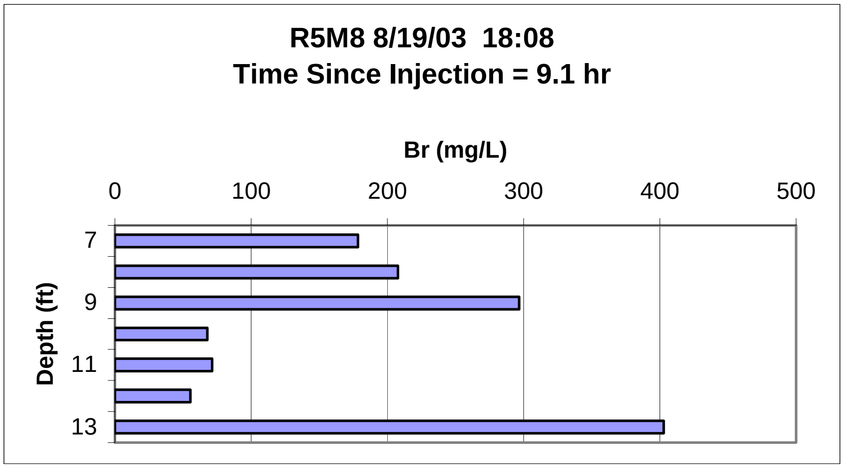


Well R5M7 (continued)

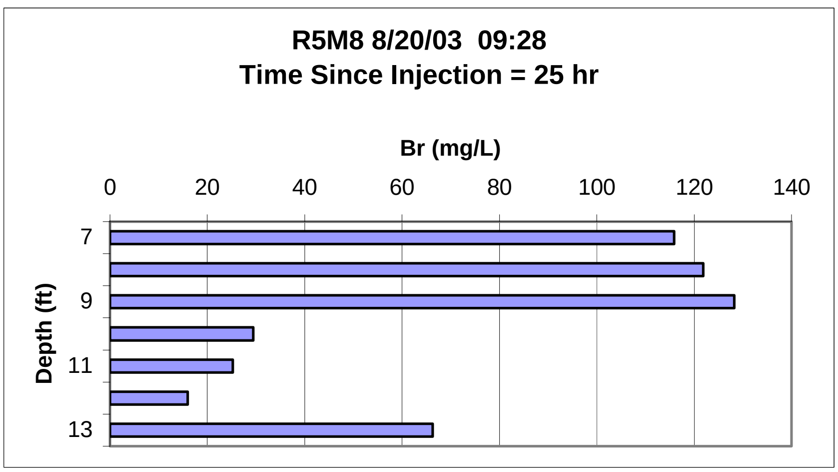




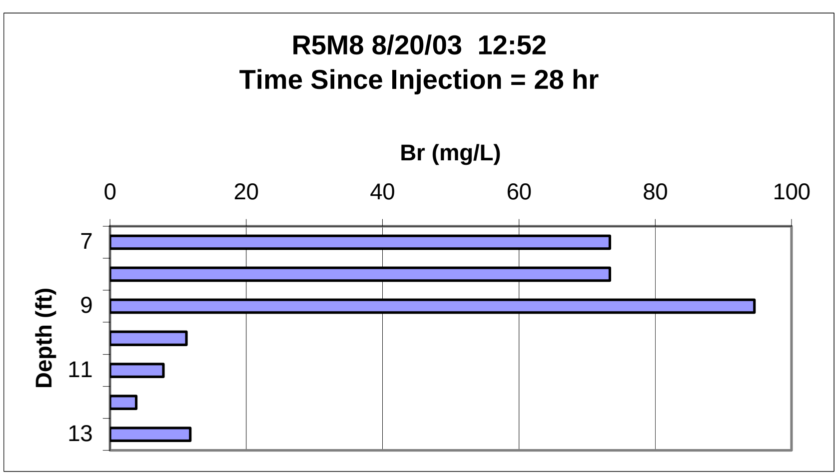
Well R5M8



R5M8 8/19/03 18:08
Time Since Injection = 9.1 hr
Br (mg/L)
0
100
200
300
400
500
Depth (ft)
7
9
11
13

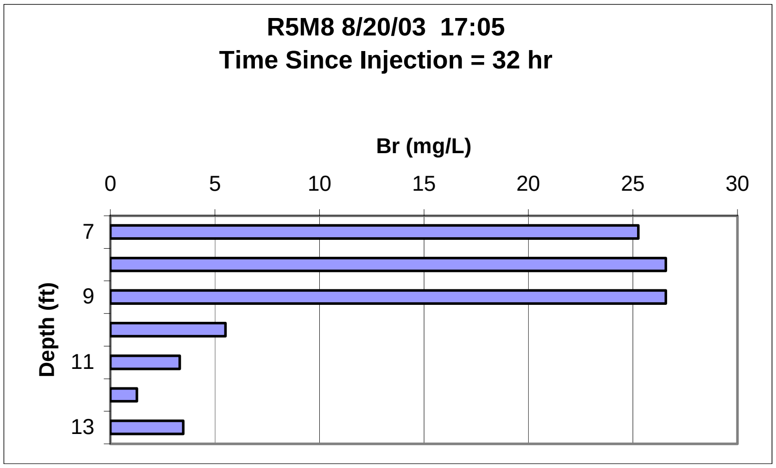


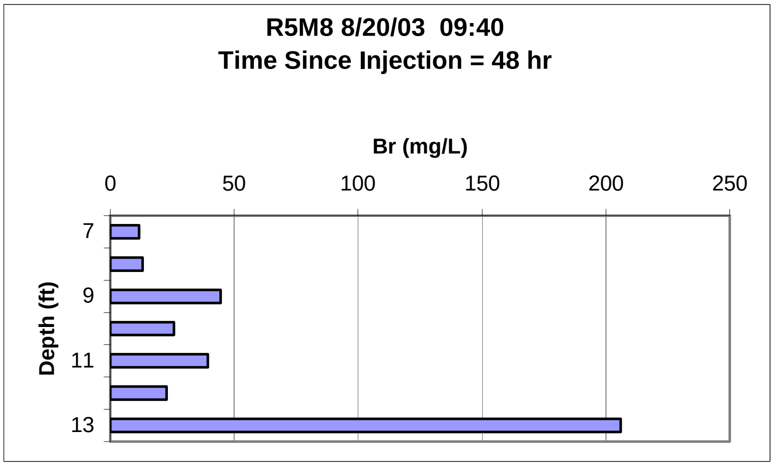
R5M8 8/20/03 09:28
Time Since Injection = 25 hr
Br (mg/L)
0
20
40
60
80
100
120
140
Depth (ft)
7
9
11
13

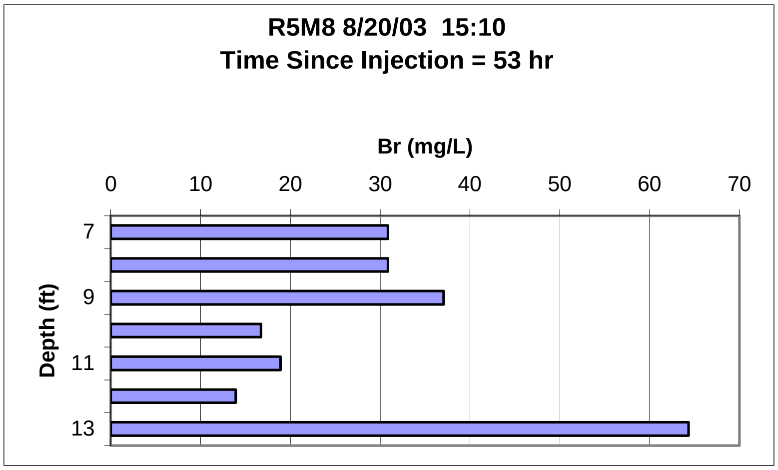


R5M8 8/20/03 12:52
Time Since Injection = 28 hr
Br (mg/L)
0
20
40
60
80
100
Depth (ft)
7
9
11
13

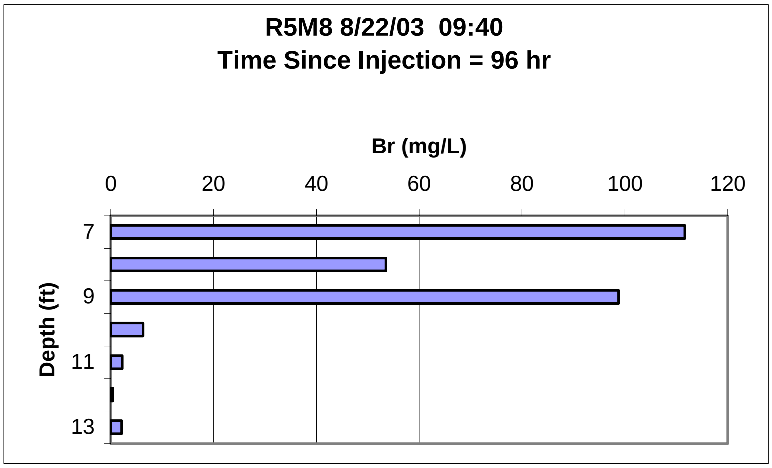
Well R5M8 (continued)

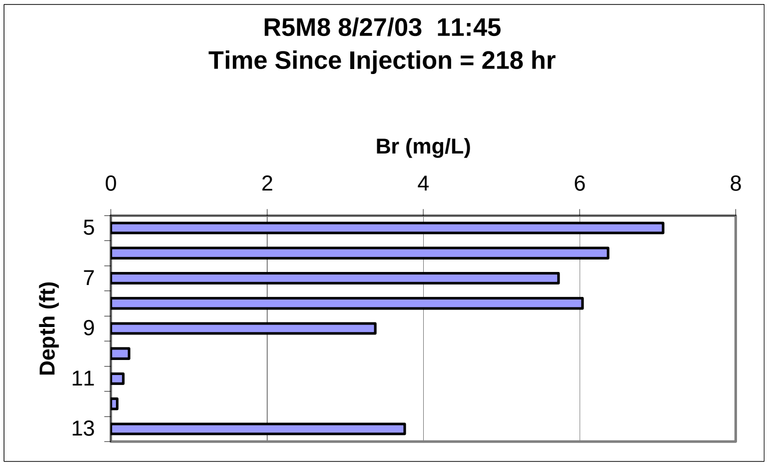




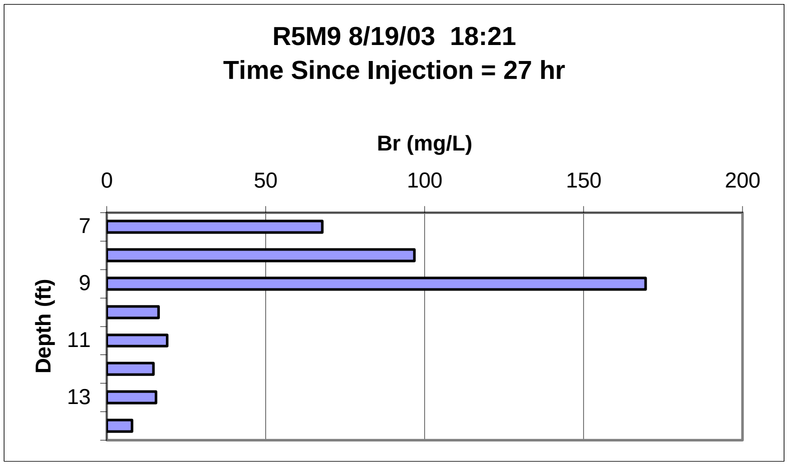


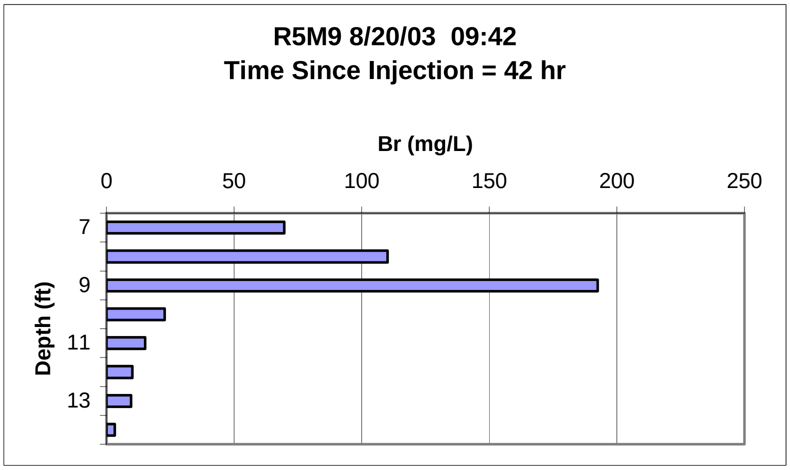
Well R5M8 (continued)

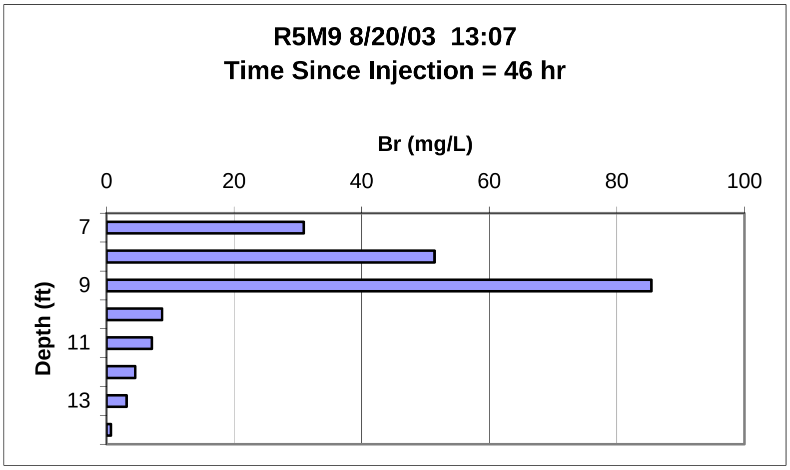




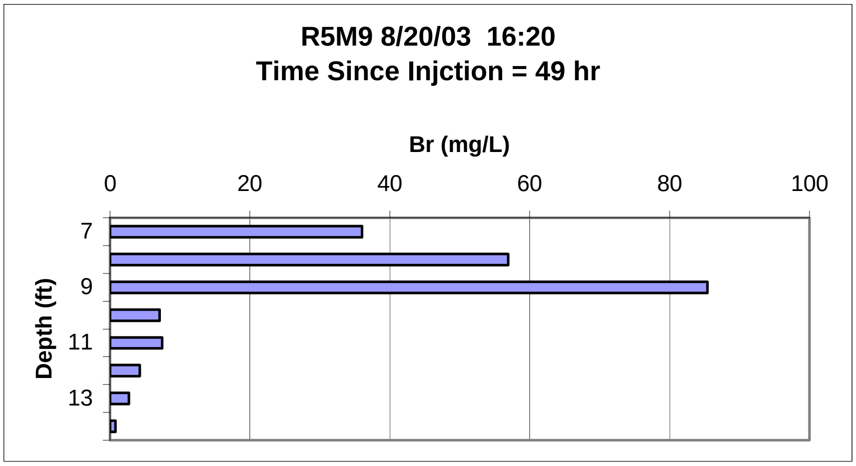
Well R5M9

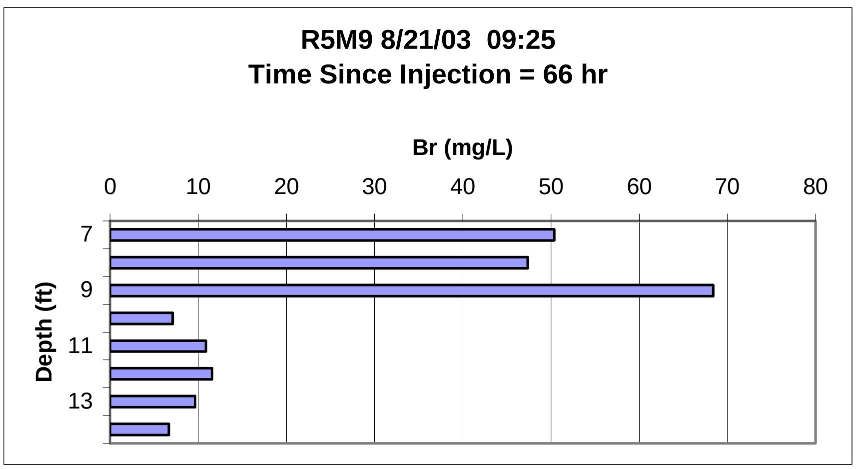

R5M9 8/19/03 18:21
Time Since Injection = 27 hr
Br (mg/L)
0
50
100
150
200
Depth (ft)
7
9
11
13

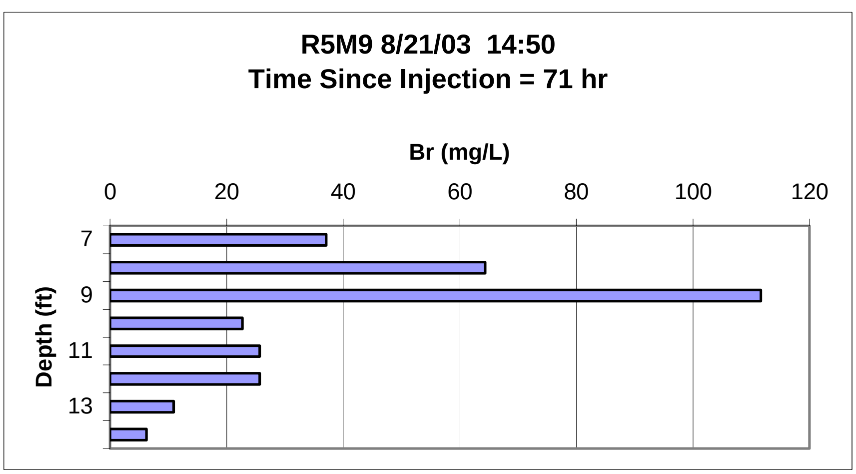

R5M9 8/20/03 09:42
Time Since Injection = 42 hr
Br (mg/L)
0
50
100
150
200
250
Depth (ft)
7
9
11
13


R5M9 8/20/03 13:07
Time Since Injection = 46 hr
Br (mg/L)
0
20
40
60
80
100
Depth (ft)
7
9
11
13

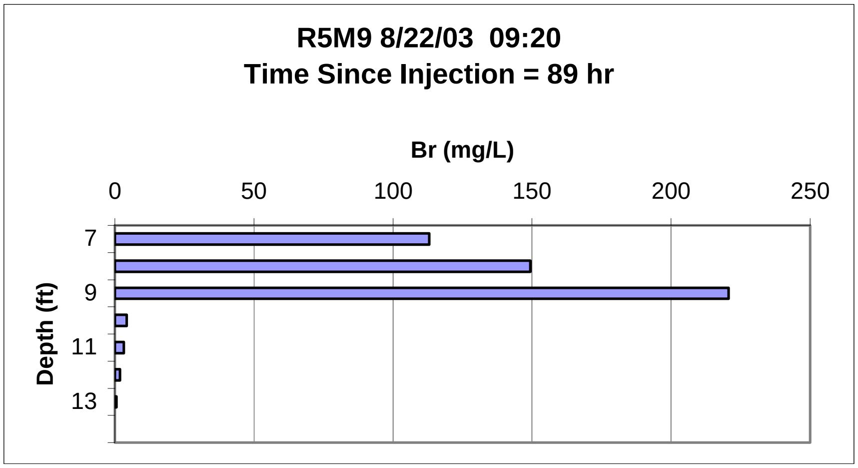
Well R5M9 (continued)

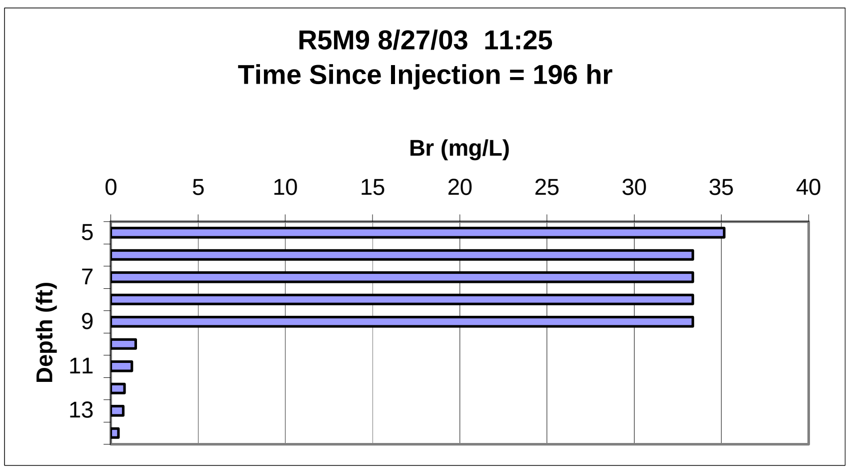




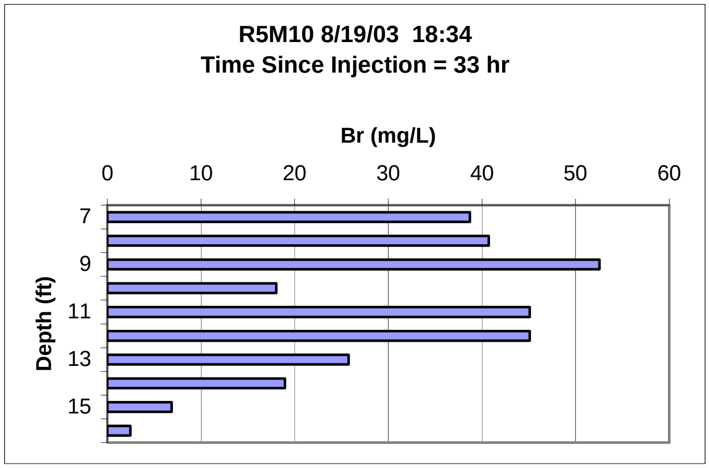


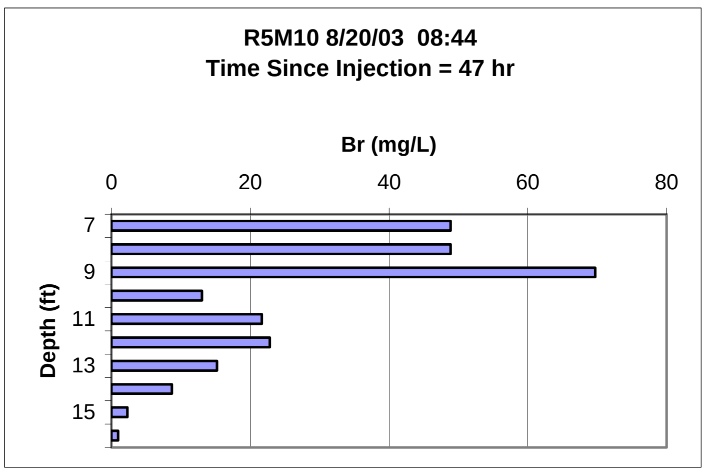
Well R5M9 (continued)

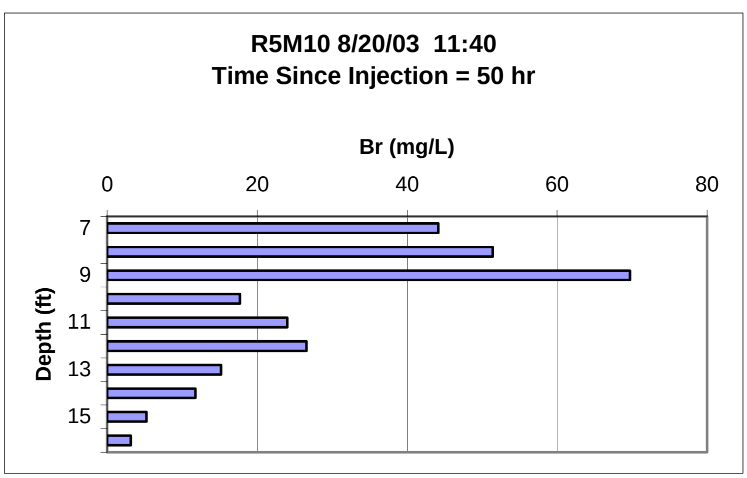




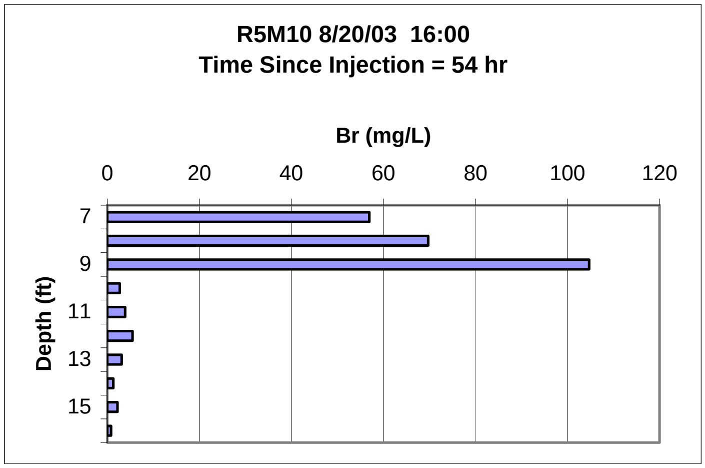
Well R5M10

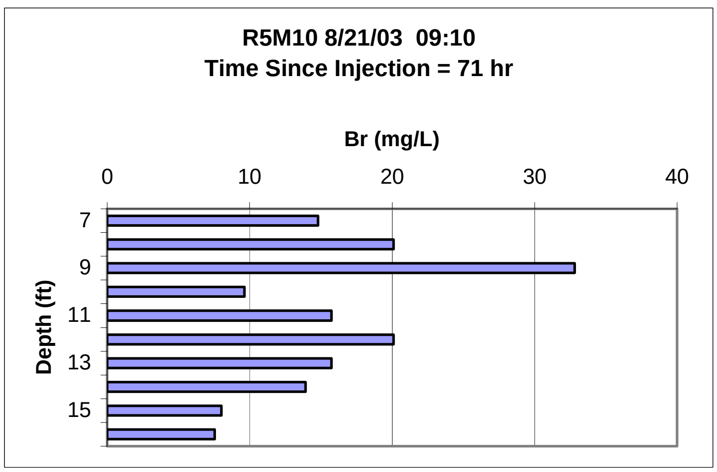

R5M10 8/19/03 18:34
Time Since Injection = 33 hr
Br (mg/L)
0
10
20
30
40
50
60
Depth (ft)
7
9
11
13
15

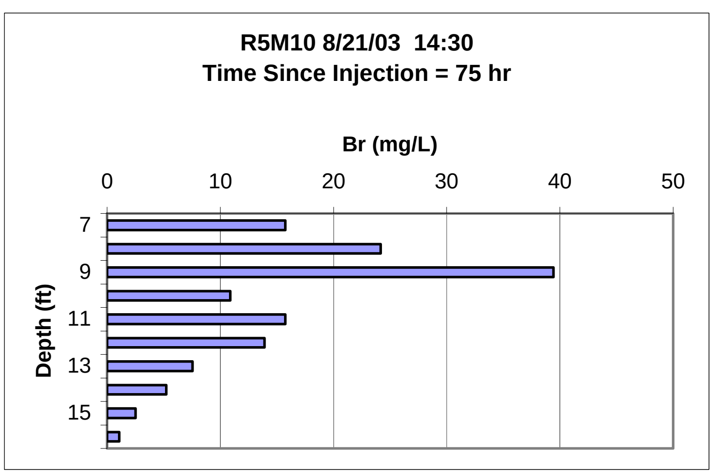

R5M10 8/20/03 08:44
Time Since Injection = 47 hr
Br (mg/L)
0
20
40
60
80
Depth (ft)
7
9
11
13
15


R5M10 8/20/03 11:40
Time Since Injection = 50 hr
Br (mg/L)
0
20
40
60
80
Depth (ft)
7
9
11
13
15

Well R5M10 (continued)







Well R5M10 (continued)