FINAL REPORT

Combining Low-Energy Electrical Resistance Heating With Biotic and Abiotic Reactions for Treatment of Chlorinated Solvent DNAPL Source Areas

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14. ABSTRACT

The effectiveness and timeframe of in situ remedies such as in situ bioremediation (ISB) and zero-valent iron (ZVI) is a function of mass transfer when applied in chlorinated solvent dense nonaqueous phase liquid (DNAPL) source zones. The ESTCP ER-0719 project demonstrated combining low-temperature subsurface heating with in situ remedies to enhance remediation performance through both increased degradation reaction rates and contaminant dissolution. Dechlorination was induced in two test cells for ZVI and ISB. For the ZVI test, increased temperature from 10^{o}C to between 35 and 45^{o}C increased dechlorination by a factor of 4 to 8. For the ISB test, increasing the temperatures (10^{o}C to between 35 and 45^{o}C) accelerated overall contaminant dechlorination by a factor of 2-4 at hotspot locations close to residual contaminant mass. Field test results demonstrated that moderate heating and minor operational costs enhanced efficiency and effectiveness of in situ treatment of trichloroethene (TCE). Capture and treatment of contaminated vapor— a major cost element of standard thermal treatment—was not needed as treatment maintained low aqueous TCE concentrations. Additional infrastructure needed for heating was limited to subsurface electrodes and a power control unit. These results suggest that combined heating and in situ treatment may be cost effective in source zones with moderate contaminant mass or when combined with high-temperature thermal.

15. SUBJECT TERMS

Chlorinated solvent, DNAPL, bioremediation, zero valent iron, thermal remediation, electrical resistance heating, combined remedy

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EXECUTIVE SUMMARY

The applicability of in situ groundwater remedies such as in situ bioremediation (ISB) or zero valent iron (ZVI) reduction in chlorinated solvent source zones (i.e. containing dense non-aqueous phase liquids [DNAPLs]) is often limited by the relatively long treatment timeframes required to meet remedial objectives at sites. Combining subsurface heating with in situ remedies can potentially accelerate the treatment rate by increasing dissolution of residual contaminants into groundwater where they are available for in situ degradation reactions. Conceptually, the goal of ESTCP demonstration project ER-0719 was to evaluate moderate heating (i.e. 35-50 ^{o}C) to accelerate dissolution/desorption of residual trichloroethylene (TCE) contamination offset by concomitant accelerated in situ degradation kinetics, and to minimize volatilization and the need for soil gas extraction and treatment, typically required for high-temperature thermal applications. This field demonstration combined electrical resistance heating with for both ZVI and ISB for TCE treatment.

The demonstration objectives included quantifying, 1) the effect of low-energy heating on the extent and rate of contaminant degradation reactions, 2) the enhanced mass removal rate, 3) the relative contribution of biotic and abiotic contaminant degradation mechanisms at different temperatures, and 4) the cost-benefit of applying low-energy heating with in situ treatments. The project was broken up into three phases. Phase 1 consisted of initial characterization and verification of the suitability of two test cells, in which ISB and ZVI to be demonstrated, to meet project objectives. Phase 2 consisted of a field demonstration of ISB and ZVI without heating to establish performance of the individual technologies including the degradation kinetics and mass balance factors at ambient temperature. Phase 3 consisted of a field demonstration of ISB with low-energy ERH to evaluate treatment performance at elevated temperatures of approximately 30-45°C, and ZVI at elevated temperatures of approximately 30-55°C. This field demonstration was used to evaluate the feasibility of various low-temperature heating applications for in situ treatment including: (1) application designs with low-temperature heating as the primary treatment, and (2) application designs with low-temperature heating in combination with high temperature heating in series and in parallel.

Phase 1 characterization included a soil gas survey, and confirmation soil and groundwater sampling which demonstrated high concentrations of TCE in soils (max. 220 mg/kg) and groundwater (max. 29 ppm) within the two test cells. Phase 2 was initiated with injection of zero-valent iron (ZVI) within the ZVI test cell. One of the most significant challenges to in situ ZVI reduction is effective distribution of ZVI particles within subsurface environments. During the ER-0719 field demonstration, micron-scale ZVI particles were suspended within a shear-thinning fluid to increase distribution of micron-scale ZVI. Approximately 190 kg of 2-micron-diameter ZVI particles were injected into the top six feet of an unconfined aquifer within the trichloroethene (TCE) source zone. Continuous monitoring during and after injection revealed ZVI concentrations at the monitoring wells at all wells within 12 feet at the end of the injection period. TCE dechlorination was monitored over a period of two months at the monitoring wells and the injection well as part of validating ZVI particle distribution. All wells showed indications of dechlorination with only dechlorination products, with high concentrations of ethene and ethane, present by the end of two months at ambient temperature. Data indicate a mixture of abiotic reactions and biotic dechlorination reactions were occurring as daughter products also included cis-DCE (biotic) and ethene and ethane (abiotic).

For the ISB test cell, efficient degradation of TCE was established during Phase 2 via monthly injections of emulsified vegetable oil and powdered whey for nine months. A reactive treatment zone approximately 20 feet in diameter and 12 feet thick was established where geochemical conditions were generally reduced to support methane production and reductive dechlorination of TCE to primarily cis-DCE with trace ethene was achieved at ambient temperature. However, relatively high groundwater velocities within the treatment zone resulted in relatively low retention of amendment within the test cell, which was the reason that monthly injections were conducted.

Electrical resistance heating was applied to raise the temperature in the test zone to between 30^{o}C and 45^{o}C in the ISB test cell and to 40^{o}C and 55^{o}C in the ZVI test cell. The elevated temperatures increased the dissolution of contaminant into the groundwater and increased the rate and extent of dechlorination in both test cells. The viability of moderately-heated in situ treatment requires that increases in physical mass transfer rates for both dissolution and volatilization as temperatures increase must be balanced by contaminant degradation to prevent transport of mobilized contaminants out of the heated treatment zone. Contaminant dissolution and volatilization generally increase with increasing temperature. Imhoff et al., 1997 empirically and predictively reported that moderate temperature increases during hot water flushing for chlorinated solvent treatment enhance the mass transfer rate of residual DNAPL by a factor of 4 to 5 when temperatures were increased from 5^{o}C to 60^{o}C. Similarly, total contaminant mass discharge observed during the ER-0719 demonstration increased by a factor of 4-16 within the ZVI test cell at approximately 45^{o}C compared to ambient temperatures of 10^{o}C. This enhanced mass transfer was evaluated largely based on reductive daughter products as the degradation kinetics were sufficiently high to keep TCE concentration low. For the ISB test cell, total contaminant mass discharge increased by a factor of approximately 4-5 at approximately 40^{o}C compared to ambient temperatures of 10^{o}C. The fraction of ethene dramatically increased during Phase3 compared to Phase 2. A longer reactive zone was required downgradient of the ISB DNAPL zone to ensure complete biodegradation of contaminants transported from the heated zone. In addition, contaminant fluxes to the vadose zone increased by less than 1.5% at the elevated temperatures compared to ambient indicating VOC losses to the vadose zone were minimal.

A summary of cost factors for low-temperature ZVI and ISB suggest that low-temperature heating is less expensive than high temperature ERH, but only incrementally so. Therefore, application of low-temperature heating likely makes sense only for sites that contain only low to moderate VOC concentrations as residual in soil where contaminant mass could be removed in less than 1-2 years. However, the benefit of heating to in situ reactions was clearly demonstrated both from an enhanced kinetics of degradation reactions and VOC mass removal rates. Therefore, combining in situ treatment with heating, especially for sites already considering high temperature heating, may provide added benefit. In addition, in situ technologies could be implemented after thermal shut down to treat any remaining contaminants in the treatment zone.

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
ARD	anaerobic reductive dechlorination
bgs	below ground surface
^{o}C	degree Celcius
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CMT	continuous multi-channel tubing
COC	contaminant of concern
COD	chemical oxygen demand
DCE	dichloroethene
DHC	Dehalococcoides spp.
DNA	deoxyribonucleic acid
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DoD	U.S. Department of Defense
EGDY	East Gate Disposal Yard (Fort Lewis)
EOS®	emulsified oil substrate
EPA	U.S. Environmental Protection Agency
ERH	electrical resistance heating
ESTCP	Environmental Security Technology Certification Program
ft	feet
gpm	gallons per minute
ISB	*in situ* bioremediation
JBLM	Joint Base Lewis-McChord
kW	kilowatt
kWh	kilowatt hour
LOTO	Lock-Out/Tag-Out
µg	microgram
µg/kg	microgram per kilogram
µg/L	microgram per liter
MBAC	Methanobacteriales
MCOC	Methanococcales
mg/L	milligram per liter
MCRF	Molecular Core Research Facility
MMIC	Methanomicrobiales
mmol	millimole
MROD	Mount Rainer Ordnance Detail
MSAR	Methanosarcina
msl	mean sea level
MVS	Mining Visualization System

MW	monitoring well
NAPL	non-aqueous phase liquid
O&M	operations and maintenance
ORP	oxidation-reduction potential
PCE	tetrachloroethene
PCU	power control unit
PID	photoionization detector
ppm	parts per million
PVC	polyvinyl chloride
POL	petroleum, oils, and lubricants
PPE	personal protective equipment
qPCR	quantitative polymerase chain reaction
RCRA	Resource Conservation and Recovery Act
RI	remedial investigation
SV	soil vapor
TCA	1,1,1-trichloroethane
TCE	trichloroethene
TMP	temperature monitoring point
TOC	total organic carbon
TRS	Thermal Remediation Services
UIC	underground injection control
uM	micromoles per liter
USACE	United States Army Corps of Engineers
USCS	Unified Soils Classification System
VC	vinyl chloride
VFA	volatile fatty acid
VOA	volatile organic analysis
VOC	volatile organic compound
WAC	Waste Acceptance Criteria
WDOE	Washington Department of Ecology
ZVI	zero valent iron

SECTION 1
INTRODUCTION

This report describes results of a field demonstration combining low energy electrical resistance heating (ERH) with *in situ* bioremediation (ISB), or with iron-based reduction using zero valent iron (ZVI), for the remediation of dense non-aqueous phase liquid (DNAPL) source zones. The field demonstration was conducted at Joint Base Lewis-McChord (JBLM) Landfill 2, formerly known as the Fort Lewis East Gate Disposal Yard (EGDY). The demonstration is focused on illustrating the benefits of combining low-energy ERH with either ISB or with iron-based reduction using injectable ZVI. This effort includes assessing the extent to which contaminant degradation is enhanced during heating compared to ambient temperatures, the relative contribution of biotic and abiotic contaminant degradation mechanisms at different temperatures, and the cost-benefit of applying low-energy heating with in situ treatments. The demonstration was conducted in three phases to allow accurate evaluation of the effects of ERH on ISB and ZVI reduction. The ISB and ZVI tests were conducted in hydraulically isolated test cells in the following three phases:

- Phase 1: Pre-characterization and verification of the suitability of each test cell to meet demonstration objectives, treatment system installation, and baseline sampling.
- Phase 2: Field demonstration of ISB and ZVI (without low-energy ERH).
- Phase 3: Field demonstration of ISB and ZVI (with low-energy ERH).

The remainder of Section 1 briefly discusses background information, overall demonstration objectives, regulatory drivers, and stakeholder/end-user issues. The technologies are described in Section 2 and performance objectives are described in Section 3. Site conditions are described in Section 4. A detailed description of the technology demonstration design is presented in Section 5. The performance assessment strategy is described in Section 6. The cost assessment and implementation issues are addressed in Sections 7 and 8, respectively.

1.1 Background

Chlorinated solvents are the most prevalent contaminants detected at hazardous waste sites according to the U.S. Environmental Protection Agency (EPA) National Priorities List. The U.S. Department of Defense (DoD) alone has approximately 3,000 sites contaminated with chlorinated solvents, with a large percentage of these sites containing residual sources of contamination containing DNAPLs, which serve as continuing, long-term sources of dissolved phase groundwater contamination.

The prevalence of chlorinated solvents has been linked to both to their widespread use and to their longevity in the environment. Their longevity is partly due to the hydrophobic nature that makes them such good solvents, as well as their relatively oxidized states that prevent them from serving as electron donors for microorganisms. Pertinent to their longevity is the fact that the solubility of the common chlorinated solvents (i.e., tetrachloroethene (PCE), trichloroethene (TCE), 1,1,1-trichloroethane (TCA), and carbon tetrachloride) ranges from about 200 to 1,400 milligram per liter (mg/L) at 25°C (Sale 1998). These relatively low solubilities play a significant role in limiting mass transfer to the aqueous phase once the solvents contaminate groundwater. Dissolution of a DNAPL into groundwater is governed by the difference between the aqueous solubility of the compound and the actual concentration in groundwater. At typical groundwater velocities, the aqueous concentration of the solvent in the immediate vicinity of the groundwater non-aqueous phase liquid (NAPL) interface approaches the solubility within the first few centimeters of the DNAPL (Bouwer and McCarty 1983). Due to the laminar flow nature of most groundwater systems, very little mixing of water occurs, even a few centimeters from the DNAPL; thus, there is limited dissolution of DNAPLs into groundwater. The result is that chlorinated solvents can persist in groundwater for many decades.

The prevalence of DNAPL sites has prompted the DoD’s Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) program to develop a technical review panel focused on developing the strategy for research, and ultimately development of cost-effective technologies, to treat these sites. In particular, ESTCP has recognized a fundamental need for assessment of source zone treatment technologies focused on better implementation of existing technologies. Three relatively mature technologies, namely enhanced ISB, *in situ* iron-based reduction using ZVI, and thermal treatment using ERH, have been demonstrated independently for residual source zones. *In situ* technologies destroy contaminants without generation of secondary waste streams, are non-hazardous to workers and the environment, have relatively low capital and maintenance costs, and generally minimize disturbance of the site.

The remedial timeframe using many *in situ* technologies, however, is relatively long due to limitations in mass transfer of contaminants from the residual to the dissolved phase, where contaminants are available for destruction. Thermal treatment through ERH, which is a proven aggressive technology for the treatment of DNAPL source zones, rapidly removes large quantities of residual mass from subsurface environments. However, high capital and maintenance costs and the requirement for vapor control and secondary waste treatment make this technology a high cost alternative at many contaminated sites. Combining *in situ* and thermal treatment may provide many of the benefits of the *in situ* treatments with the shorter remedial timeframe associated with thermal treatment. This proposal is focused on demonstrating the benefits of combining low-energy ERH with either ISB or with iron-based reduction using injectable ZVI, including the assessment of the extent to which contaminant degradation is enhanced during heating compared to ambient temperatures, the relative contribution of biotic and abiotic contaminant degradation mechanisms at different temperatures, and the cost-benefit of applying low-energy heating with *in situ* treatments.

In providing thermally enhanced ISB or ZVI treatment, dissolution of DNAPL would be enhanced by the following phenomena:

1. At elevated temperatures, the dissolution rate of DNAPL is increased compared to lower temperatures. Dissolution of DNAPL is proportional to the diffusion rate in the water film. Because diffusion rate increases with temperature, so does the dissolution rate. For the

proposed technology, it is important to maximize dissolution of DNAPL while minimizing volatilization so that the contaminants are transferred and maintained in the aqueous phase (where *in situ* reactions occur),but not transferred to the gas phase (where they must be captured to avoid spread of contamination).

2. At elevated temperatures, the desorption rate is increased compared to lower temperatures. An increase in temperature will enhance the rate of contaminant desorption and thereby improve the availability of these contaminants for degradation.

Although ERH, ISB, and ZVI are relatively mature technologies, the benefits of combining these technologies have not been fully demonstrated or validated. The overall cost for a combined system will be significantly lower than the cost for standard ERH because of the utilization of a low-energy system. Additionally, combining technologies will make *in situ* contaminant destruction reactions more effective for source area treatment. This combined technology approach is expected to provide more rapid source area cleanup than the ambient temperature *in situ* technologies alone but without the high cost of conventional ERH associated with boiling the entire water column and extracting and treating contaminants at the surface.

1.2 Objective of the Demonstration

This demonstration is designed to evaluate the benefits of combining low-energy ERH with either ISB or with iron-based reduction using injectable ZVI. To evaluate the potential for decreased costs and increased efficiency of the combined remedies, the specific technical objectives of this demonstration are as follows:

- **Objective 1:** To validate the rate and extent to which contaminant degradation is increased during enhanced ISB at a temperature of approximately 30 to 40°C compared to ISB at ambient temperature.

- **Objective 2:** To validate the rate and extent to which contaminant degradation is increased during iron-based reduction at a temperature of approximately 50 to 60°C compared to ambient temperature.

- **Objective 3:** To determine the relative contributions of biotic and abiotic degradation at different temperatures in order to optimize each.

- **Objective 4:** To use data collected from a controlled field demonstration at a DoD site to develop cost and performance data for the combined remedies.

The goal of using heating to enhance *in situ* reactions is to treat a source area more cost effectively than is possible with only heating (e.g., ERH) or only an *in situ* remediation technology (e.g., ISB). A key data need for determining how to meet this goal is in finding the “sweet spot” where the cost of heating is more than offset by the gains in treatment efficiency for the *in situ* remediation technology. The demonstration provided a controlled field setting to test the impact of increased temperature on treatment efficiency using these *in situ* technologies. The demonstration also provided key engineering data relative to how ERH can be cost-effectively designed and applied to provide moderate heating rather than the standard design for heating to the boiling point.

1.3 Regulatory Drivers

As stated in Section 1.1, chlorinated solvents are the most prevalent contaminants detected at hazardous waste sites, with the DoD alone having an estimated 2,151 sites with volatile organic compound (VOC) contamination in groundwater, with an estimated 85% of these sites containing residual sources (e.g., DNAPL) of contamination (EPA 2004). As stated previously, the solubilities of the common chlorinated solvents (PCE, TCE, TCA, and carbon tetrachloride) range from about 200 to 1,400 mg/L at 25°C (Sale 1998). These solubilities exceed Federal Safe Drinking Water Act maximum contaminant levels (see **Table 1-1**) by five to six orders of magnitude. The persistence of chlorinated solvents in groundwater, their prevalence, and their solubilities far in excess of health-based levels drive the need for cost-effective remediation technologies.

1.4 Stakeholders/End-User Issues

This demonstration involves technologies (i.e., ISB, ZVI injections, and ERH) that are generally well received by the regulators and the public for many reasons. There are many advantages to the technologies (outlined in Section 2.4), including lower overall risks, low secondary waste generation, lower cost, and minimal impacts during operation.

There are several additional issues of concern to stakeholders/end-users specifically related to the use of thermally-enhanced treatments, including:

1. How will the application of heat affect the performance of ISB and ZVI?
2. Can the thermal systems be designed to minimize volatilization of contaminants such that *in situ* treatment is effective at treating released contaminant mass?
3. Is low-temperature heating cost-effective relative to implementing ZVI and ISB at ambient temperature?

The sampling and analysis strategy includes monitoring the ZVI and ISB at ambient and at elevated temperature. Potential risks posed by increased contaminant flux due to increased groundwater temperatures will be mitigated by the concomitant increase in rates and extents of biotic and abiotic degradation. A mass balance approach will be implemented that evaluates the fate of contaminants in the vadose and saturated zones of the aquifer system to address the first issue. Comprehensive groundwater, soils, and soil gas analyses will be conducted to understand, in detail, performance of the treatments at ambient and elevated temperature. In addition, evaluation of the soil gas will be conducted during each of the three phases to ensure that volatilization of contaminant mass is not occurring without treatment to address the second issue. The third issue will be addressed by assessing overall treatment performance at ambient and elevated temperature and detailed cost assessment performed to determine the relative change in cost-effectiveness of treatment.

Table 1-1. Safe Drinking Water Act maximum contaminant levels for Ft. Lewis EGDY contaminants of concern (COCs).

Compound	Regulatory Limit (μg/L[1])
PCE	5
TCE	5
cis-DCE	70
trans-DCE	100
Vinyl chloride	2

[1] 40 CFR 141.61

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SECTION 2
TECHNOLOGY DESCRIPTION

The low-energy ERH with ISB and ZVI demonstration was conducted in two test cells at the JBLM Landfill 2 as shown in **Figure 2-1**. ERH, ISB, and ZVI are individually relatively mature technologies that have all been previously applied for chloroethene residual source area remediation. Each technology is described below with emphasis on information pertinent to application of combined treatment/heating configurations. The demonstration described in this report was the first field test for the combination of ISB/ERH and ZVI/ERH.

2.1 Low-Energy ERH

ERH has been used historically to treat soil and groundwater aggressively in contaminant source areas by increasing subsurface temperatures to the boiling point of water. At this temperature, steam is created *in situ* and contaminants are directly volatilized. The steam acts as a carrier gas to strip volatiles from the subsurface and route them to the surface under vacuum for treatment. The low-energy ERH approach discussed here is based on raising subsurface temperatures to approximately 30 to 60°C to enhance the rate of biotic and abiotic contaminant dechlorination, respectively (see **Figures 2-2** and **2-3** for biotic and abiotic degradation mechanisms). This less aggressive approach will use electrodes installed on a wider spacing using boring, pile-driving, or direct push technology and will eliminate vapor and steam recovery and treatment. As a result, the total cost of ERH can be reduced by 50 to 75%.

2.2 *In Situ* Bioremediation

ISB for chlorinated ethenes has been investigated, demonstrated, and implemented at numerous sites, including NAPL Area 3 of Landfill 2 at JBLM. Biostimulation techniques use injection of amendments as electron donors to grow indigenous bacteria capable of dechlorinating chloroethenes. In cases where complete dechlorination to non hazardous end products cannot be obtained by activity of indigenous bacteria, bioaugmentation has been applied to inoculate the subsurface with bacteria that are capable of complete dechlorination. Bioaugmentation is most effective for smaller treatment zones where the bacteria can be effectively distributed.

Enhanced dissolution of contaminants has also been demonstrated during ISB as a result of increasing the concentration gradient during removal of contaminants from the aqueous phase and producing more soluble reductive daughter products (Yang and McCarty 2000; Carr et al. 2000). In addition, high-concentration electron donor amendments also enhance dissolution of contaminants (Sorenson 2002; Macbeth et al. 2006; ESTCP ER-0218). Collectively, these data have suggested that an increase in dissolution of contaminants (by a factor of 4 to 16) can be expected during ISB. The added value of increasing temperatures may not only enhance dissolution further, but *biological reaction rates increase with increasing temperature within a specific range of temperature*. Microbial activity is a function of temperature, and for mesophilic microorganisms, which include *Dehalococcoides ethenogenes* (Empadinhas et al. 2004) as well as other dehalogenators (Suyama et al 2002), optimal metabolic rates are typically near 30 to 40°C, which ERH can stimulate (Heath and Truex 1994). **Figure 2-4** illustrates the spatial variation in *Dehalococcoides* spp. (DHC) concentrations at different temperatures during thermal

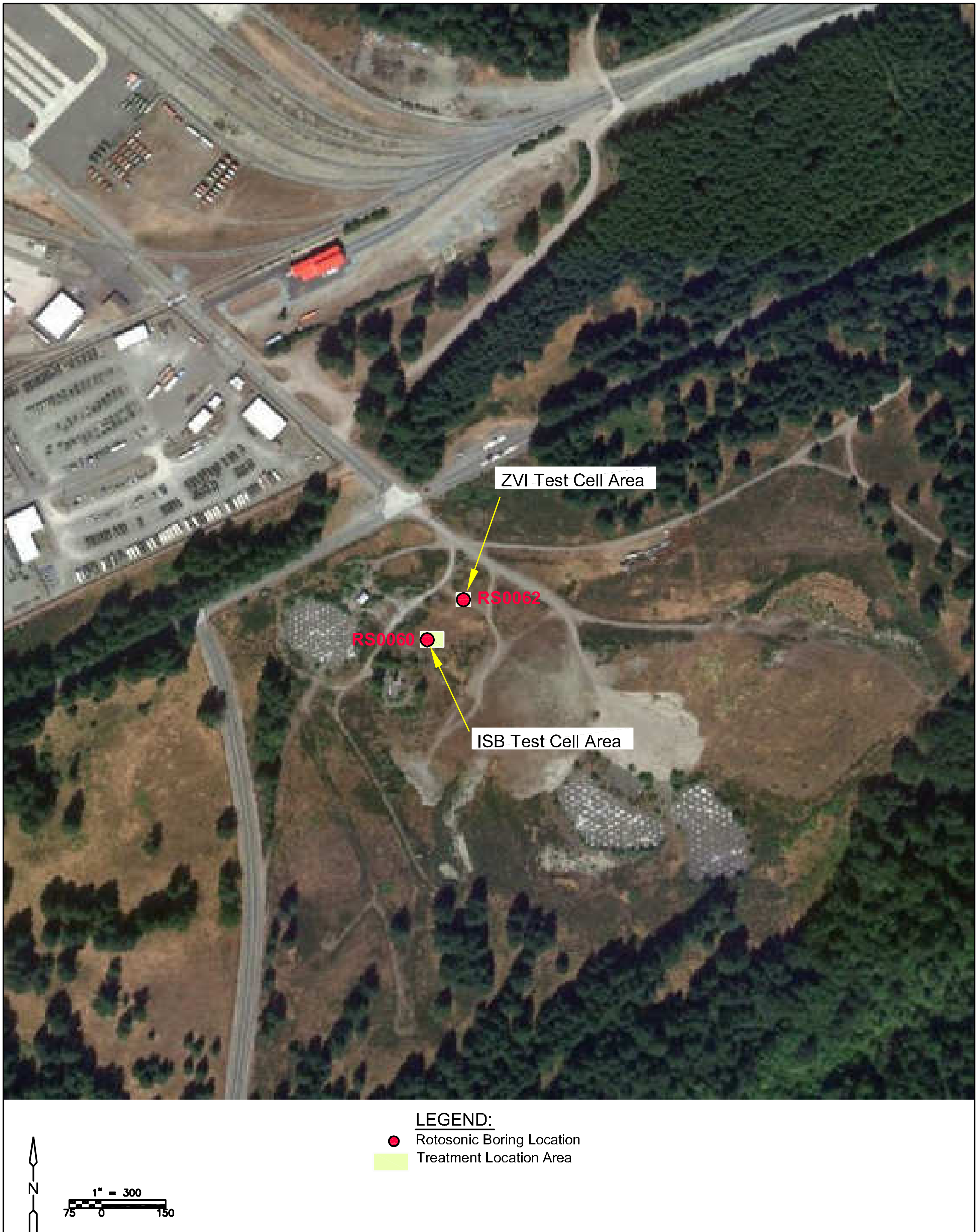

Figure 2-1.
Aerial view of Ft. Lewis EGDY and location of demonstration test cells.

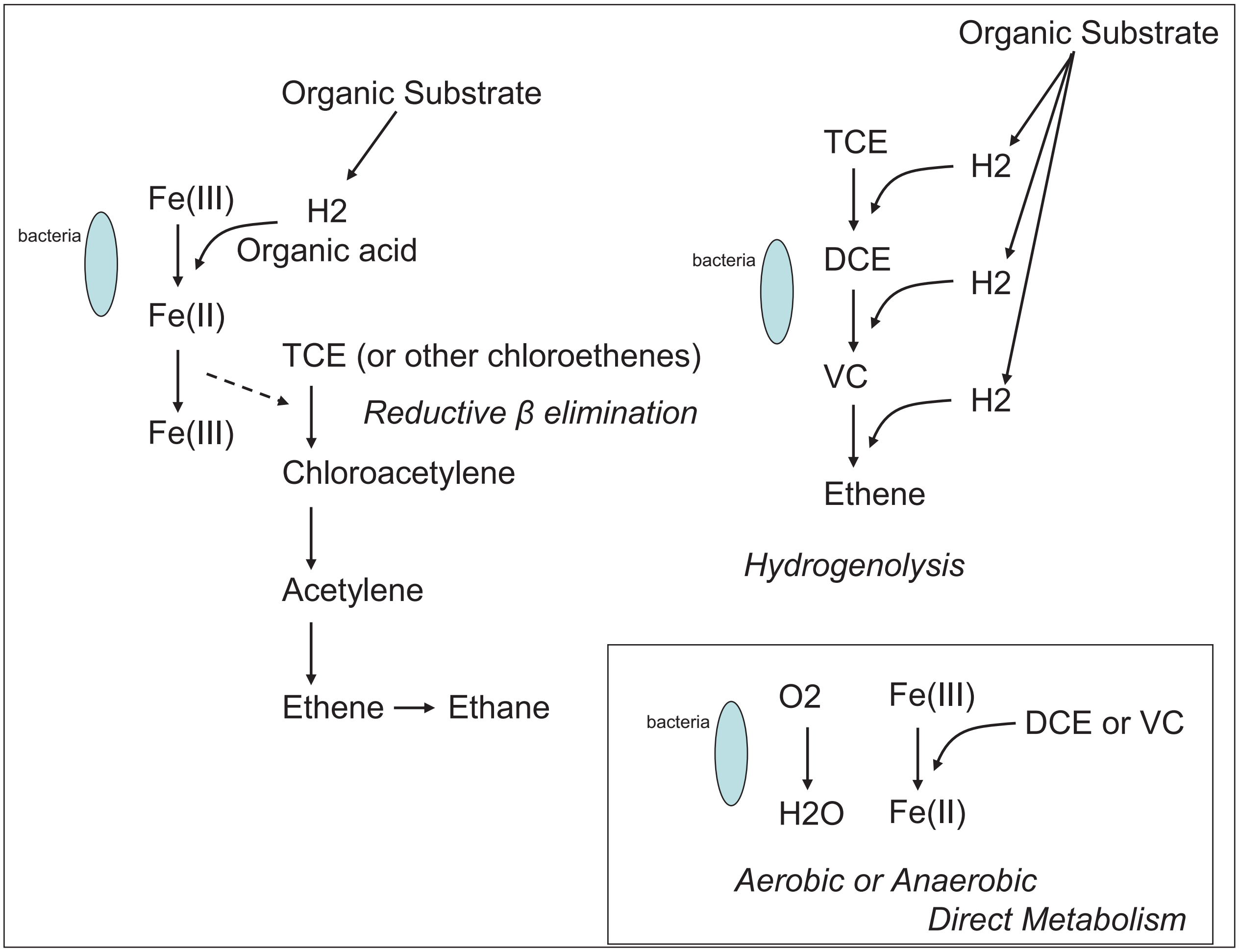

Figure 2-2. Potential reactions during ISB.

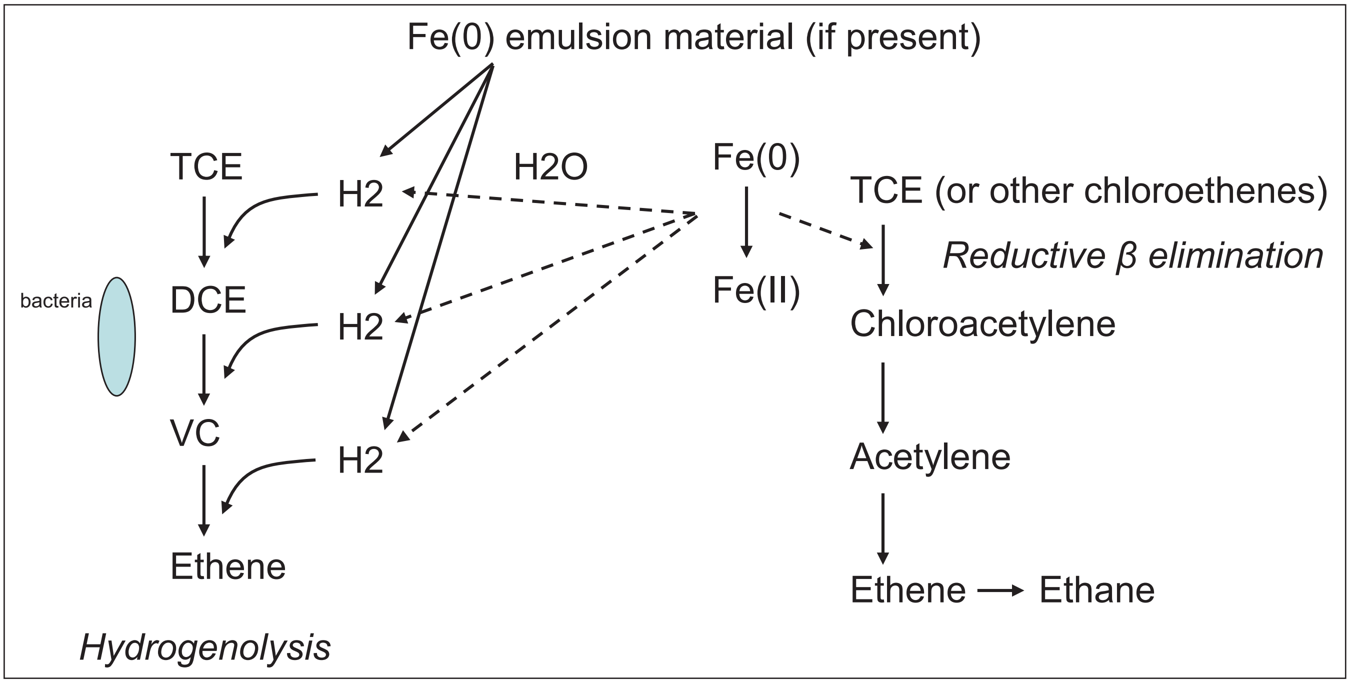

Figure 2-3. Potential reactions with ZVI.

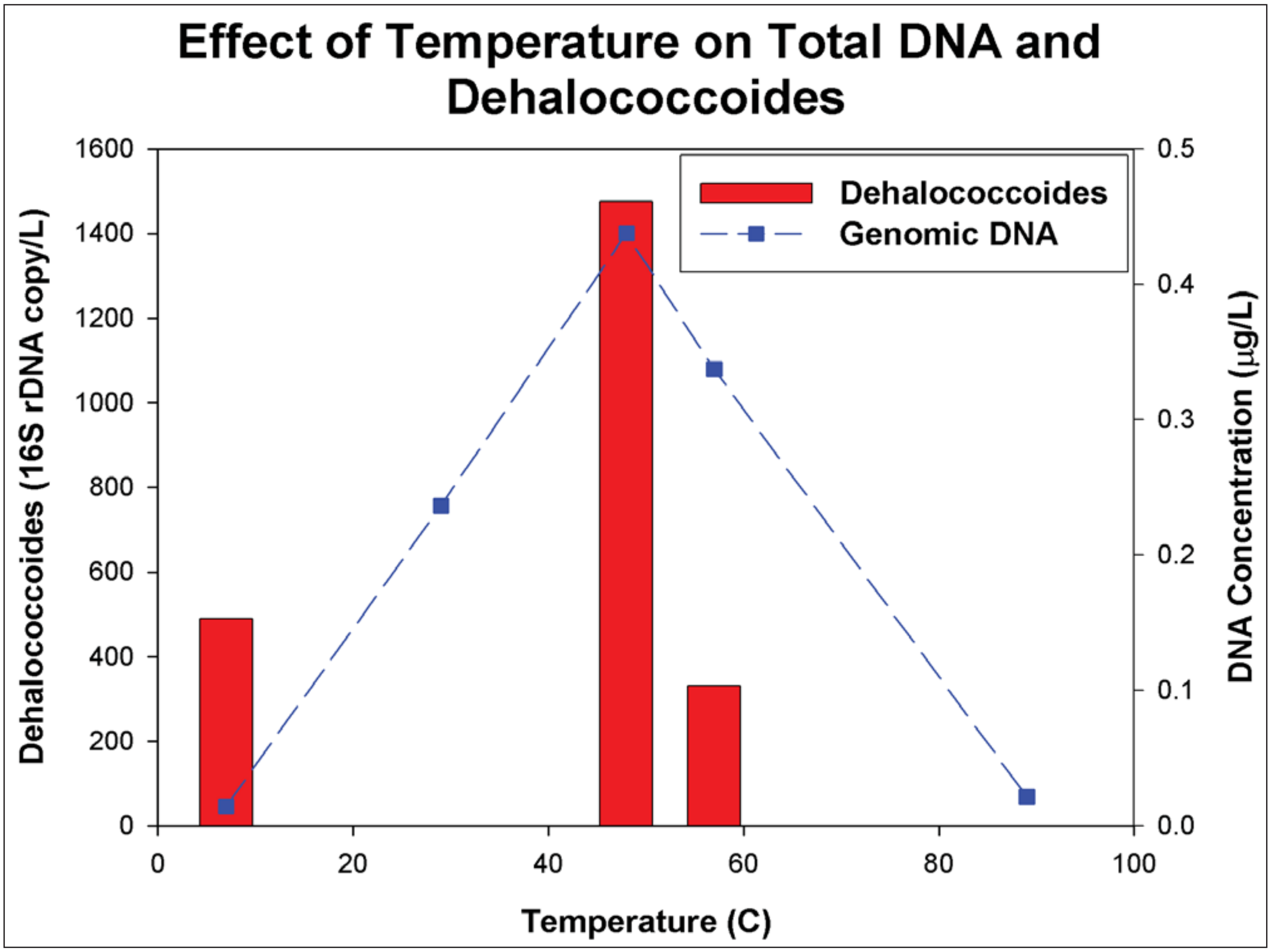

Figure 2-4. Preliminary data from Ft. Lewis show that DHC might have an optimal temperature range for growth that is well above typical ambient groundwater temperatures.

treatment at Fort Lewis Landfill 2, suggesting that DHC concentrations were higher at 48°C compared to ambient (10°C) (note: represents the natural response in groundwater where no other change in condition, besides a change in temperature, was effected).

In addition, **Figure 2-5** illustrates the response of DHC 16S rRNA gene and functional reductase genes *tceA*, *bvcA*, and *vcrA* at Fort Lewis NAPL Area 3 before and during ERH heating. DHC had been enriched at this location during ESTCP project ER-0218, which evaluated bioremediation in a source area. Following the onset of heating, a two order of magnitude increase in DHC and functional genes was observed at 33°C relative to ambient temperature (approximately 12°C). At high temperatures (>70°C), however, DHC concentrations were significantly reduced and only detected near the method detection limit (MDL).

2.3 ZVI Technology

Application of injectable ZVI and factors related to combination of ZVI with heating are described in detail by Truex et al. (2010 and 2011) and summarized in this section. Zero-valent iron (ZVI) has been developed and applied for *in situ* remediation of inorganic compounds and chlorinated solvents. Reaction mechanisms for ZVI and chlorinated solvents have been described by Arnold and Roberts (2000) and Roberts et al. (1996). Abiotic reductive elimination reactions facilitated by ZVI are beneficial for treatment of chlorinated contaminants, such as TCE), because no persistent hazardous degradation products are generated. ZVI reactions can also directly generate dichloroethene (DCE) (Arnold and Roberts 2000; Su and Puls 1999) and indirectly generate DCE (Hendrickson et al. 2002) and vinyl chloride (VC) (Maymo-Gatell et al. 1997) through facilitation of biotic reductive dechlorination. Initial kinetics of TCE dechlorination by ZVI are relatively fast and have been studied as a function of temperature (Su and Puls 1999), TCE concentration (Orth and Gillham 1996; Grant and Kueper 2004), type of iron (Miehr et al. 2004; Lin and Lo 2005; Ebert et al. 2006), and presence of multiple chlorinated solvents and other organic and inorganic species (Dries et al. 2004; Dries et al. 2005; D'Andrea et al. 2005). While initial kinetics of ZVI reactions are relatively fast, reaction kinetics can diminish over time due to corrosion and mineral precipitation, and the rate and extent of decrease in reaction rates are a function of groundwater chemistry (Farrell et al. 2000; D'Andrea et al. 2005; Kohn and Roberts 2006). Hydrogen is produced by ZVI reactions with water (Reardon et al 1995) and may stimulate biotic dechlorination of TCE with products including DCE, VC, and ethene.

A key aspect of ZVI application is successful distribution of sufficient ZVI particles in the subsurface to allow for necessary contact and reaction with the contaminant of concern (COC). Installation via trenching or physical mixing has been implemented (Wadley et al. 2005; ITRC 2005) but is not relevant for some situations. ZVI can be emplaced in an aquifer as either nano-scale or micron-scale particles. For longevity and overall cost-effectiveness, micron-scale particles are preferred, but injection of these particles using a standard groundwater well can be problematic. Their high density and size prevent the particles from being suspended in water and they cannot be injected without some form of facilitated transport. Research on improved injection strategies for iron particles has been conducted using emulsified oil (Quinn et al. 2005),

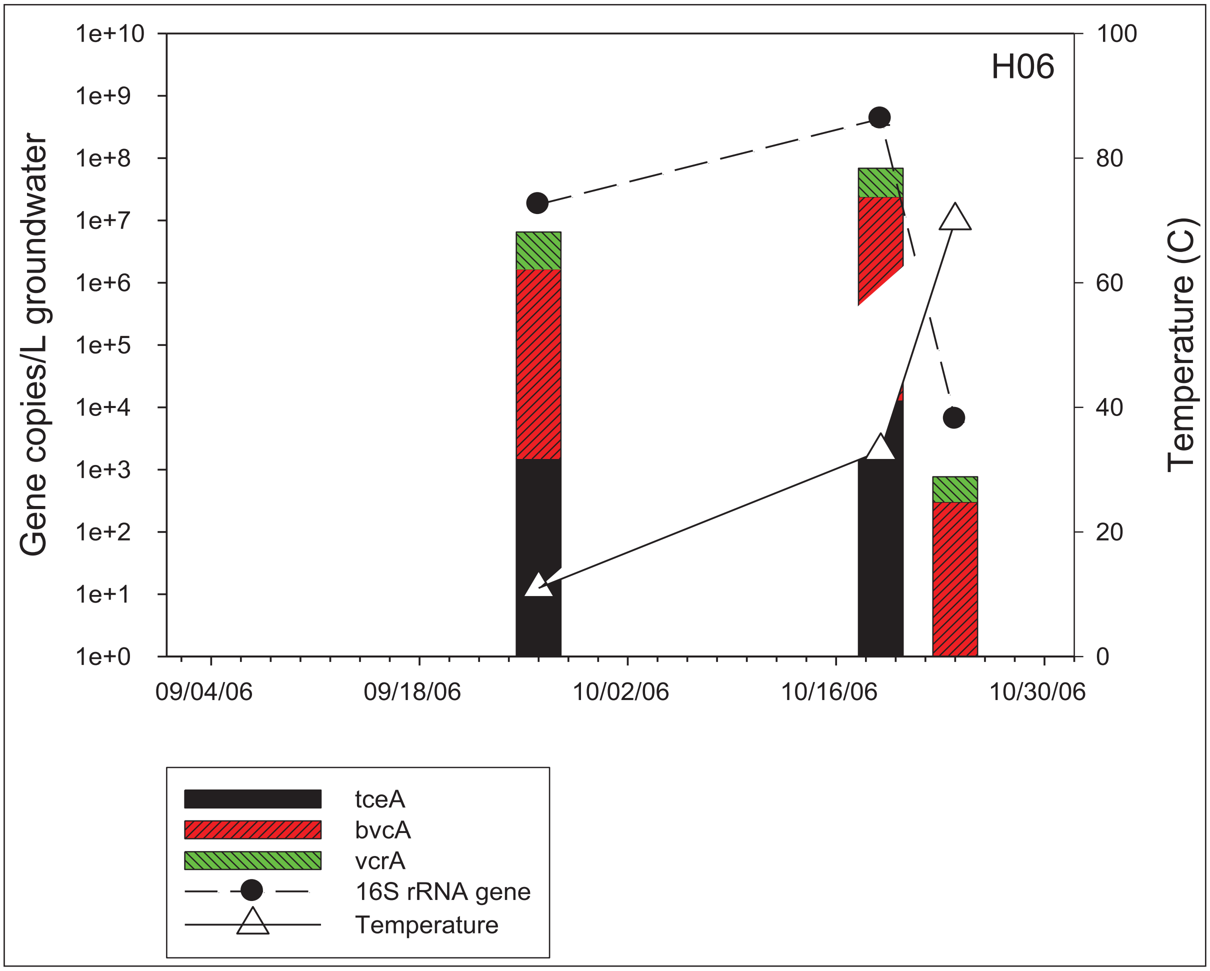

Figure 2-5. Ft. Lewis NAPL Area 3 data showing the response of DHC and functional reductase genes *tceA*, *bvcA*, and *vcrA* on increasing temperature during thermal heating during the ERH remedy.

hydrofracturing of the aquifer (Schnell and Mack 2003), use of carrier particles (Schrick et al. 2004), and co-injection of iron with polymers (Cantrell et al. 1997a,b; Oostrom et al. 2005, 2007). Shear-thinning polymers have been demonstrated to improve transport characteristics of micron-scale ZVI and show considerable promise for emplacing ZVI within the subsurface. These polymers have been shown to promote distribution of ZVI particles in columns and meter-scale wedge-shaped flow cells (Cantrell et al. 1997a, b; Oostrom et al. 2005, 2007), but have not been field-demonstrated.

Shear-thinning fluids are non-Newtonian fluids in that their viscosity is a function of the fluid shear rate, with higher shear resulting in lower fluid viscosity. The static viscosity of the fluid may be relatively high (e.g., 100 cP). With no shear-thinning properties, injection of a 100 cP fluid into porous media would require significant pressure. However, when a shear-thinning fluid is injected into porous media, movement through the pores creates high shear conditions and the viscosity decreases significantly, enabling injection at moderate pressure (Zhong et al. 2008). Shear-thinning fluids are effective for transporting ZVI particles because the high static viscosity of the fluid results in a low settling rate for the particles compared to the settling rate in water. Thus, the ZVI particles stay suspended for a relatively long time and can be moved through the porous media. The distance that the particles can be transported is a function of how far the fluid can be moved before the particles settle and contact the sediment. Filtration of particles also limits movement, so the ZVI particles must be sufficiently small relative to the pore size to minimize filtration.

An additional benefit of using shear-thinning fluid for applications that target residual contaminant mass in soils is that the treatment volume, once emplaced, can be designed to be hydraulically isolated. During injection, the ZVI particles are carried into the targeted zone and injection pressures remain moderate due to the shear-thinning effect. Once injection ceases, however, the shear rate declines and the fluid viscosity returns to near the static value. Because the injected fluid, at low velocity, has a much higher viscosity than the groundwater (i.e., 100 cP compared to 1 cP for water), the groundwater cannot readily displace the injected solution. In an unconfined aquifer, the groundwater tends to bypass the higher viscosity injected fluid rather than displace it. Thus, the injected fluid forms a relatively isolated treatment volume within the injection zone until the shear-thinning fluid degrades or dissipates. While isolated, the desired dechlorination reactions can proceed with minimal influx of dissolved oxygen (DO) and other solutes that can passivate the ZVI. For permeable barrier applications, flow through the barrier would be slow until the shear-thinning fluid dissipates or degrades. Use of shear-thinning fluids for creating a permeable reactive barrier and the rate of shear-thinning fluid dissipation were not investigated in this effort.

In situ remediation using ZVI, similar to other *in situ* remedies, has potential benefits including, destruction of contaminants without generation of secondary waste streams, limited hazards to workers and the environment, relatively low capital and maintenance costs, and generally minimal disturbance of the site. For *in situ* remedies such as the application of injectable ZVI amendments, contaminant mass destruction only occurs in the aqueous phase. Thus, the effectiveness and timeframe of these technologies, especially when applied where non-aqueous phase or significant sorbed contaminant mass is present, can be impacted by limitations in mass transfer of contaminants to the aqueous phase.

Enhanced mass transfer rate of contaminants from sorbed or DNAPL phases to the aqueous phase has been demonstrated during *in situ* treatment through: 1) increasing the degradation reaction rate can increase the concentration gradient between the DNAPL and water interface (Yang 2000; Cope 2001; Yang 2002; Christ 2007) and can generate more soluble, less sorbing degradation daughter products which increases the amount of contaminant mass that can be carried in the aqueous phase (Carr 2000); and 2) environmental conditions can be manipulated to enhance mass transfer (e.g. dissolution) of contaminants to the aqueous phase using cosolvents (Imhoff et al 1995), surfactants (Johnson et al 1999; Rathfeldera 2003, Singh 2007), and through dissolved organic matter partitioning (Macbeth 2008). Combining subsurface heating with *in situ* treatment has the potential to accelerate mass transfer further and to enhance remediation performance because higher temperatures can increase degradation reaction rates, dissolution, and volatilization.

The rate of both biologically-mediated reactions and ZVI reactions are expected to increase from temperatures typical of most groundwater systems (10-12˚C) to reach a maximum and then decline with further temperature increase. This type of temperature function is well documented for microbial processes (Atlas and Bartha 1987; Empadinhas et al 2004; Suyama et al 2002), and for reductive dechlorination reactions in particular (Kohring et al 1989, Holliger 1993, He 2003), and was observed for ZVI dechlorination processes (section 5.3). Note that the rate of some reactions, such as hydrolysis, may also continue to increase with increasing temperature.

Contaminant dissolution and volatilization generally increase with increasing temperature (Yaws et al. 2009, Sleep and Ma 1997, Horvath 1982). Typical thermal treatment applications increase temperatures to near the boiling point and mobilize DNAPL through generation of vapors which are extracted and treated. Imhoff et al, 1997 empirically and predicatively demonstrated that moderate temperature applications of hot water flushing for chlorinated solvent treatment enhance the mass transfer rate of residual DNAPL by a factor of four to five when temperatures were increased from 5 degrees Celsius (^{o}C) to 60^{o}C. Combining subsurface heating to moderate temperatures with *in situ* technologies, such as such as ZVI could negate the requirement for vapor extraction and treatment, which is a large fraction of the cost of typical thermal applications that reach boiling temperatures. For this approach to be viable, however, increases in physical mass transfer rates for both dissolution and volatilization as temperature increases must be balanced by reaction or contaminants will migrate out of the heated treatment zone without being degraded.

2.4 Advantages and Limitation of the Technology

Factors significantly affecting cost and performance of this technology include:

- **Ability to identify the NAPL or sediment-associated contaminants and adequately deliver electron donor or ZVI.** This factor is associated with site-specific properties, including depth, permeability and heterogeneity of the formation, and NAPL/sediment-associated contaminant distribution. This factor can be assessed by baseline characterization using NAPL-locating techniques, including geophysics, tracer tests, groundwater sampling, and boreholes. This factor can be addressed by installing adequate numbers of electron donor and/or ZVI injection wells in the source area and/or adjusting volumes and/or concentrations of amendments used to achieve adequate contact. Wells may be screened or packers installed to target selected intervals for amendment delivery.

- **Ability to treat large source mass.** Both ZVI and ISB would have a limited overall capacity for source treatment. Zones with high NAPL saturation would require a high dosing of ZVI or ISB substrates and long treatment times. In those cases, other treatment **approaches may be more cost effective.**

- **Presence/absence of a microbial community capable of complete conversion of TCE to ethene (ISB test cell).** This factor can be assessed through baseline sampling for the presence/absence of VC and ethene; or through molecular evaluation of the microbial community, including quantitative polymerase chain reaction (qPCR) or deoxyribonucleic acid (DNA) based microarrays. These latter techniques can identify specific ribosomal DNA community profiles for comparison to those known to perform complete dechlorination. This factor may be addressed through bioaugmentation.

There are significant advantages of coupling low energy thermal treatment with either ISB or ZVI injections relative to implementing each of these technologies alone. These include:

- **Minimal above ground infrastructure—**The coupling of *in situ* technologies with moderate heating negates the need for above ground treatment systems generally necessary for conventional thermal applications.

- **Lower safety hazards—**Moderate heating also has the advantage of minimizing safety hazards associated with high temperature heating of the subsurface.

- **Low risks—**The remediation strategies take advantage of *in situ* treatment where most or all of the contaminant treatment occurs in the soil or groundwater, thereby reducing risks to human health and the environment during implementation compared to ex situ technologies.

- **Low secondary waste generation—**Most of the contaminant treatment occurs on-site, with little off-site disposal of residuals required. In addition, secondary treatment usually associated with thermal treatment (i.e., soil vapor (SV) extraction and ex-situ treatment) will not be required.

- **Lower cost—**The cost assessment from the field demonstration showed moderate cost increases by adding heating infrastructure, in addition, the technology can be coupled to high temperature thermal applications where much of the infrastructure is already available.

- **Overall risk reduction**—Demonstration data show that heating-enhanced ZVI and ISB can achieve moderate treatment endpoint conditions for groundwater and sediment contamination.

These technologies, however, face several limitations, including:

- **Greater uncertainty in treatment performance and life cycle costs.** Uncertainties are inherent with *in situ* processes because conditions throughout the entire targeted region cannot be explicitly manipulated to create conditions that are optimal for the desired *in situ* reaction at all locations in the subsurface.
- Site-specific conditions can limit application of many *in situ* remedial technologies, including complex lithology, low permeability media, and/or complex geochemistry.

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SECTION 3
PERFORMANCE OBJECTIVES

As previously stated, the overall objective of this demonstration was to evaluate the cost-benefit of applying low-energy ERH in combination with ISB and iron-based reduction technologies. With this in mind, detailed performance objectives were developed for each phase of the demonstration that will help meet the overall objective. **Table 3-1** outlines the overall qualitative and quantitative performance objectives for the demonstration. It is important to note that interpretation of the data relies on a comparison of the reaction kinetics and evaluation of mass balance components in soils, soil gas, and groundwater (including contaminants and reductive daughter products) between Phases 2 and 3 in each individual cell. This approach avoids the difficulties in interpretation that would be introduced due to unknown differences in hydrogeologic heterogeneity and DNAPL distribution if ambient and heating tests were conducted in separate locations. That is, it allows treatment performance measurements in Phase 3 to be normalized by those made in Phase 2 in each cell. For instance, changes in treatment efficiency from Phase 2 to Phase 3 within a cell were used to quantify the effect of heating on remediation performance. The cost benefit of heating was also assessed.

Information for the cost benefit assessment includes the capital and operating cost data for the amendments, injection/hydraulic control systems, and heating system and demonstration data used to estimate the remediation timeframe and operational conditions necessary for the ambient temperature and the heated treatment. For instance, amendment quantities, electricity usage, equipment costs, and labor requirements were tracked during the test (see Section 5). The contaminant degradation rate data was measured and used to estimate treatment timeframe. This information was then used to develop a life-cycle cost estimate, including capital and operating costs and a present value assessment, so that overall remediation costs for the ambient and heated treatments can be effectively compared.

Table 3-2. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Performance (Metric)
Qualitative	Induce dechlorination of chlorinated ethenes.	Dechlorination to desired endpoints will be achieved in each treatment cell.
	Reduction in parent compounds and accumulation of abiotic and/or biotic reductive daughter products.	Biotic contaminant removal will be the primary mechanism at ambient and elevated temperature in the ISB test cell. Abiotic and biotic contaminant removal will be significant in the ZVI test cell at ambient temperature; however, abiotic mechanisms will predominate at elevated temperature.
Quantitative	Characterize nature of contamination with test cell.	Sufficient contaminant mass will be present in both test cells to meet demonstration objectives.
	Define rate of dechlorination as a function of temperature.	The rate of dechlorination will be enhanced at elevated temperature in both test cells relative to ambient temperature.
	Quantify test cell mass balance and loss mechanisms for chlorinated ethenes in the test cells as a function of temperature.	Contaminant mass removal will be enhanced at elevated temperature in both test cells relative to ambient temperature.
	Evaluate cost-effectiveness of heating.	The overall treatment efficiency at elevated temperature will be enhanced sufficiently to offset the cost of heating in both test cells.

SECTION 4
SITE DESCRIPTION

4.1 Site Location and History

Construction at the Logistics Center site began in 1941 with construction of the Quartermaster Motor Base, which was renamed the Mount Rainier Ordnance Depot (MROD) in 1942. It operated until 1963, furnishing ordnance supplies, maintenance and rebuilding services for Fort Lewis until 1963. In 1963, the MROD was turned over to the Logistics Center to serve as the primary non-aircraft maintenance facility for the post.

TCE was used as a degreasing agent at this facility until the mid-1970s, when it was replaced with TCA. Waste TCE was co-disposed with waste oils at several locations. The EGDY was used between 1946 and 1960 as a disposal site for waste generated at the MROD. Trenches were excavated in the yard and reportedly received TCE and petroleum, oils, and lubricants (POL) from cleaning and degreasing operations. These materials were transported to the EGDY in barrels and vats from the various use areas; about six to eight barrels per month of waste TCE and POL may have been disposed. These materials were also used to aid in burning other wastes.

4.2 Site Geology/Hydrogeology

4.2.1 Geology

At least three glacial and three non-glacial units have been identified in the sediments occurring above sea level at the EGDY. These units and a brief description are listed below, sequentially from youngest (shallowest) to oldest (deepest):

- Holocene-Anthropomorphic Deposits. These consist of man-made fill in the trench areas and include debris and burned material. These materials typically extend to less than 12 feet (ft) bgs (for reference, nominal site ground surface is 278 ft elevation with respect to the NGVD29 vertical datum).

- Vashon Glacial Drift Deposits. These consist of glacial deposits including recessional outwash, till and ice contact deposits, advance outwash and glaciolacustrine silt/clay. Vashon drift deposits typically extend from ground surface to approximate depths of 70 to 95 ft. The only Vashon Glacial Drift deposit present within the vertical extent of the demonstration area was recessional outwash.

    - Vashon Recessional Outwash–Interbedded brown to gray sandy gravel and sand with minor silt intervals; also loose, well-graded brown to gray sandy, cobbly gravel from at or near ground surface to 5 to 50 ft bgs.

    - Vashon Till and Ice Contact Deposits–Dense, gray silty-sandy gravel and gravelly sandy silt, 4 to 35 ft thick were present; typically 10 to 60 ft bgs at EGDY, although deeper than 30 ft bgs within the demonstration area.

    - Vashon Advance Outwash–Interbedded brown to gray sandy gravel and sand, some cobbles, with minor silt interbeds.

- Glaciolacustrine Silt/Clay–Gray, laminated to massive silt and clayey silt with minor fine sand interbeds. Also very stiff to hard, dark gray clayed massive silt varying in thickness from 10 to 150 ft, typically between depths of 80 and 230 ft.

- Olympia Beds–Mottled, massive, organic-rich clayey sandy gravel or lavender silt, peat, sand and gravelly sand. May be up to 40 ft thick. May not be present in the demonstration area.

- Pre-Olympia Drift–Gray to brown, fine-to medium-grained sand with minor sandy gravel interbeds, oxidized at the top, common silt interbeds at the base, with discontinuous till. Where present this unit is typically 10 to 70 ft thick.

- Second Non-Glacial Deposits–Mottled, massive, organic rich, clayey, sandy gravel (mudflows) or lavender silt, peat, sand, and gravelly sand (fluvial overbank deposits).

- Third Glacial Drift–Interbedded, orange to dark gray sand gravel and sand with minor silt interbeds, intensely iron oxide-stained at top (recessional outwash), dense, gray, silty, sandy gravel and gravelly sandy silt (till); and interbedded, gray to brown, to dark gray sandy gravel and sand with minor silt interbeds (advance outwash).

- Third Non-Glacial Deposits–Lavender silt, peat, sand and gravelly sand.

4.2.2 Hydrogeology

The primary aquifers and aquitards are listed below, sequentially from shallowest to deepest:

- Vashon Aquifer or Upper Aquifer. The Vashon drift, Olympia beds, and Pre-Olympia drift comprise the Vashon unconfined aquifer. Vashon till and Olympia beds may act locally as discontinuous aquitards within the Vashon aquifer. Vashon outwash and pre-Olympia drift deposits comprise the aquifer materials within the Vashon aquifer. The Vashon aquifer varies in thickness from 100 to 130 ft and is continuous throughout the EGDY.

- Intermediate Aquitard. A somewhat laterally continuous till layer may separate the Vashon aquifer locally into an upper and lower permeable unit separated by this relatively low-permeability till or glaciolacustrine silt. This till is notably absent immediately north of NAPL area 3 where low permeability units do not separate the upper and lower portions of the Vashon aquifer. The demonstration was performed in the upper Vashon aquifer, above the intermediate aquitard.

- Non-Glacial Aquitard. A regional aquitard consisting of low permeability second non glacial deposits separating the Vashon aquifer from the Sea Level (lower) aquifer.

- Sea Level Aquifer. Third glacial drift deposits and permeable lower deposits of the second non-glacial unit comprise the Sea Level aquifer. This unit is widely used as a source of groundwater for industrial and municipal use.

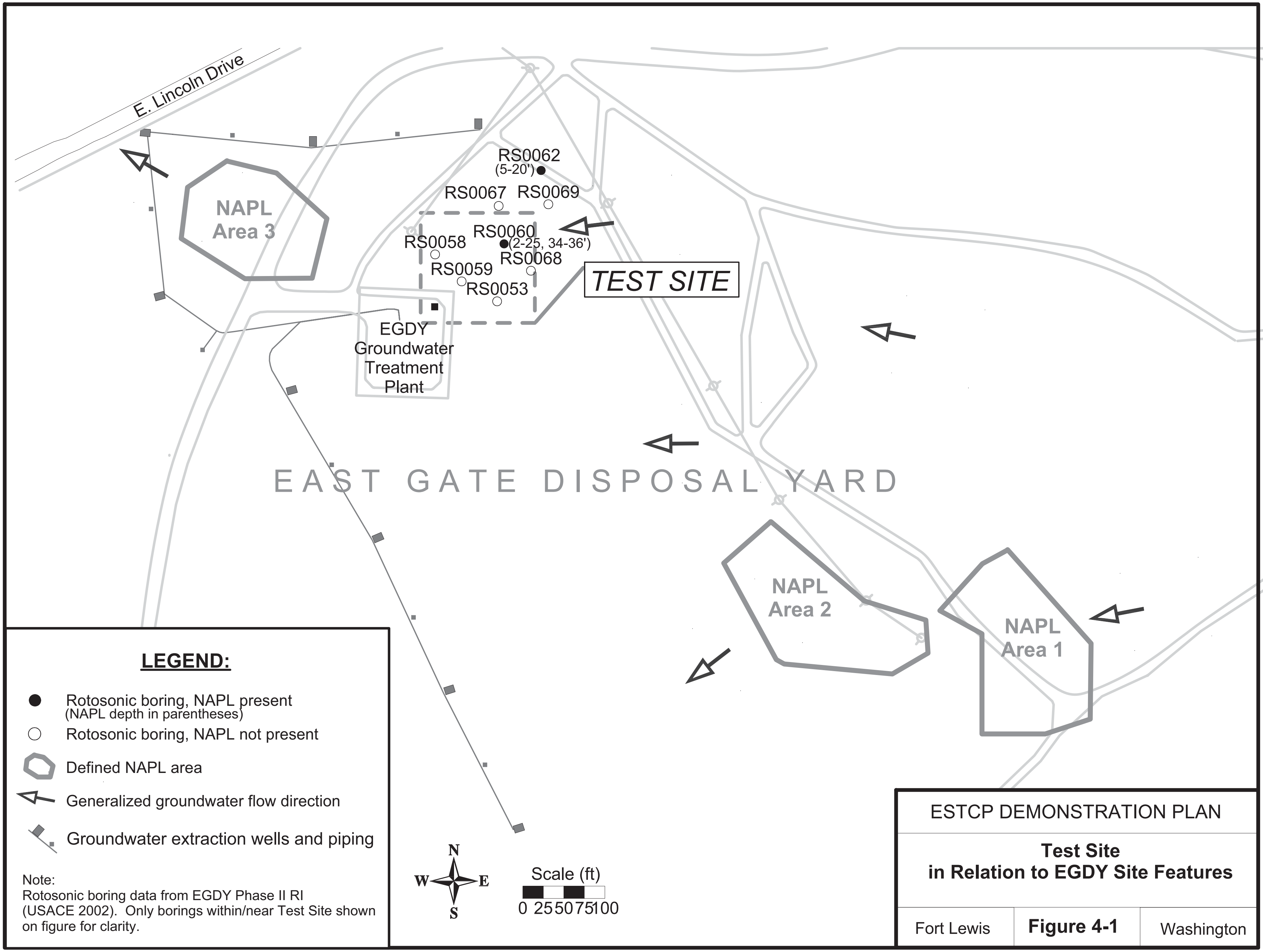
4.3 Contaminant Distribution

The test site is located in the north-central portion of what is known as Landfill 2, also referred to as the EGDY. Landfill 2 was used between 1946 and the mid-1970s as a disposal site for waste generated at the Fort Lewis Logistics Center. The Landfill 2 vicinity has been well characterized by extensive borehole stratigraphic sampling and logging and is situated on an upland glacial drift plain that occupies much of Fort Lewis and central Pierce County. Shallow stratigraphy is generally characterized by permeable sands and gravels of glaciofluvial origin underlain by a layer of dense, confining till and/or dense lacustrine silt. In addition to physical characterization, Landfill 2 had been extensively sampled for contaminant characterization, including soil, geophysical, and direct push and monitoring well (MW) groundwater analytical testing. These investigations have occurred dating back to 1988, when the Landfill 2 was first pinpointed as the principal source area of the Logistics Center TCE groundwater plume. A 13.5-acre portion of the Landfill 2 has been determined to contain the vast majority of former disposal trenches and wastes. Principal contaminants included TCE and daughter products and POL from cleaning and degreasing operations. Thermal remediation via ERH occurred at the three highest-concentration TCE-containing NAPL areas between 2003 and 2007 to reduce source mass significantly and ultimately to reduce the overall clean-up time frame of the plume. None of the three treated areas are within the direct hydraulic path of the test site, although NAPL Area 3 is approximately 250 ft downgradient and west of the site. **Figure 4-1** shows the treated NAPL areas in relation to the test site.

The immediate area surrounding the demonstration test site was characterized by continuous soil coring and logging of eight rotosonic-drilled borings during the Phase II EGDY Remedial Investigation (RI) in 2001 and- 2002. A geophysical investigation and follow-up drum removal project in 2000–2001 found the approximate locations of two NAPL-positive borings to be within or near separate former disposal trenches, each containing metal debris (including waste drums). The test site area, including the area investigated by the eight borings, is approximately 150 ft x 150 ft (22,500 ft^2). The test site is gently sloped to the southwest (4-foot elevation difference, ranging from 277 to 281 ft). The centers of the proposed test cells were each identified by a single NAPL-positive boring surrounded by several NAPL-negative borings (see **Figure 4-1**).

Based on the RI borings, the test site was characterized as consisting of sandy, well-graded gravel with few cobbles (Unified Soils Classification System [USCS] of well-graded gravel) ranging from 12 to 19 ft bgs, followed by a poorly-graded gravel with minor coarse sand and few cobbles to about 30 to 32 ft bgs. At some locations (i.e., RS0062), 2 to 4 foot thick interbeds of gravelly, medium- to coarse-grained sand were present within the 12 to 22 ft bgs range. The first significant low-permeability unit was encountered between 32 and 47 ft bgs and consisted of stiff, dense sandy lacustrine silt.

Depth to water at the test site reportedly was 8 ft bgs at RS0060 and 15.75 ft bgs at RS0062 in February/March 2002, which correlates to elevations of approximately 265 to 268 ft, respectively. Historical records indicate a likely seasonal fluctuation of up to 5 ft, with the lowest



Note:
Rotosonic boring data from EGDY Phase II RI (USACE 2002). Only borings within/near Test Site shown on figure for clarity.

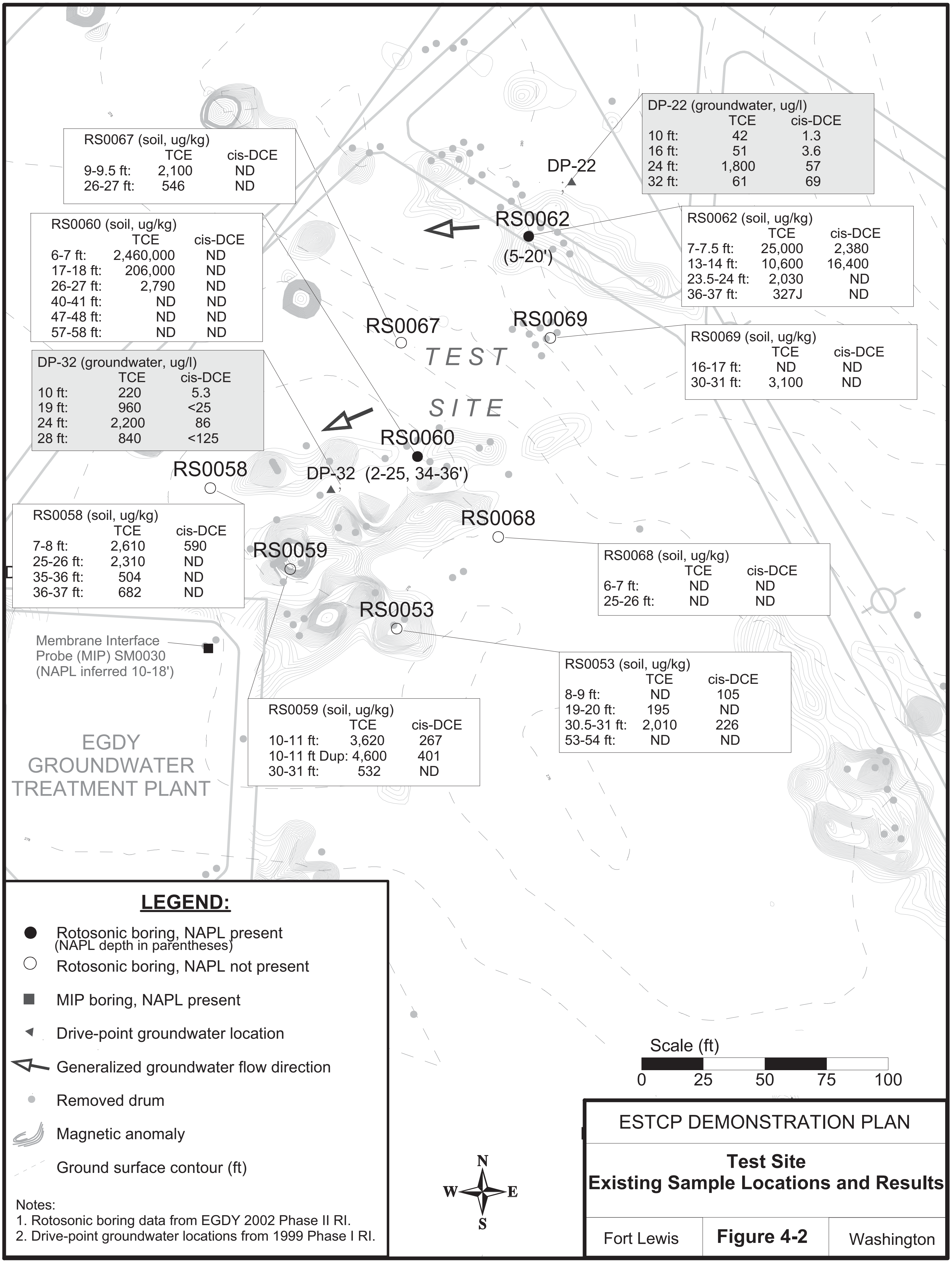
ESTCP DEMONSTRATION PLAN

Test Site in Relation to EGDY Site Features

Fort Lewis **Figure 4-1** Washington

groundwater levels in October and the highest levels in April. The horizontal hydraulic gradient is approximately 0.004 ft/ft in a westerly to southwesterly direction.

NAPL was observed within one of the NAPL-positive borings from approximately 5 to 20 ft bgs (designated RS0062) consisting predominantly of TCE (up to 25 mg/kg) and cis-DCE (up to 16.4 mg/kg). TCE was the predominant constituent (up to 2,460 mg/kg) within the second NAPL positive boring (RS0060), which contained NAPL from 2 to 25 ft bgs and 34 to 36 ft bgs. No cis-DCE was detected in samples from this boring. See **Figure 4-2** for a summary of existing TCE and DCE analytical results. NAPL consisting primarily of TCE from approximately 10 to 18 ft bgs was interpreted at membrane interface probe boring SM0030 conducted as part of the RI, as shown on **Figure 4-3**. All of the NAPL contamination was observed to be within permeable gravels and sands. **Figure 4-3** illustrates results of membrane interface probe SM0030 located at the edge of the EGDY groundwater treatment plant.



DP-22 (groundwater, ug/l)

	TCE	cis-DCE
10 ft:	42	1.3
16 ft:	51	3.6
24 ft:	1,800	57
32 ft:	61	69

RS0067 (soil, ug/kg)

	TCE	cis-DCE
9-9.5 ft:	2,100	ND
26-27 ft:	546	ND

RS0060 (soil, ug/kg)

	TCE	cis-DCE
6-7 ft:	2,460,000	ND
17-18 ft:	206,000	ND
26-27 ft:	2,790	ND
40-41 ft:	ND	ND
47-48 ft:	ND	ND
57-58 ft:	ND	ND

RS0062 (soil, ug/kg)

	TCE	cis-DCE
7-7.5 ft:	25,000	2,380
13-14 ft:	10,600	16,400
23.5-24 ft:	2,030	ND
36-37 ft:	327J	ND

RS0069 (soil, ug/kg)

	TCE	cis-DCE
16-17 ft:	ND	ND
30-31 ft:	3,100	ND

DP-32 (groundwater, ug/l)

	TCE	cis-DCE
10 ft:	220	5.3
19 ft:	960	<25
24 ft:	2,200	86
28 ft:	840	<125

RS0058 (soil, ug/kg)

	TCE	cis-DCE
7-8 ft:	2,610	590
25-26 ft:	2,310	ND
35-36 ft:	504	ND
36-37 ft:	682	ND

RS0068 (soil, ug/kg)

	TCE	cis-DCE
6-7 ft:	ND	ND
25-26 ft:	ND	ND

RS0053 (soil, ug/kg)

	TCE	cis-DCE
8-9 ft:	ND	105
19-20 ft:	195	ND
30.5-31 ft:	2,010	226
53-54 ft:	ND	ND

RS0059 (soil, ug/kg)

	TCE	cis-DCE
10-11 ft:	3,620	267
10-11 ft Dup:	4,600	401
30-31 ft:	532	ND

LEGEND:

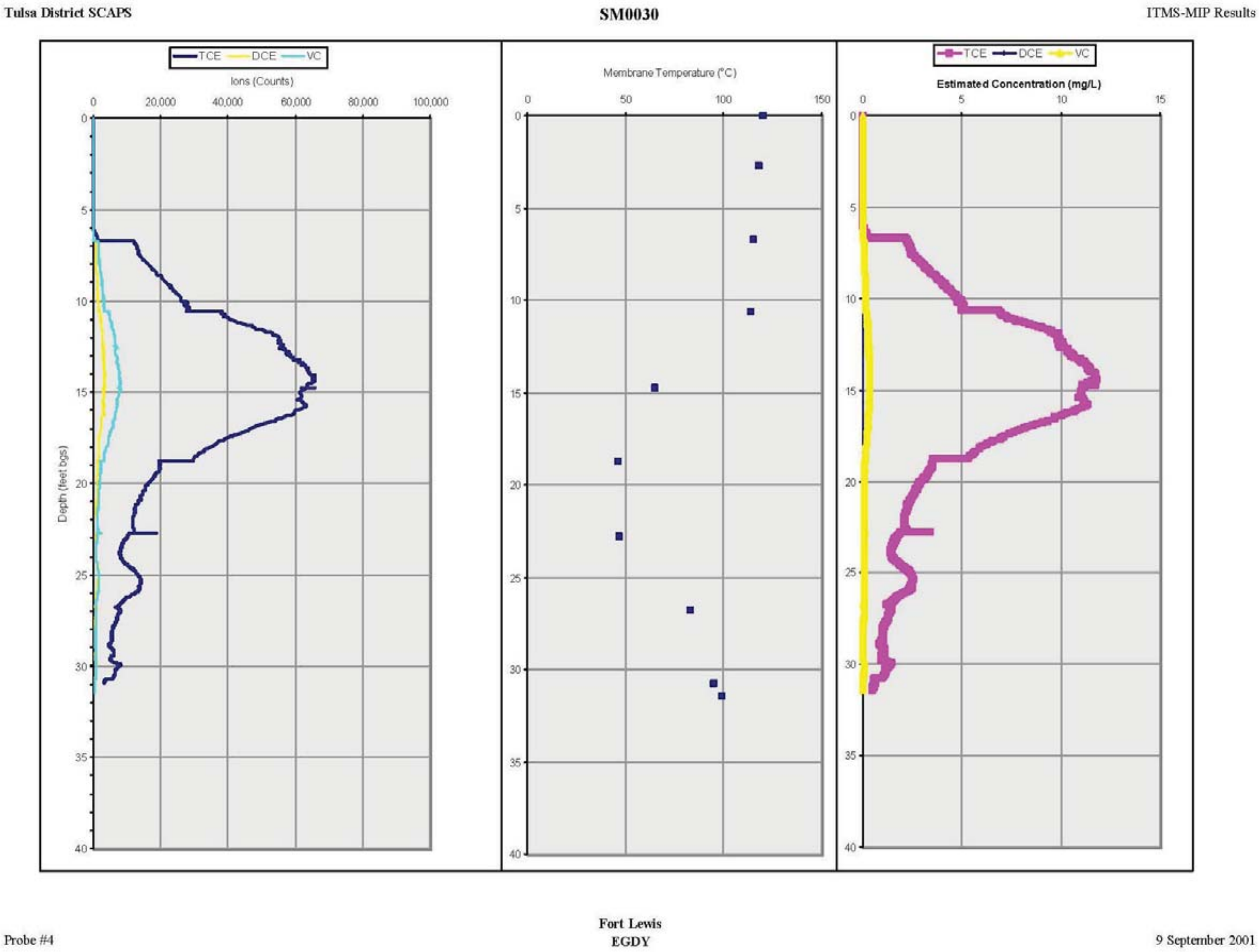
- ● Rotosonic boring, NAPL present (NAPL depth in parentheses)
- ○ Rotosonic boring, NAPL not present
- ■ MIP boring, NAPL present
- ▲ Drive-point groundwater location
- ⇦ Generalized groundwater flow direction
- • Removed drum
- Magnetic anomaly
- Ground surface contour (ft)

Notes:
1. Rotosonic boring data from EGDY 2002 Phase II RI.
2. Drive-point groundwater locations from 1999 Phase I RI.

ESTCP DEMONSTRATION PLAN

Test Site
Existing Sample Locations and Results

Fort Lewis **Figure 4-2** Washington


Tulsa District SCAPS

SM0030

ITMS-MIP Results

Probe #4

Fort Lewis
EGDY

9 September 2001

Figure 4-3. Results of Membrane Interface Probe data collected during the RI at SM0030 located at the corner of EGDY Treatment Plant.

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SECTION 5
TEST DESIGN

5.1 Conceptual Experimental Design

This demonstration was designed to evaluate the benefits of low-energy ERH combined with ISB and iron-based reduction technologies for treatment of chlorinated solvent residual source areas. The demonstration included use of two test cells to evaluate each combination of technologies. The demonstration was executed in three phases, including:

- Phase 1: Initial characterization and verification of the suitability of each test cell to meet project objectives, which provided information for a "go/no-go" decision on test cell placement. Once the test site was selected, each treatment system was installed with implementation of hydraulic characterization and baseline sampling.
- Phase 2: Field demonstration of ISB and ZVI without heating. This phase of the demonstration established the reaction kinetics and mass balance factors at ambient temperature.
- Phase 3: Field demonstration of ISB and ZVI with low-energy ERH. This phase of the demonstration established reaction kinetics and mass balance factors at elevated temperatures of approximately 35°C for the ISB cell and 55°C for the ZVI cell. Results were compared to Phase 2 to determine if objectives were met.

Phase 1 of the demonstration included pre-design characterization to determine the suitability of the test cells for the demonstration (i.e., confirm presence of sufficient residual DNAPL mass within the test cell); test cell installation, baseline contaminant characterization via groundwater sampling, soil gas sampling, and soil boring and sampling; and hydraulic tracer testing within the ISB test cell (note that for the ZVI test cell, tracer was injected along with the ZVI amendment and so is discussed as part of Phase 2 for that test cell).

Phase 2 of the demonstration evaluated performance of the ISB and ZVI *in situ* technologies at ambient groundwater temperatures. This phase included amendment injection, groundwater, soil gas, and soil boring and sampling as a baseline for comparison to the heated condition (Phase 3).

Phase 2 activities for the ISB test cell included establishing efficient anaerobic reductive dechlorination (ARD) at ambient temperature through injection of electron donors, emulsified oil (EOS$^{®}$) and then whey powder. Relatively low substrate concentrations were used in the test to minimize the substrate impact on dissolution so that increases in dissolution could be primarily attributed to temperature and ARD. The desired transformation reactions, which convert TCE to DCE, VC, and ultimately to ethene are illustrated in **Figure 2-2**. In addition, some sediment iron reduction and subsequent TCE dechlorination may occur once anaerobic conditions are established, dependent on the presence, extent, and availability of reducible iron (Szecsody et al. 2004). During the ISB study, products of each reaction shown on **Figure 2-2** were measured in soils, groundwater, and soil gas, as appropriate, to determine the relative rates of these reactions at ambient test temperatures. The extent and rate of ARD and contaminant mass removal will be established under the ambient temperatures. In addition, a mass balance approach was used to evaluate mass reduction rates and extents based on a mass-discharge approach.

Phase 2 activities for the ZVI test cell included first establishing *in situ* destruction of TCE using injectable micron-scale ZVI (see Truex et al. 2010 for details). The ZVI injection concentration was established based on laboratory treatability studies. The desired primary transformation reaction converts TCE to ethene and ethane via beta-elimination, and is illustrated in **Figure 2-3**. In addition to abiotic reactions, some biological transformation was expected due to hydrogen production (also illustrated in **Figure 2-3**), although potentially some reductive dechlorination may occur through direct interaction with the ZVI. During the ZVI study, products of each reaction were measured in soils, groundwater and soil gas, as appropriate, to determine the relative rates of these reactions at ambient temperatures. In addition, a mass balance approach was used to evaluate mass reduction rates and extents based on a mass-discharge approach (see Truex et al. 2011 for details).

Phase 3 of the demonstration evaluated the effect of low-temperature heating of the test cells to 30 to 40°C for the ISB cell and 40-50°C for the ZVI test cell. Again, groundwater, soil gas, and soil boring and sampling data were collected. In this way, the demonstration allowed for the measurement of the relative impact of heating on the overall rate and extent of TCE dechlorination under the heated condition (Phase 3) compared to the ambient condition (Phase 2) (see Truex et al. 2011 for details).

5.2 Phase 1: Baseline Characterization

One of the most significant technical uncertainties of this demonstration was whether the quantity of residual contaminant mass within the test cells was sufficient to meet project objectives. A key objective of the project is to evaluate the relative increase in contaminant removal rates under heated conditions relative to the ambient condition. Therefore, sufficient residual contaminant mass in soil was required to observe enhanced mass transfer to the aqueous phase during Phases 2 and 3 of the demonstration. The selection of the planned test cells was based on two soil cores collected during the RI (2001–2002) that were positive for NAPL, suggesting favorable localized conditions for the demonstration (**Figure 4-2**). However, both of the NAPL-containing soil cores were surrounded by additional soil cores containing no NAPL (see **Figure 4-2**). Therefore, the pre-design characterization effort was undertaken to further characterize the area within and around the planned test cells. **Table 5-1** illustrates the characterization activity and the objectives of the activity.

Table 5-1. Summary of ER-0719 Phase 1: Pre-Design Characterization/Baseline Activities.

Activity	Objective
Gore Sorber™ survey	Verify high-concentration “hot spots” in and around the proposed test cells in order to confirm placement of test cells within the hotspots and to aid in placement of pre-design characterization soil borings. The data were used to evaluate the planned test cell locations and to identify alternate test cell locations that may be evaluated during the soil boring and sampling and groundwater sampling.
Soil boring with PID screening of the soil cores, as well as, visual NAPL inspection, oil-in-soil dye test kits, and sheen testing.	To determine presence and vertical distribution of NAPL in soils within the planned test cells.
Soil sampling	To determine presence and vertical distribution of residual contaminant mass in soils within the planned test cells.
Installation and sampling of groundwater monitoring wells.	To determine concentrations of contaminants in groundwater both vertically and horizontally within test cells. In addition, a triangulation analysis was performed to evaluate the magnitude and direction of the hydraulic gradient and to confirm groundwater flow direction.

5.2.1 Gore™ Sorber Survey

A Gore™ Sorber survey was conducted within the two target ISB and ZVI test cell areas. The survey was conducted to determine the spatial orientation of high-concentration chlorinated solvents and petroleum hydrocarbons in soil gas as an indication of the presence of residual NAPL, which would be confirmed with soil boring and sampling. The survey provided valuable information that allowed for development of a strategy for targeting areas with high concentration source material and for making "real-time" field decisions during pre- design characterization soil boring and MW installation.

The Gore™ Sorber survey consisted of emplacing the passive diffusion sampler (Sorber) 3 to 4 ft below ground surface (bgs) using a rotary hammer drill per the manufacturer’s recommendations (See **Figure 5-1** for a Gore™ Sorber schematic) in both the ISB and ZVI test cells, as shown in **Figure 5-2**. The Sorbers were deployed on July 7, 2008, retrieved on July 11, 2008 and analyzed using modified EPA Methods 8260 and 8270 to assess chlorinated VOCs and petroleum hydrocarbons. Selection of the Sorber grids was based on logs of drum removal activities conducted during the RI.

Soil gas survey results were used to optimize the soil boring and MW locations within the two test cells. The planned test cell locations were modified in the ZVI test cell to install ZVI-INJ well 5 ft to the north of RS0062. The planned ISB test cell location was configured as shown in

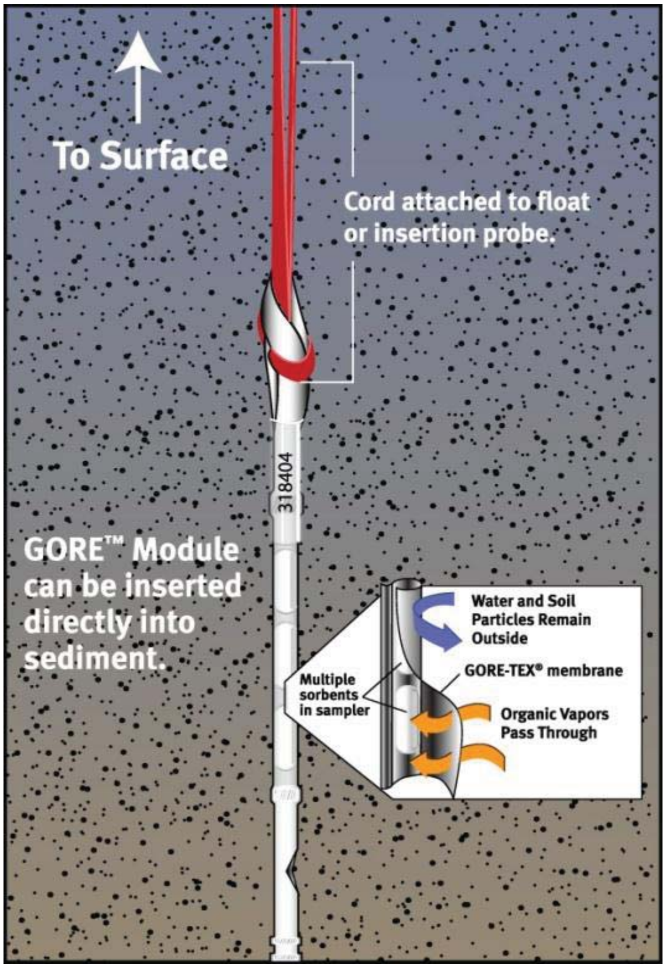

Figure 5-1. Schematic of emplaced Gore™ Sorber.

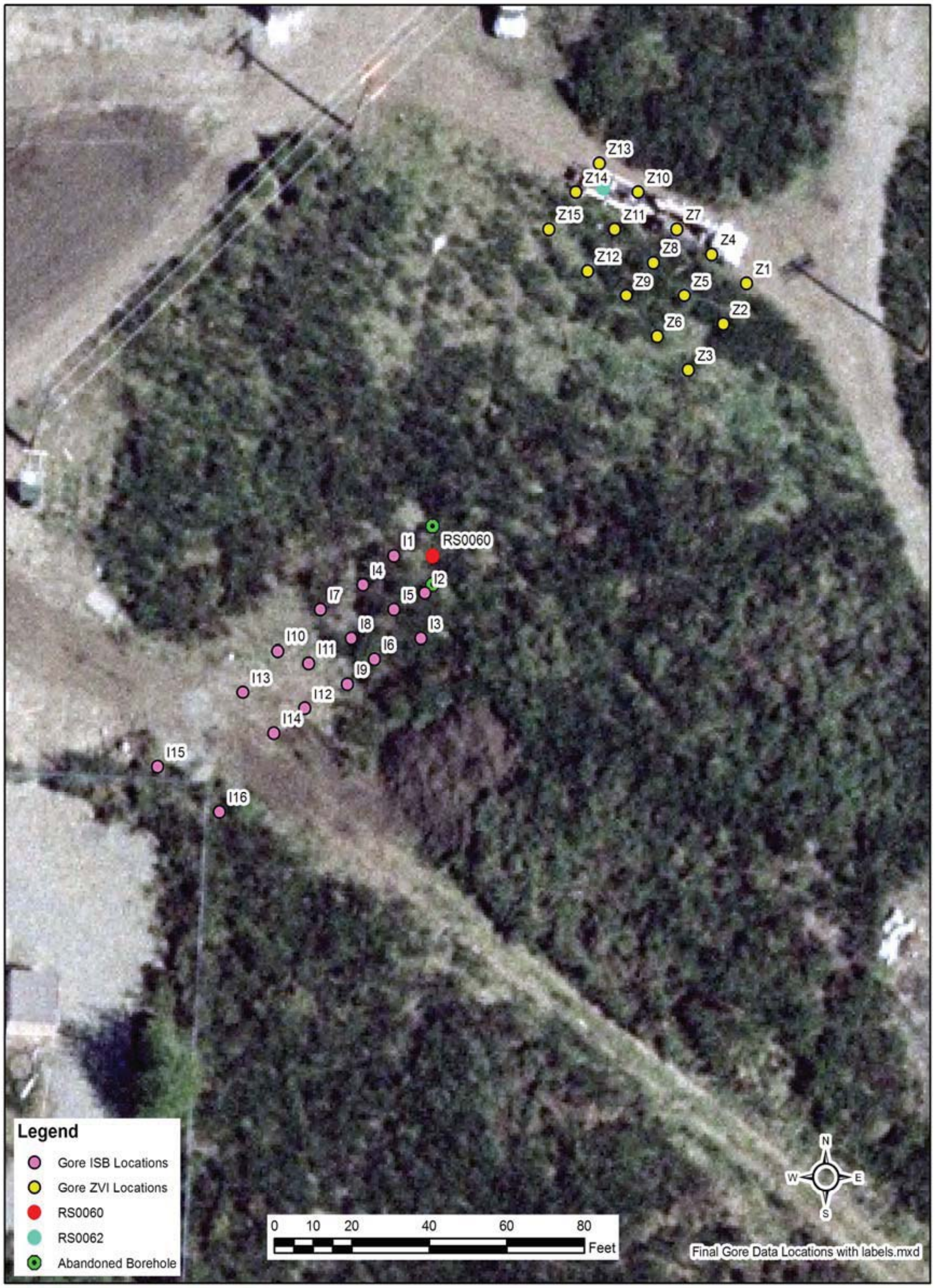

Figure 5-2. Gore™ Sorber deployment locations.

the Demonstration Plan with ISB- MW2 corresponding to Sorber location I1 and ISB-MW1 and ISB-MW3 to the north and south of RS0060 (**Figure 5-3**). An alternate location was identified near Gore™ Sorber locations I15 and I16 if the soil boring and sampling indicated that one or the other test cells was not suitable. A strategy for soil boring, screening and decision criteria for MW installation was developed. The decision strategy included the following steps:

1. Soil boreholes were advanced and soil cores were collected along the entire vertical interval.

2. Photoionization detector (PID) measurements were collected along the core at approximately 2-ft intervals. Previous investigation at the site indicated that relatively high PID readings (>200 parts per million (ppm)) and visual observation of NAPL corresponded to high (>10,000 microgram per kilogram (µg/kg)) concentrations of VOCs in soils.

3. Sheen and dye testing was used to determine the presence of NAPL.

4. If PID readings indicated high concentrations of volatiles and/or if the sheen and dye testing indicated NAPL was present, three soil samples were collected from the soil intervals with the highest detected concentrations, and the groundwater well was installed within the borehole.

5. If PID readings and sheen and dye testing did not indicate the presence of contaminants, the borehole was abandoned, and the technical team convened in real time to discuss re-configuration and placement of additional boreholes.

The ability to evaluate field data and make decisions in real time about well placement was intended to maximize drilling mobilization efficiency and increase the probability of well placement in high contaminant concentration areas suitable for meeting demonstration objectives.

5.2.2 Soil Characterization and Installation of ISB Test Cell Wells

Following the Gore™ Sorber survey, pre-design characterization subsurface drilling, soil sampling, and well installation was conducted. Pre-design characterization work included drilling and lithologic logging of soil borings at three locations identified as ISB-MW1, ISB-MW2, and ISB-MW3 (boring logs provided in **Appendix B**). These borings were originally

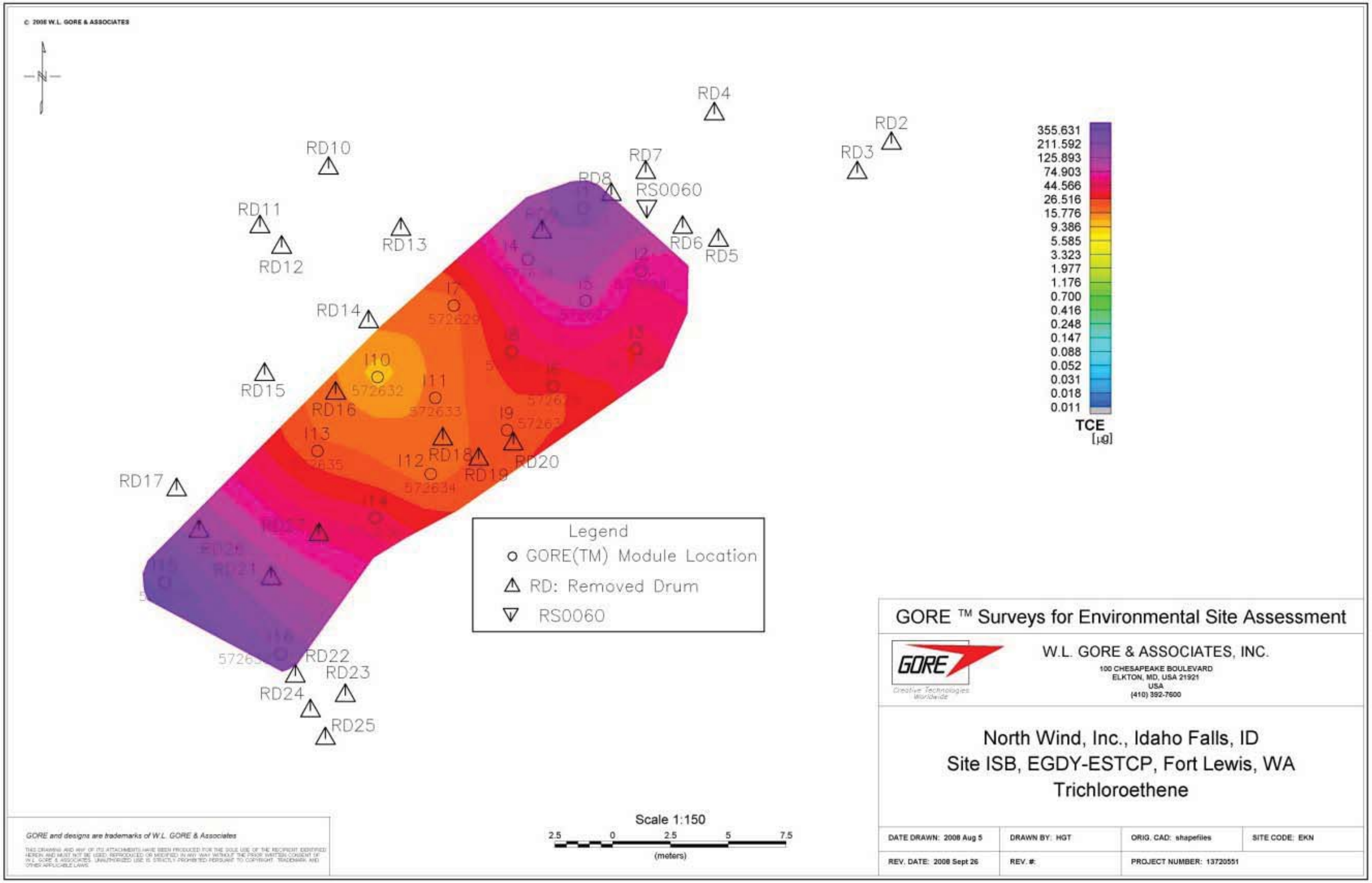

Figure 5-3. TCE Gore™ Sorber results ISB test cell.

positioned such that the planned centerline well ISB-MW2 would be at high soil gas sample location I1, and ISB-MW1 and ISB-MW3 would be north and south of RS0060. Original locations for ISB-MW1 and ISB-MW3 were abandoned because field screening results indicated that no NAPL contaminant mass was present (**Appendix B**). Alternate locations that were bored, screened and completed as MWs included a location that corresponded directly with RS0060 and one that corresponded to the area between Gore™ Sorber locations I4 and I5 that indicated relatively high contaminant mass levels. Field screening results indicated both locations contained sufficiently high levels of contamination for completion as ISB-MW1 and ISB-MW3 (see **Figure 5-5** for location of actual well placements).

Analytical soil samples were collected at the three depths from each soil core collected for a boring that was completed as a MW. Sample points were selected based on areas that demonstrated the highest potential for contamination based on elevated PID readings, visual NAPL evidence, dye testing and sheen testing results. Soil sample depths at ISB-MW1 occurred at 17.5, 19, and 27.5 ft bgs (**Table 5-2**). At ISB-MW2, sample depths were 9, 14, and 19 ft bgs; at ISB-MW3, depths were 9, 14.5, and 16 ft bgs.

Table 5-2. Summary of Baseline Analytical Results from Field Screening and Soil Sampling.

Cell	Borehole Location	Analytical Sample Point (ft bgs)	Analytical Result TCE (µg/kg)	Analytical Result cis-1,2-DCE (µg/kg)	Maximum PID Measurement (ppm)	Interpreted NAPL Depth Interval
ISB	ISB-MW1	**17.5**	**76,000**	**11**	**715**	16.5-20 ft bgs
		19	**10,000**	**5.6**	**98**	
		27.5	4,900	28	44	
	ISB-MW2	9	5,100	11	63	14.0-20 ft bgs
		14	**130,000**	**91**	**1,555**	
		19	**65,000**	**30**	**9,300**	
	ISB-MW3	9	17,000	8	197	None
		14.5	8,500	7.9	142	
		16	4,000	16	2,662	
ZVI	ZVI-INJ1	8.8	220,000	180	629	5-13 ft bgs
		10.5	11,000	110	15	
		15.3	6,800	**48**	4	
	ZVI-MW1	11	2500	38	10.6	None
		16	470	33	0.7	
		20.5	250	16	0.7	
	ZVI-MW2	12	1600	100	32.9	None
		16.5	1400	34	1.4	
		20	1900	110	9.8	

Note: Area shaded in grey indicates soil samples that met the "Go" decision criteria of 10,000 µg/kg. The grey areas that also have bold lettering indicate samples collected within the saturated interval and gray areas without bold lettering indicate samples collected within the vadose zone.

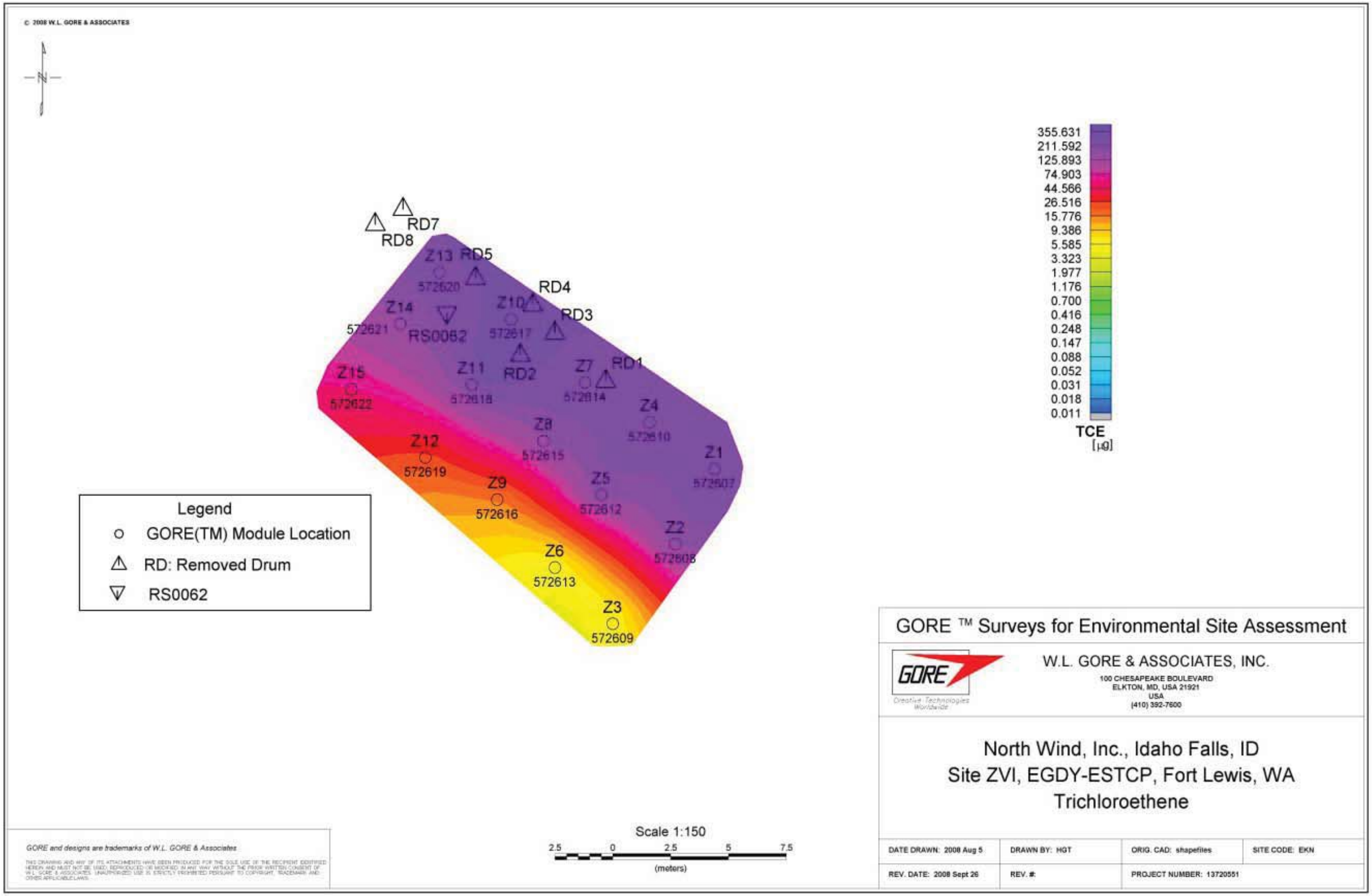

Figure 5-4. TCE Gore™ Sorber results ZVI test cell.

FIGURE 5-5
Final Placement of ISB and ZVI Test Cells

Results of the soil sampling are presented in **Table 5-2**. High concentrations of TCE that met the “Go” decision criteria of 10,000 µg/kg in soils were observed in at least one soil sample collected from each of the three boreholes that were completed as ISB-MW1, -MW2 and -MW-3. Interestingly, ISB-MW3, which corresponded to RS0060 used to place the test cell, contained the lowest overall TCE mass of the three boreholes. The highest TCE contaminant mass levels were observed in the borehole that was completed as ISB-MW2, which also corresponded to the I1 Gore™ Sorber that indicated the highest contaminant mass within the ISB survey area.

Each boring was completed as a continuous multi-channel tubing (CMT) multi-port groundwater MW. Each well was developed to remove fines from within the well casing and around the screened interval using 0.25-inch outer diameter Teflon-lined tubing and a peristaltic pump. The wells were 6-port polyethylene CMT multi-port wells constructed with the upper two ports as vadose zone soil gas ports and the lower four ports as groundwater sample ports. Each well was constructed with vadose zone ports at 3 and 7 ft bgs and with groundwater monitoring ports at 12, 17, 22, and 27 ft bgs, nominally. Port IDs are numbered consecutively, from shallowest to deepest, as Ports 1 through 6. Each multi-port well sample chamber is 0.4-inches in diameter.

5.2.3 Soil Characterization and Installation of ZVI Test Cell Wells

During Phase 1, pre-characterization subsurface drilling, soil sampling, and well installation associated with the ZVI cell was also conducted. Initial drilling and lithologic logging of soil at three borehole locations installed in a southeast-northwest trending line centered on Z13 (**Figure 5-2**) were abandoned because the majority of the residual mass was found in the vadose zone (data not shown). Therefore, the ZVI test cell was placed in an alternate location as shown in **Figure 5-5** and near RI membrane interface probe boring SM0030.

Table 5-2 presents results of the soil characterization activities within the ZVI test cell area. Significant TCE soil concentrations were observed at the injection well. TCE soil concentrations at locations ZVI-MW1 and ZVI-MW2 were substantially lower. The mass of TCE within the targeted ZVI treatment zone was estimated to be about 2 kg. The estimate assumes that the TCE concentration measured at the injection well applies to a radius of 1 m from the injection well and that the concentrations measured at ZVI-MW1 and ZVI-MW2 apply to the remainder of the volume. While soil samples were not collected from all of the wells, screening of soil samples during drilling using a field instrument suggested that the highest TCE concentration was centered around the injection well and that concentrations were lower at the other well locations and likely similar to the concentrations measured at ZVI-MW1 and ZVI-MW2.

All wells except ZVI-MW3 were screened over a 1.5 m interval nominally between 2.4 and 4 m bgs at the top of the aquifer. Well ZVI-MW3 was screened over a 0.6-m interval at the top of the water table in a till feature adjacent to ZVI-MW2. The intent of well ZVI-MW3 was to examine processes occurring in the till feature compared to those at the fully screened ZVI-MW2 that intersected outwash material in the lower part of its screen. MWs were completed as conventional 2-inch diameter polyvinyl chloride (PVC) wells. The injection well was a 4-inch diameter PVC injection well. All MW screens were slotted PVC with a 0.020-inch slot size (i.e., "20 slot"). The injection well screen was a continuous wire-wrap PVC screen with a 0.020-inch slot size. Borehole and well construction details are provided in **Appendix B**.

5.2.4 Hydraulic Characterization: ISB Test Cell

A detailed hydraulic evaluation was conducted for the ISB test cell. Substantial variation in the groundwater flow direction and gradient was observed during all of the sampling events conducted during the demonstration (**Table 5-3**). The following sections describe the detailed characterization conducted before and during the demonstration to use in subsequent data evaluation and modeling.

Table 5-3. Groundwater Flow Direction and Horizontal Hydraulic Conductivity at the ISB Test Cell

Date	Groundwater Flow Direction (Azimuth Degrees)	Estimated Horizontal Hydraulic Gradient
1/26/2009	304	0.010
2/10/2009	287	0.005
3/9/2009	297	0.019
5/7/2009	291	0.012
7/2/2009	251	0.019
8/17/2009	289	0.013
10/16/2009	297	0.010
11/20/2009	273	0.013
12/21/2009	286	0.018
1/29/2010	262	0.013

Tracer Test Design

A conservative tracer test was performed at the ISB test cell using bromide to conduct a hydraulic analysis of the aquifer as part of Phase I of the demonstration. A total of 1,887 gallons of bromide solution containing 2,500 mg/L of bromide was injected into the injection well, ISB-INJ. The tracer injection design specifications are listed in **Table 5-4,** with the exception of the injection rate and duration. Head losses in the injection line resulted in lower than the 10 gallon per minute (gpm) design injection rate. The actual injection rate was 7.7 gpm with an injection duration of 245 minutes, which was longer than the 192 minute design duration.

Bromide concentrations were monitored at the injection well and MWs on the day of the tracer injection and the following day. Bromide arrival times and breakthrough were measured at each of the ports of the multi-depth CMT MWs ISB-MW1, ISB-MW2, and ISB-MW3 by frequent sample collection and bromide laboratory analysis. At the downgradient MWs ISB-MW4, ISB-MW5, and ISB-MW6, the bromide arrival times and breakthrough were measured using in-situ bromide probes and data loggers set for continuous recording. **Table 5-5** lists the MW screen intervals, sample collection depth, method of bromide analysis and sample frequency.

Table 5-4. ISB Tracer injection strategy.

Parameter Constants	Sodium Bromide	Comments
ROI, ft	10	
H, ft	10	Injection well screen length
n	0.3	Total Porosity
Wt. % Br in NaBr	7.76E-01	
Volume, gal	1,887	Volume of tracer injection per well
Variables		
Desired C avg, mg/L	500	Average concentration of Br in situ assuming radial flow(at ROI 10 ft)
Required mass NaBr ,kg	22	Mass injected/well
Desired injection line concentration, mg/L	2,500	
Desired injection flow rate per well, gal/min	10	
Sodium salt stock solution concentration, mg/L	129,000	Solubility is 7.33E+05
Bromide stock solution concentration, mg/L	100,000	77.6% of stock solution
Output		
Volume of tracer stock solution required, gal	45	129,000 ppm NaBr solution
Required flow rate stock solution, gal/min	0.33	Used a dosatron to administer this in-line
Required % stock solution (vol/vol)	2.5%	
Total tracer injection time, hours	3.2	

Table 5-5. Tracer Test Bromide Sampling Schedule.

Well ID	Port ID	Screened Interval (bgs ft)	Sample Depth (from top of casing, ft bgs)	Sample Equipment	Sampling Frequency	
					Day 1	**Day 2**
Injectate solution	-	-	In injection line	Flow through cell, probe, laboratory sample	3 during injection	NA
INJ1	-	9-19	14.2-15.2	Flow through cell, probe, laboratory sample	4 times during and after the injection	1 time
MW1	3	12-13	13.4-14.4	Flow through cell, probe, laboratory sample	5 times during and after the injection	1 time
MW1	4	17-18	18.4-19.4			
MW1	5	22-23	23.4-24.4			
MW1	6	27-28	28.4-29.4			
MW2	3	12-13	14.1-15.1	Flow through cell, probe, laboratory sample	5 times during and after the injection	1 time
MW2	4	17-18	18.1-20.1			
MW2	5	22-23	24.1-25.1			
MW2	6	27-28	29.1-30.1			
MW3	3	12-13	13.65-14.65	Flow through cell, probe, laboratory sample	5 times during and after the injection	1 time
MW3	4	17-18	18.65-19.65			
MW3	5	22-23	23.65-24.65			
MW3	6	27-28	28.65-29.65			
MW4	-	9.2-24.2	15-16, 24-25	In situ probe and data logger	Continuously	Continuously
MW5	-	9.7-24.7	15-16, 24-25	In situ probe and data logger	Continuously	Continuously
MW6	-	9.4-24.2	15-16, 24-25	In situ probe and data logger	Continuously	Continuously

Hydraulic Testing Results

Bromide tracer arrival times were used to determine the groundwater seepage velocity during the tracer test. These results were used along with hydraulic gradient information to calculate the groundwater seepage velocity during ambient (i.e., non-injection) conditions and to estimate the hydraulic conductivity at discrete depths within the ISB test cell. The following sections describe the calculation approach and results.

Hydraulic Gradient

To evaluate the horizontal hydraulic gradient during ambient conditions and during an injection event, groundwater elevation measurements were collected during the Phase 3 whey injection event that occurred on January 29, 2010. This injection took place over a 247-minute period at an average injection rate of 6.1 gpm. ISB-INJ1 was utilized as the injection well. The groundwater elevation at each of the ISB test cell MWs was measured immediately prior to and 2.9 hours after the start of the injection. The EGDY pump and treat system was operating continuously throughout the injection period.

Table 5-6 lists the groundwater elevation monitoring results, including the ambient groundwater flow direction and hydraulic gradient, the average hydraulic gradient during the injection, amount of groundwater mounding at each monitoring point, and the distance between the injection well and each monitoring point. The results indicate that the ambient groundwater flow direction and hydraulic gradient was 262° at 0.013 foot/foot and that a radial flow pattern developed as a result of the injection. Observed groundwater mounding ranged from a maximum of +0.56 ft at the MW located 7 ft away from the injection well to a minimum of +0.10 ft at the MW located 37 ft away.

Groundwater Velocity

Figures 5-6, **5-7**, and **5-8** show the breakthrough curves for the ISB test cell MWs (ISB-MW1, ISB-MW2, and ISB-MW3). The breakthrough curves for the downgradient MWs (ISB-MW4, ISB-MW5, and ISB-MW6) are shown in **Figure 5-9**. The peak of each curve represents the maximum bromide concentration or peak breakthrough. Because the tracer injection occurred as a 245-minute injection and was not instantaneous, the midpoint of the injection period, time (t) = 122.5 minutes, was selected as the start travel time (t_0) for the purpose of groundwater velocity calculation. The advective travel time is the time from t_0 until peak breakthrough at a particular monitoring point. The groundwater seepage velocity is derived by dividing the distance between the injection well and the MW by the advective travel time.

The advective travel times and corresponding groundwater seepage velocity for each monitoring point within the ISB test cell are listed in **Table 5-7**. The seepage velocities ranged from 64 to 252 ft/day within the ISB test cell during the tracer test.

The seepage velocities observed during the groundwater tracer test are much higher than ambient due to groundwater mounding centered on the injection well and the resulting increased horizontal hydraulic gradient. In order to estimate a seepage velocity under ambient conditions,

Table 5-6. Groundwater elevations during and after ISB tracer test.

East Gate Disposal Yard ISB Test Cell
Fort Lewis, Washington

		Ambient Conditions			During Injection - 2.9 Hours After Start			
Monitoring Point ID	Distance Between Injection Well and Monitoring Point (ft)	Groundwater Elevation (ft)	Groundwater Flow Direction	Hydraulic Gradient[1] (ft/ft)	Groundwater Elevation (ft)	Groundwater Flow Direction	Hydraulic Gradient[1] (ft/ft)	Amount of Groundwater Mounding (ft)
ISB-INJ	0	270.31	262^0	0.013	272.35	Radial	0.022	2.04
ISB-MW1-3	21	270.09			270.17			0.08
ISB-MW2-3	15	270.01			270.29			0.28
ISB-MW3-3	7	270.16			270.72			0.56
ISB-MW4	37	269.82			269.92			0.10
ISB-MW5	37	269.85			269.96			0.11
ISB-MW6	36	270.12			270.17			0.05

Notes:

The EGDY groundwater extraction system was operating continuously prior to and during the injection event.

[1] The hydraulic gradient listed is the average gradient between the ISB-MW1, ISB-MW2, ISB-MW3 well clusters and the downgradient ISB-MW4, ISB-MW5, and ISB-MW6 monitoring wells.

Table 5-7. Hydraulic parameters calculated based on the tracer test and used for calculations.

Landfill 2, Fort Lewis, Washington: ISB Test Cell

Monitoring Point	Distance from Injection Point (ft)	Depth of Screen (ft bgs)	Tracer Travel Time[1] (minutes)	Groundwater Velocity During Tracer Test (ft/d)	Estimated Ambient Groundwater Velocity (ft/d)	Estimated Horizontal Hydraulic Gradient During Tracer Test[2]	Estimated Effective Porosity[3]	Hydraulic Conductivity[3] (ft/d)
INJ	0	5 - 19	--	--	--	--	--	--
MW1-3	21	12	440	67	31	0.028	0.18	455
MW1-4	21	17	310	95	36	0.034	0.18	532
MW1-5	21	22	430	69	32	0.028	0.18	466
MW1-6	21	27	460	64	31	0.027	0.18	452
MW2-3	15	12	240	87	28	0.040	0.18	413
MW2-4	15	17	250	84	27	0.040	0.18	397
MW2-5	15	22	150	139	45	0.040	0.18	661
MW2-6	15	27	NA	NA	NA	NA	NA	NA
MW3-3	7	12	50	202	66	0.040	0.18	958[5]
MW3-4	7	17	70	144	47	0.040	0.18	684[5]
MW3-5	7	22	40	252	82	0.040	0.18	1,197[5]
MW3-6	7	27	>1573	NA	NA	NA	NA	NA

Notes:

[1] Tracer travel time is defined as the time from midpoint of the bromide injection period to the time of breakthrough at the monitoring point.

[2] The hydraulic gradient is estimated based on the gradient observed during the whey injection event that occurred in cell in 2009 and 2010.

[3] Literature derived porosity estimate (Vermeul et al. 2000).

[4] The hydraulic conductivity (K) is calculated as K = (Groundwater Velocity X effective porosity)/horizontal hydraulic gradient

NA - Not analyzed due to no measurable response

[5] Hydraulic conductivities estimated for MW3 were not used in modeling of mass discharge because of uncertainty in their representativeness due to tracer arrival times that occurred before the tracer injection had ended.

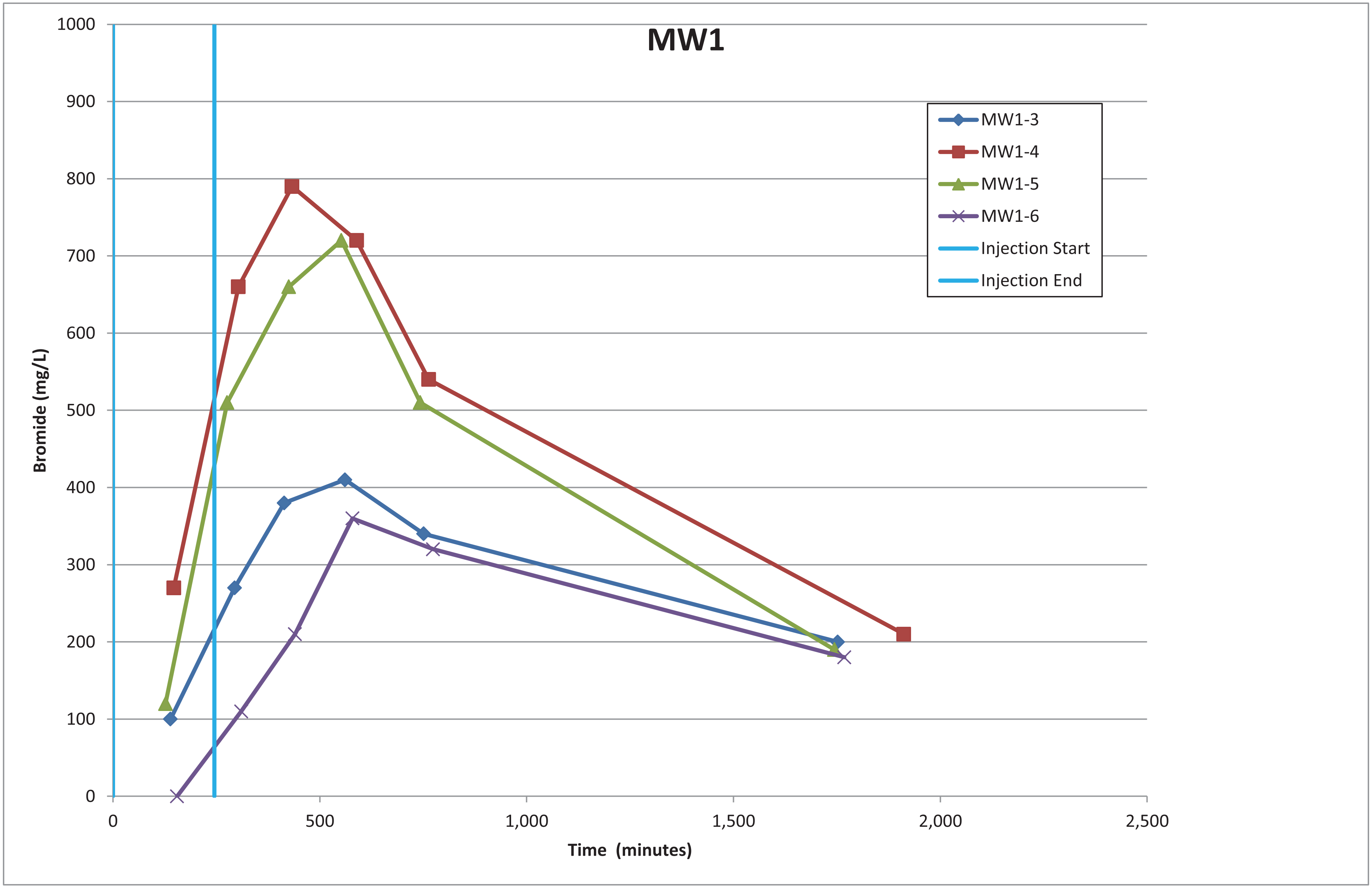

Figure 5-6. Breakthrough curve ISB-MW1.

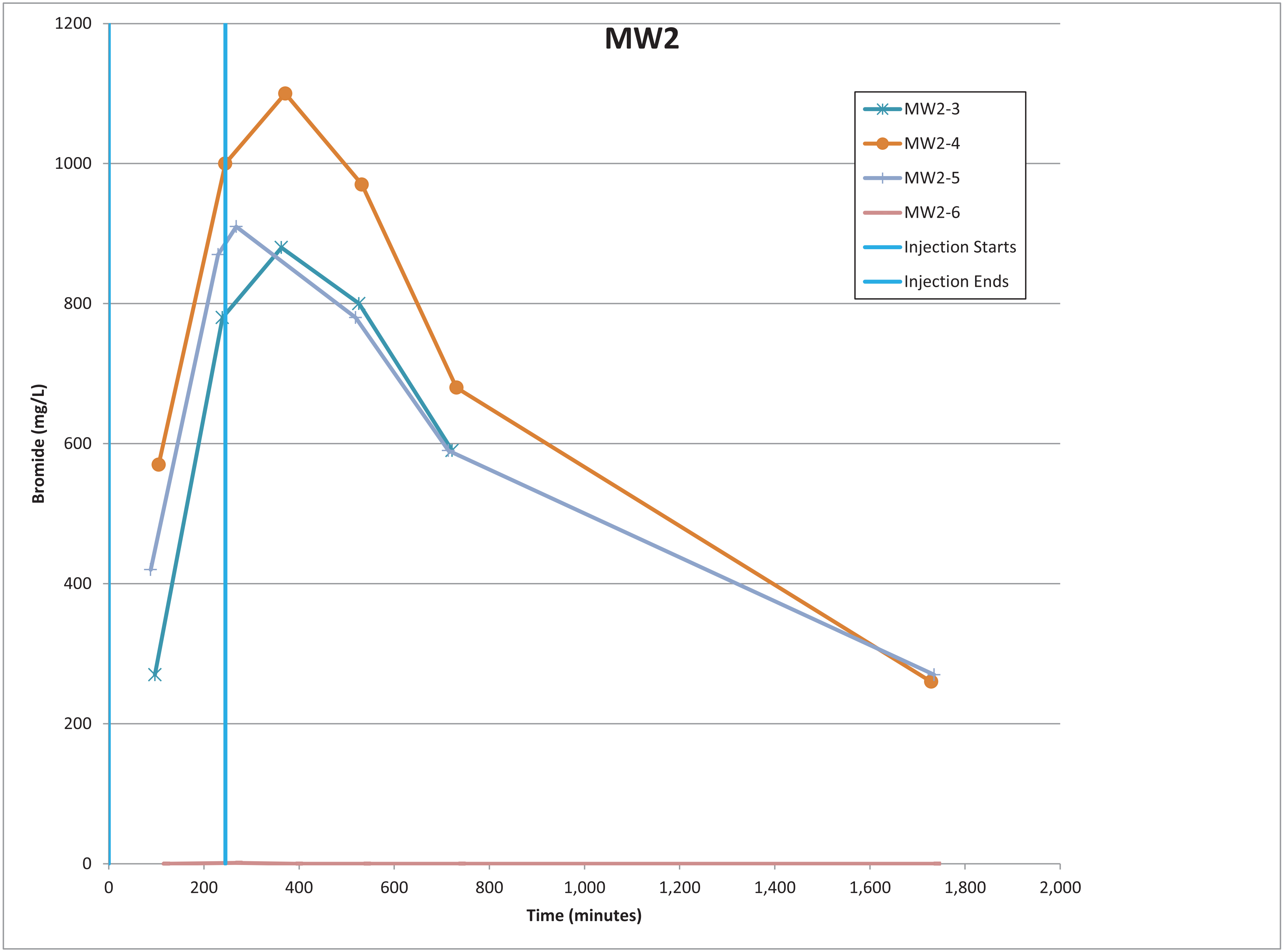

Figure 5-7. Breakthrough curve ISB-MW2.

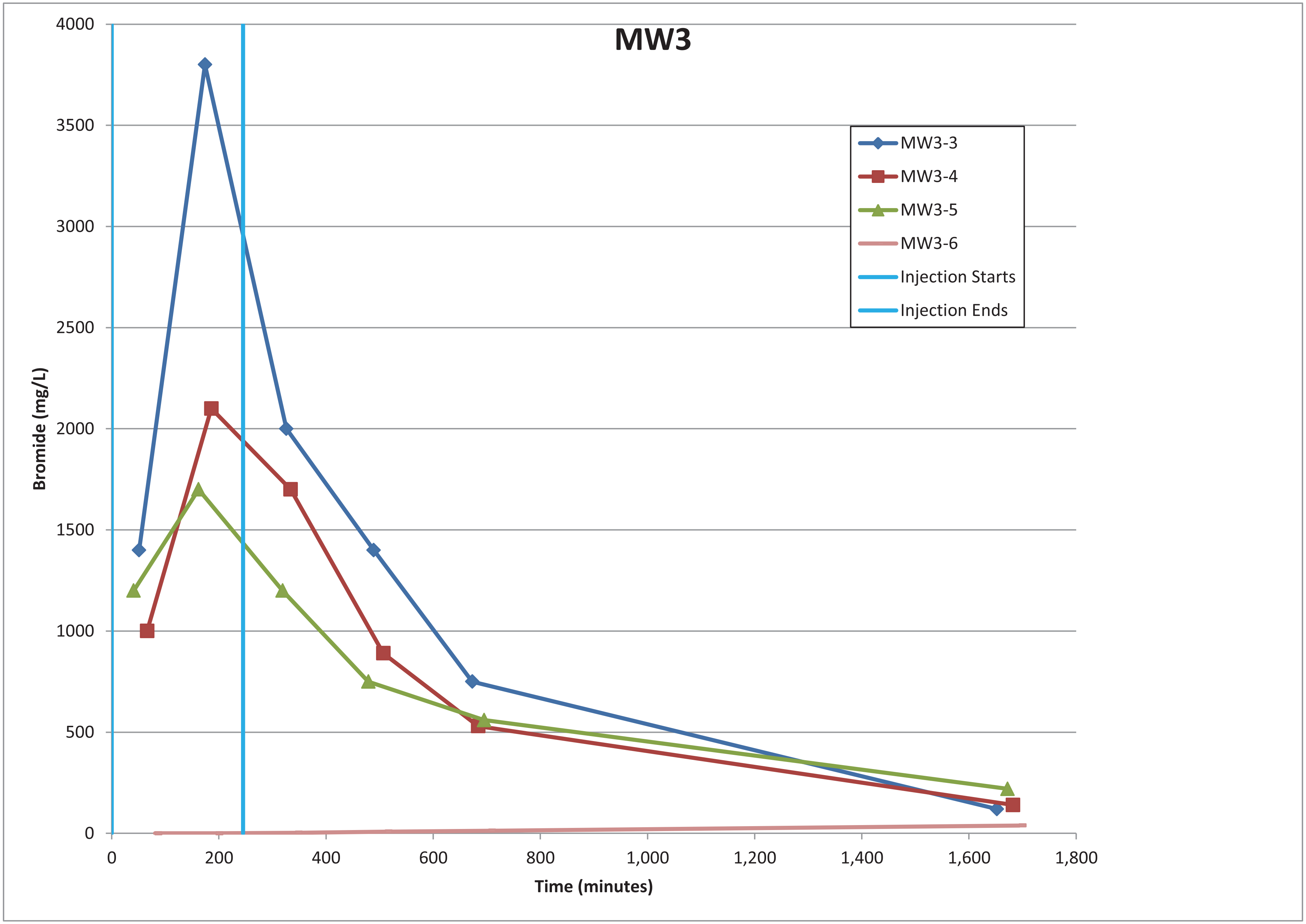

Figure 5-8. Breakthrough curve ISB-MW3.

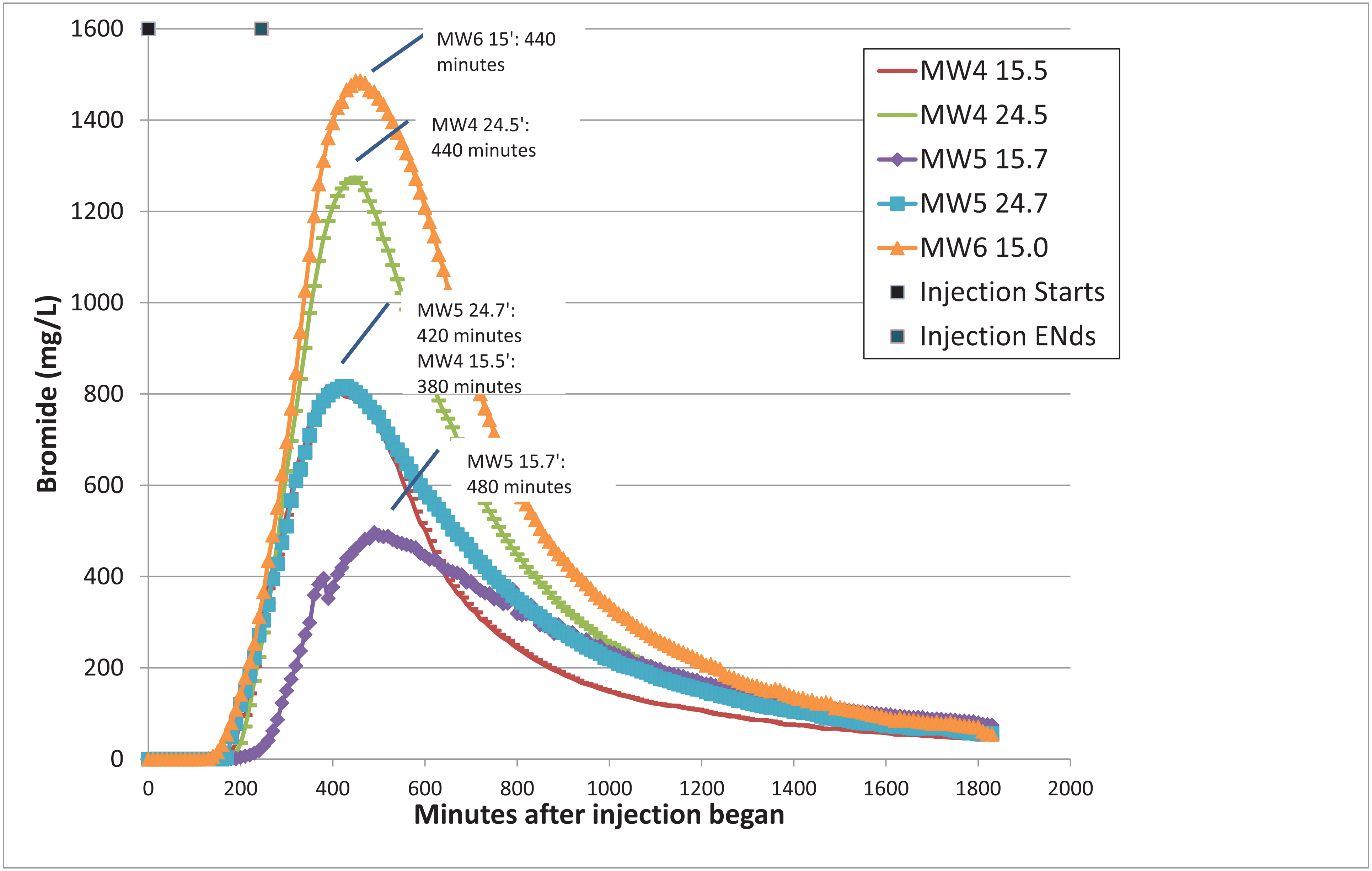

Figure 5-9. Breakthrough curves for ISBMW4, ISBMW5, ISBMW6.

the seepage velocities calculated for the groundwater tracer test must be corrected for ambient hydraulic gradient conditions. The correction is derived as follows:

During the groundwater tracer test:

$$V_{\text{tracer test}} = \frac{K * I_{\text{tracer test}}}{n_e}$$ **[Equation 1]**

During ambient conditions:

$$V_{\text{ambient}} = \frac{K * I_{\text{ambient}}}{n_e}$$

By substitution:

$$V_{\text{ambient}} = V_{\text{tracer test}} * \frac{I_{\text{ambient}}}{I_{\text{tracer test}}}$$ **[Equation 2]**

Where:

V = seepage velocity

K = hydraulic conductivity

I = horizontal hydraulic gradient

n_e = effective porosity

As discussed in the previous section, the hydraulic gradient induced by an injection at the ISB test cell was evaluated during the January 29, 2010 whey injection event. The average horizontal hydraulic gradient during the ISB cell tracer test was approximated in the vicinity of each of the ISB cell MWs based on the amount of groundwater mounding observed during the January 29, 2010 whey injection event.

Table 5-7 lists the estimated groundwater seepage velocities for ambient conditions, which were calculated using **Equation 2** and the hydraulic gradients that were assumed for the tracer injection event. The seepage velocities under ambient (i.e. non-injection) conditions within the ISB test cell are estimated to range from 27 to 82 ft/day.

Hydraulic Conductivity

The hydraulic conductivity for each groundwater monitoring point within the ISB test cell was calculated using **Equation 1**, shown in the previous section. The groundwater seepage velocity and hydraulic gradient during the tracer test were used for this calculation. **Table 5-7** lists the calculated hydraulic conductivities. The calculated hydraulic conductivity ranged from 397 ft day to 1,197 ft/day. Depth discrete conductivity values measured for ISB- MW1 and ISB-MW2 were averaged and used for mass discharge calculations. ISB-MW 3 values were not included because the tracer arrival time occurred before the tracer injection was complete.

5.2.5 Hydraulic Characterization: ZVI Test Cell

A tracer study was also conducted at the ZVI test cell just prior to injection of ZVI to evaluate the injection hydraulic response, finalize ZVI injection parameters, and to evaluate groundwater flow velocity through elution monitoring. Results of the ZVI tracer test are discussed in conjunction with the ZVI injection results in **Section 5.5.2** (see also Truex et al. 2010).

5.3 Laboratory Study Results

The laboratory tests were conducted to 1) finalize selection of the polymer as the delivery mechanism for the ZVI, 2) determine injection parameters (i.e., quantity of ZVI/polymer addition), and 3) provide baseline reaction kinetics to assist in field data interpretation. The laboratory tests demonstrated that SlurryPro™ does not impact the dechlorination rate of TCE by ZVI in the presence of site sediments. It was observed that zero-order reaction rates in SlurryPro™ range from about 80 to over 100% of the rates in water. Thus, the impact of SlurryPro™ on the ZVI reactions is deemed to be minimal (Truex et al. 2011; see also treatability test in **Appendix B**). Additionally, the laboratory tests demonstrated that the solubility of TCE is not impacted by SlurryPro™ (Truex et al. 2010). For treatments containing site sediments, reaction rates at 40^{o}C are about 2.5 to 4 times faster than rates at 20^{o}C. As such, the reaction rate is expected to be significantly enhanced by the heating process during the field test. The full treatability test report is provided in **Appendix B**.

During installation of field test site wells, sediment samples from three of the wells were analyzed for TCE. The mass of TCE within the targeted ZVI treatment zone was estimated to be 2 to 6 kg-TCE. The lower estimate assumes that the TCE concentration measured at the injection well applies to a radius of 1 m from the injection well (220 mg/kg) and that the concentrations measured at MW1 (1.6 mg/kg) and MW2 (11 mg/kg) apply to the remainder of the volume. The high estimate applies the average concentration of the three measurements across the entire treatment volume. While sediment samples were not collected from all of the wells, screening of sediment samples during drilling using a field instrument suggest that the highest TCE concentration is centered around the injection well and that concentrations are lower at the other well locations and likely similar to the concentrations measured at MW1 and MW2.

Results of laboratory treatability tests (ER-0719 project report submitted in October 2008) were used as input to select the ZVI mass to be injected into the test cell. The factors considered for selection included 1) the observed stoichiometry of TCE degraded per mass of ZVI from laboratory treatability tests, 2) the ratio of TCE concentration to ZVI concentration expected in the groundwater within the test zone and how this ratio compares to the ratio in the laboratory treatability tests that were used to determine the TCE degradation rate, 3) the required weight percentage of ZVI in the injection solution and how this percentage compares to the previous tests for ZVI injection and transport (Oostrom et al., 2007), and 4) the material cost of ZVI per treatment volume. **Table 5-8** shows the estimated required mass of ZVI in the treatment zone based on the average and maximum stoichiometry observed in the laboratory treatability tests.

Table 5-8. Estimated ZVI injection based on laboratory measured stoichiometry of TCE degraded per ZVI mass.

TCE mass (kg)	Required ZVI (kg) using average stoichiometry (0.012)	Required ZVI (kg) using maximum stoichiometry (0.034)
2	160	60

Based on this information, a target ZVI injection of 150 kg was selected. This mass of ZVI is sufficient for the estimate of total TCE mass in the treatment zone.

Table 5-9 shows the selected 150-kg ZVI mass in terms of the ratio of TCE to ZVI concentrations in the pore water for comparison to the laboratory treatability test ratios. The field ratio is based on an expected TCE concentration of 10 mg/L in the pore water. During previous full-scale thermal treatment at EGDY, the groundwater TCE concentration increased to between 5 and 10 ppm when subsurface temperatures were increased to between 40 and 60^{o}C. Thus, similar pore water concentrations of TCE were expected when the subsurface is heated during the demonstration.

Table 5-9. Concentration ratios for TCE and ZVI in laboratory tests compared to the selected ZVI injection for the field test.

Test	TCE concentration (mg/L)	ZVI concentration (g/L)	Ratio of TCE to ZVI concentration (mg/g)
High TCE laboratory	1000	200	5
Low TCE laboratory	100	200	0.5
Field Test with 150 kg ZVI injected	10	13	0.75

5.4 Design and Layout of Technology Components

5.4.1 ISB Field Test Design

ISB Test Cell Layout

The ISB test cell location was selected at the Fort Lewis Landfill 2 site based on the pre-characterization data collected during the Phase 1 of this demonstration, which revealed that this area contains soil concentration of TCE indicative of residual saturation. The target treatment depth of 9 ft to 20 ft bgs was selected based on the soil coring data which indicated that much of the source material was located at this depth interval in the saturated zone. The test cell wells were installed (as detailed in **Table 5-10**), and the well configuration, as surveyed by the U.S. Army Corps of Engineers (USACE) Seattle District, is illustrated in **Figure 5-5**. The test cell was aligned northeast to southwest; approximately parallel to the estimated (not actual) direction

Table 5-10. Details of completed wells within ISB test cell.

Well ID	Date Installed	Well Diameter (inches)	Screen Interval (ft bgs)
ISB-INJ	11/19/2008	4	9 - 19
ISB-MW1	8/22/2008	1.7	7,12,17,22,27
ISB-MW2	8/20/2008	1.7	7,12,17,22,27
ISB-MW3	8/21/2008	1.7	7,12,17,22,27
ISB-MW4	11/20/2008	2	9 - 24
ISB-MW5	11/20/2008	2	10 - 25
ISB-MW6	11/20/2008	2	9- 24

of groundwater flow as shown in **Figure 5-5**. Groundwater flow direction at the time of well installation was controlled by the nearby pump-and-treat system to an azimuth of about 233 degrees. During the test, however, several of the well pumps in this system failed and the average groundwater direction during the test changed to an azimuth of 294 degrees. The test cell was comprised of an injection well (ISB-INJ) and six downgradient MWs (ISB-MW1 through ISB-MW6).

ISB Field Injection Equipment

During the injections, the injection hose was placed in the injection well ISB-INJ at an approximate depth of 15 ft bgs. An in-line, spring-loaded flow meter and a digital flow totalizer were used to measure injection rates. Depth to groundwater measurements at the injection well and flow readings at the flow meter and totalizer were recorded throughout the injection events and recorded on an amendment injection log. The feed-water for all injections was obtained from 2-inch diameter discharge ports (FX-01 and FX-02) located on the groundwater conveyance line of the Landfill 2 pump and treat system. The discharge ports were equipped with valves and the groundwater was conveyed from the discharge ports to the injection site using ¾-inch diameter rubber hoses. The TCE concentration in the feed-water was approximately 150 microgram per liter (µg/L), based on a sample collected at the conveyance line during the injection.

5.4.2 ZVI Field Test Design

ZVI Test Cell Layout

The ZVI test design is described in Truex et al. (2010 and 2011) and summarized here. The project test cell was located within JBLM Landfill 2 in a region where TCE had been disposed to surface trenches in quantities sufficient to migrate through the shallow vadose zone (~9 ft thick) and into the top portion of the aquifer. The layout of the test cell encompassed a targeted ZVI treatment volume with a 9-12 foot radius that was about 5 ft thick (approximately 10 to 15 ft bgs) (**Figure 5-10**). The test cell was comprised of one groundwater injection well and nine MWs nominally screened within the upper Steilacoom Gravel, although some till features are also present within this targeted interval. Groundwater flow direction at the time of well installation was controlled by the nearby pump-and-treat system to an azimuth of about 233 degrees. During the test, however, several of the well pumps in this system failed and the average groundwater

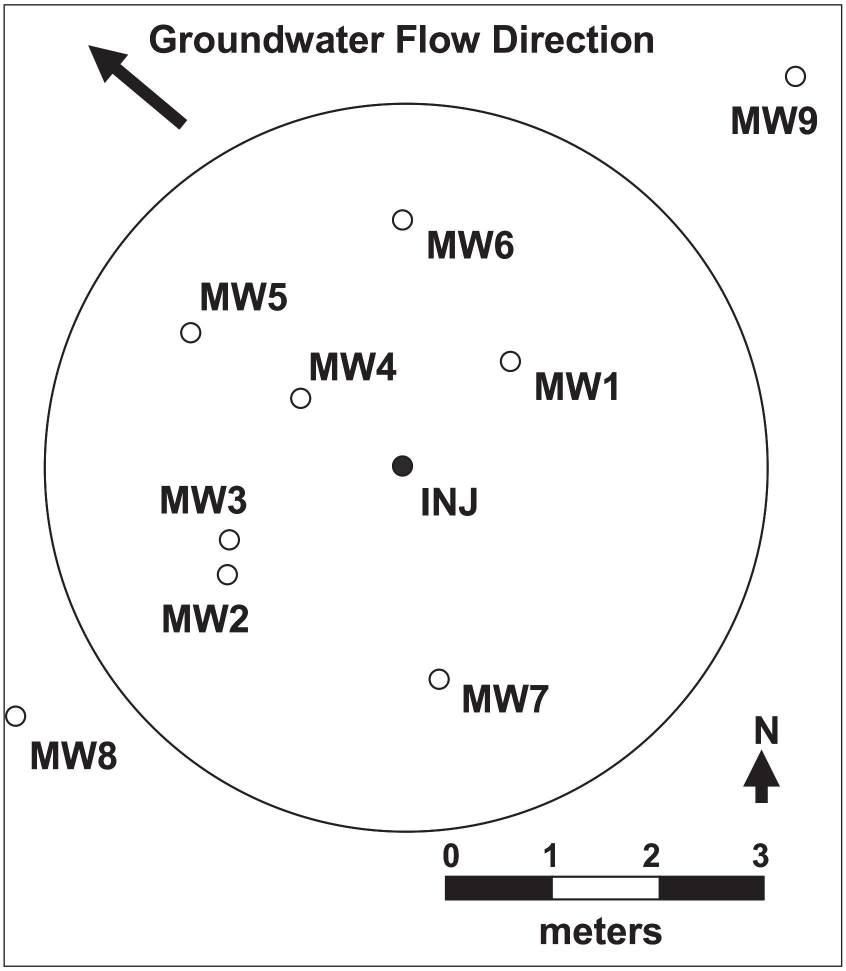

Figure 5-10. ZVI test cell well layout. The large circle shows the nominal target 3.5 m injection radius.

direction during the test changed to an azimuth of 294 degrees. As such, wells MW8 and MW9 were cross-gradient wells rather than the intended downgradient and upgradient wells, respectively.

ZVI Injection Equipment

The micron-scale ZVI was injected using a modification of equipment originally designed for injection of powdered whey (equipment rented from North Wind, Inc.). The injection equipment was configured as shown schematically in **Figure 5-11**. A picture of the injection system is shown in **Figure 5-12**. The solids injection system used a screw feeder equipped with a variable speed controller to meter solid ZVI particles from a hold tank at the desired feed rate into a wash down hopper equipped with spray nozzles, which was added inline through an eductor. The ZVI was mixed with the injection water using an eductor located at the bottom of the wash down hopper, and the mixture was pumped into the injection well.

5.4.3 ERH System Design

ERH Power Control Unit

The ERH Power Control Unit (PCU) regulates the application of electrical energy for optimum subsurface heating. This equipment is manufactured specifically for the application of the ERH technology. The ERH PCU selected for the ESTCP project was designed for 100% cycle duty and sized for a maximum power output of 500 kilowatts (kW). The electrical utility connection to the PCU was provided with typical over current and short circuit protection as required by the National Electrical Code and the equipment manufacturer. An electrical one line diagram is referenced in **Figure 5-13**.

Safeguards and controls were designed into both the PCU and the operating program to protect the ERH equipment and field personnel by placing limitations on voltage and current output. The parameters of the safeguards and controls are programmed by the ERH operator based on Thermal Remediation Services (TRS) operational experience and site conditions.

PCU control and data acquisition were performed on a dedicated computer running the Windows™ operating system. Remote data acquisition software was used to collect and store temperature, power, voltage, current, and operational status data. Operations personnel access the

ZVI Field Injection Equipment

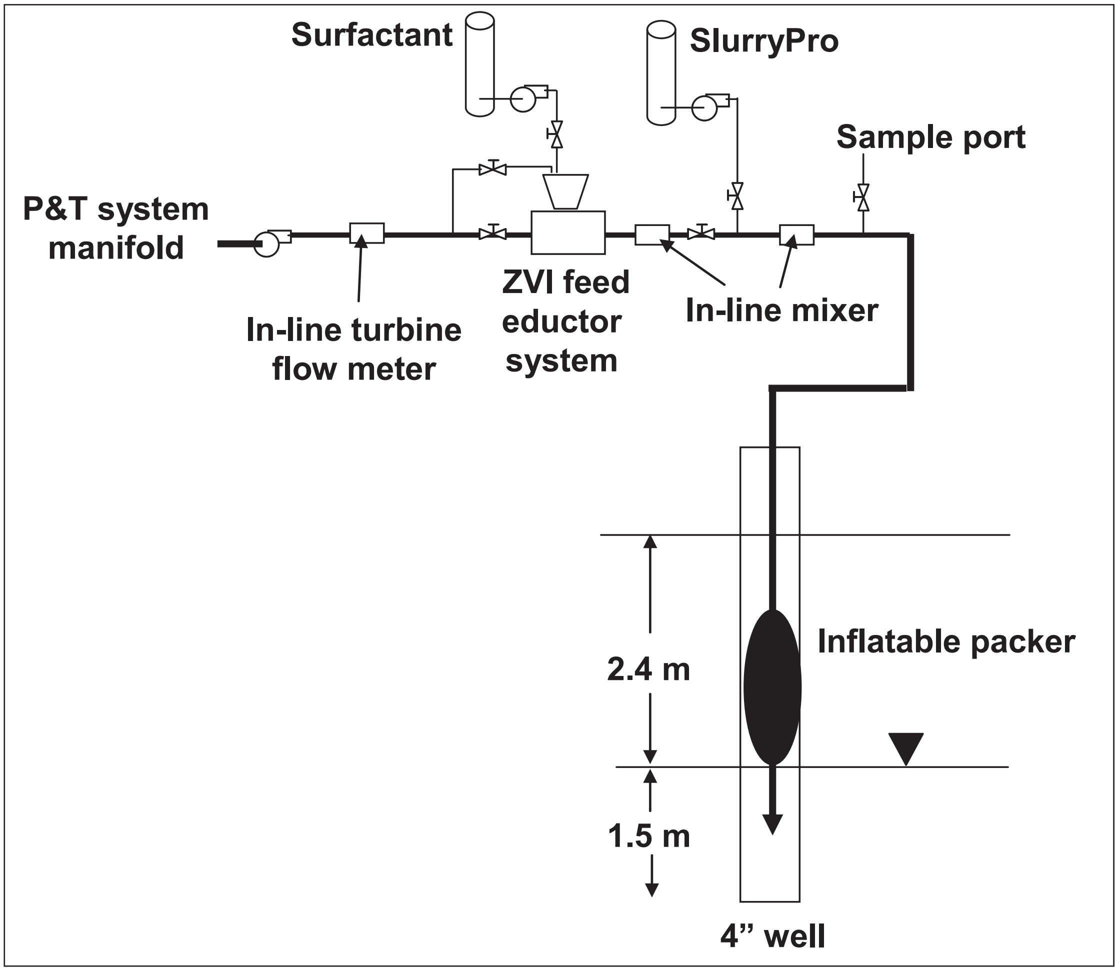

Figure 5-11. Test equipment schematic.

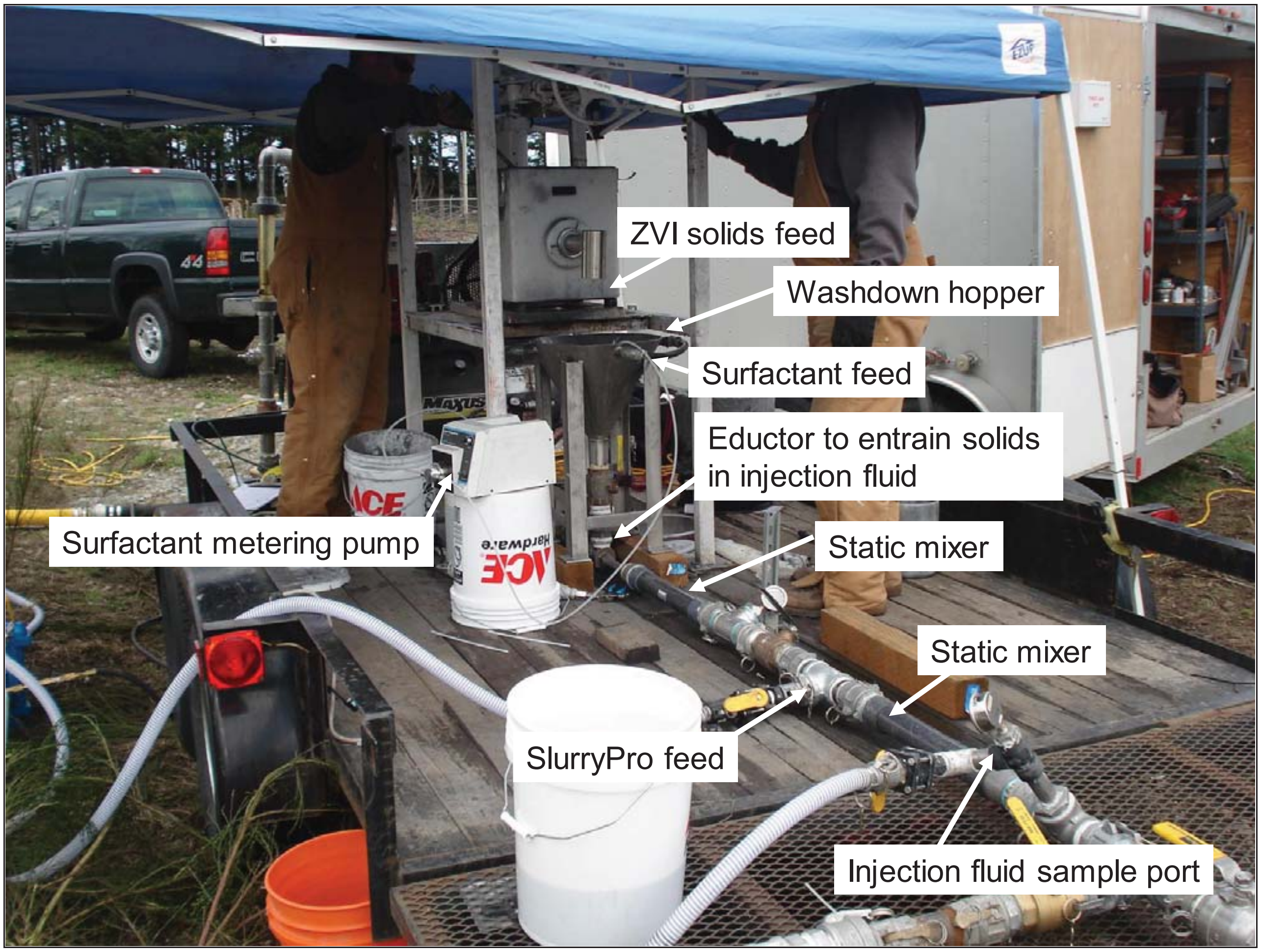

Figure 5-12. ZVI Injection System.

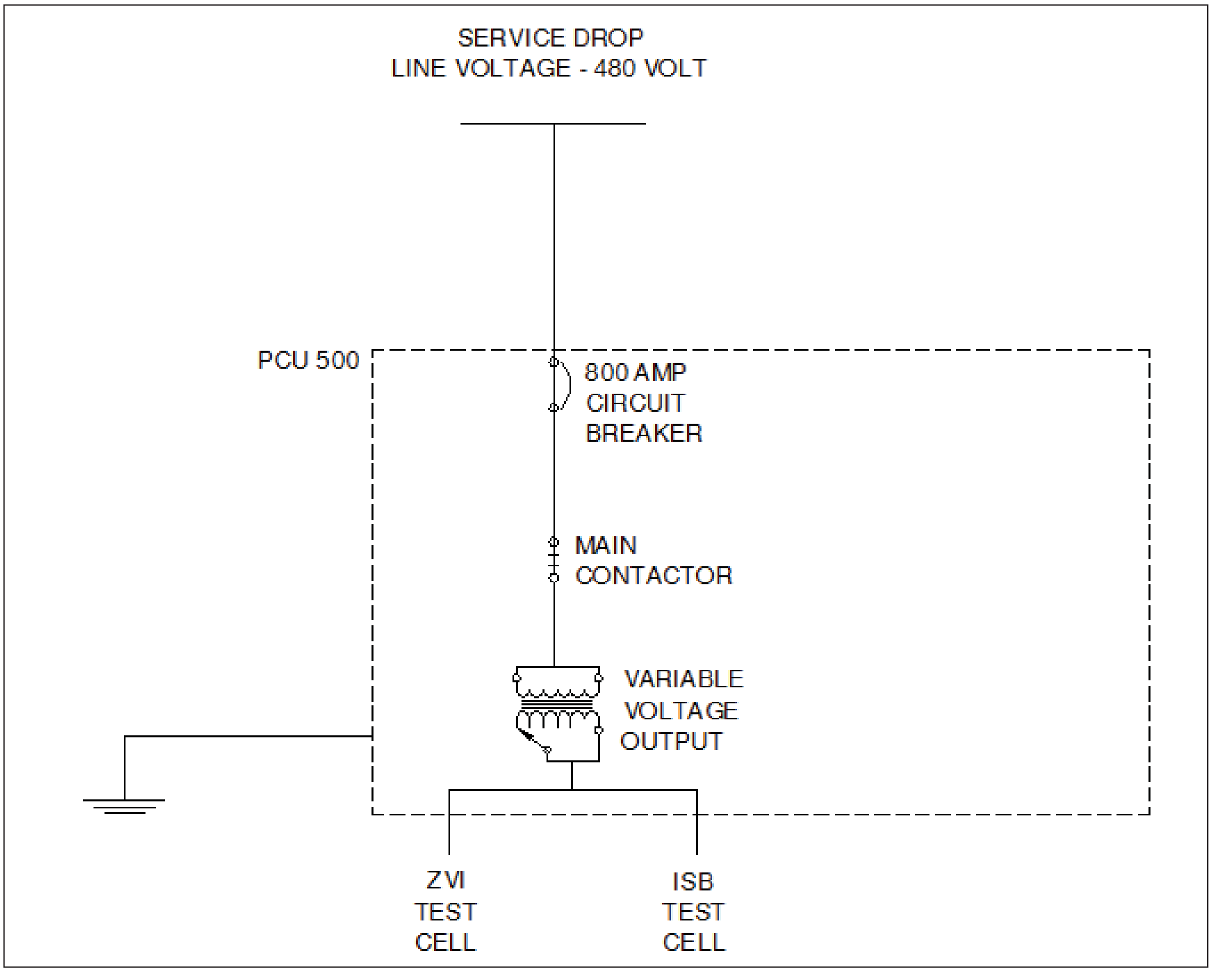

Figure 5-13. Power Control Unit (PCU) Electrical One-Line Drawing.

data acquisition system to download data, or monitor and control the ERH process either directly or by remote connection.

Each ERH application is designed to perform in the specific soil and groundwater properties encountered at the site. The ERH PCU is equipped to handle a wide range of electrical conductivity conditions in the subsurface.

ERH Electrode Layout

Both the ISB and ZVI test cells employed 7 electrodes each located as shown in **Figure 5-14** and **Figure 5-15** respectively. Each electrode location consisted of a single 12-foot electrode element which is connected to the surface via a high temperature electrical cable.

The ERH electrodes are simply devices used to transfer electrical energy to subsurface soil and groundwater. Relatively speaking, there is no radius of influence with respect to temperature associated with an individual electrode. It is best to consider the entire electrode array when considering the radius of thermal influence. During ERH, the primary *in situ* heating mechanism is the resistance to electrical current flow in the soil and groundwater being treated and is not the thermal conductivity from heat generated at the electrode.

Electrical current flows in all directions from each electrode borehole, but is most strongly directed to adjacent electrodes of a different electrical phase. The electrical current exits the borehole radially, and then bends towards the nearest electrode. This radial travel allows for heating a certain distance away from each border electrode at the perimeter of the electrode array. The distance is estimated to be slightly less than one-half the distance between electrodes of a different phase. Field observations have confirmed this to be a reliable estimate of the radius of active heating.

Both the ISB and ZVI test cell electrodes were installed within a 12-inch diameter electrode borehole to a depth of approximately 20-ft bgs. The annular space surrounding the electrically conductive interval of the electrodes (from 8 to 20-ft bgs) was filled with TRS' patented conductive backfill to transfer electrical current to the treatment volume. In the shallow portion, where the electrode is not electrically conductive, (0 to 8-ft bgs), the annular space was filled with non-conductive materials such as native soil or neat cement grout. Electrode completion details are provided in **Figure 5-16**.

Electrodes were positioned at an average spacing of 11.5-ft on center to allow the optimal energy application that would provide the required subsurface temperatures without the formation of steam at the electrodes.. The electrode spacing was determined by a number of factors unique to the EGDY and this project including soil type, geometry of the treatment area, groundwater elevation and flux, groundwater conductivity, depth of treatment, the total organic carbon (TOC) content of soil in the treatment area, and the distribution, concentration, and clean-up goals of the contamination to be treated, to name a few. Electrode spacing was also determined based on a balance of power, they key consideration for managing temperatures. For each kW of power applied to the site, a small percentage is lost to the subsurface surrounding the treatment volume.

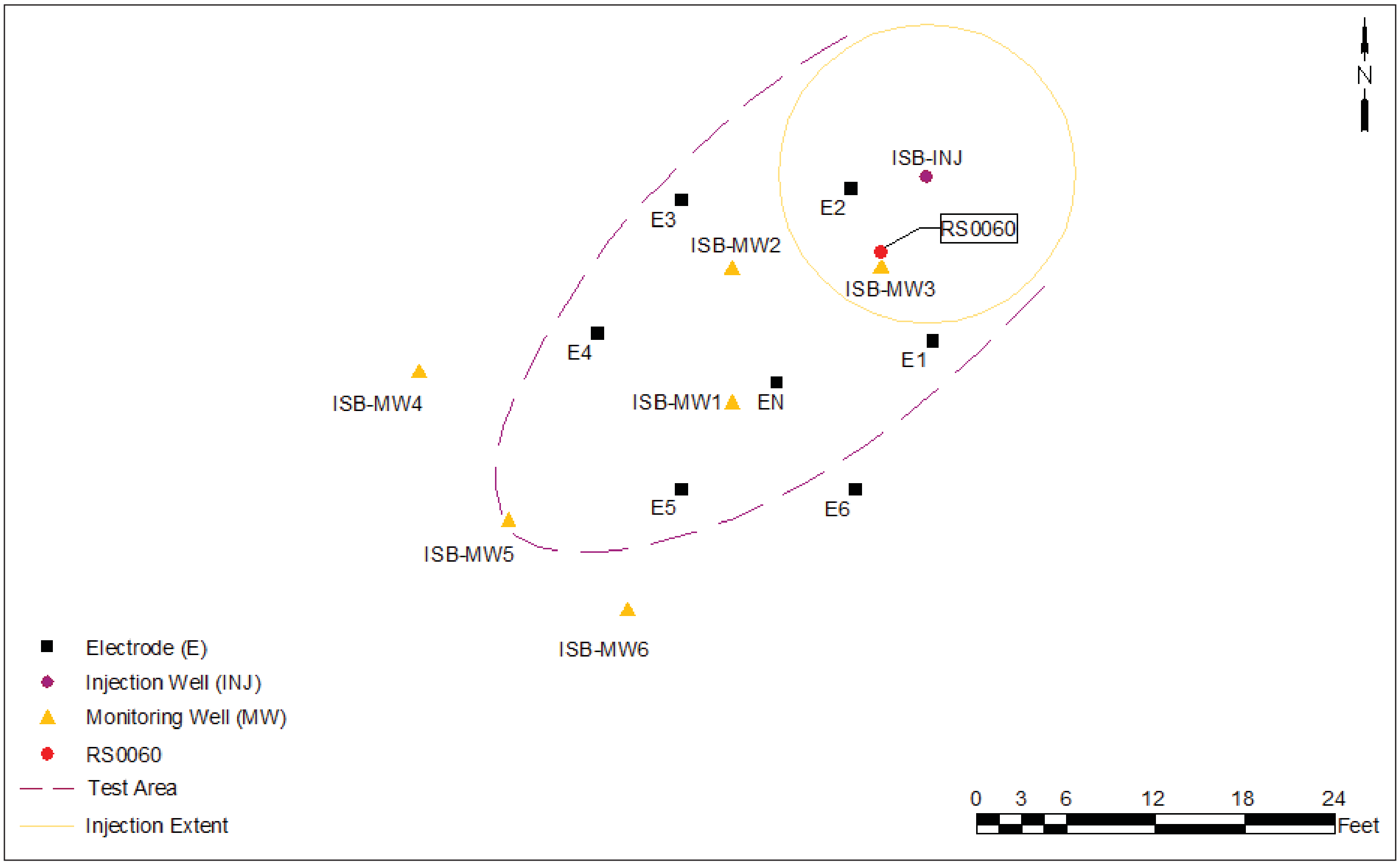

Figure 5-14. ERH Electrode Locations of the ISB Test Cell.

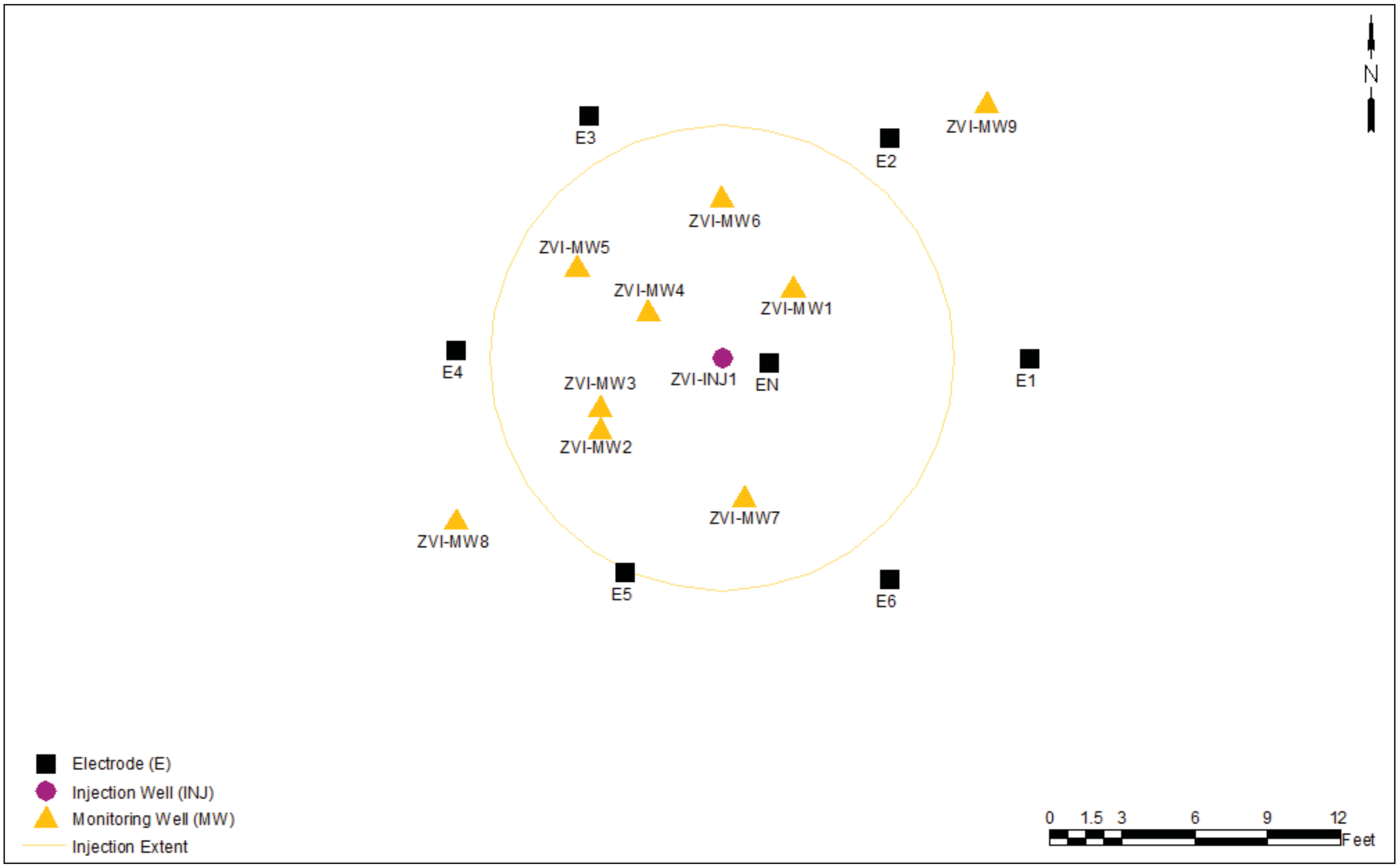

Figure 5-15. ERH Electrode Locations of the ZVI Test Cell.

ZVI ELECTRODE
WELL DETAIL

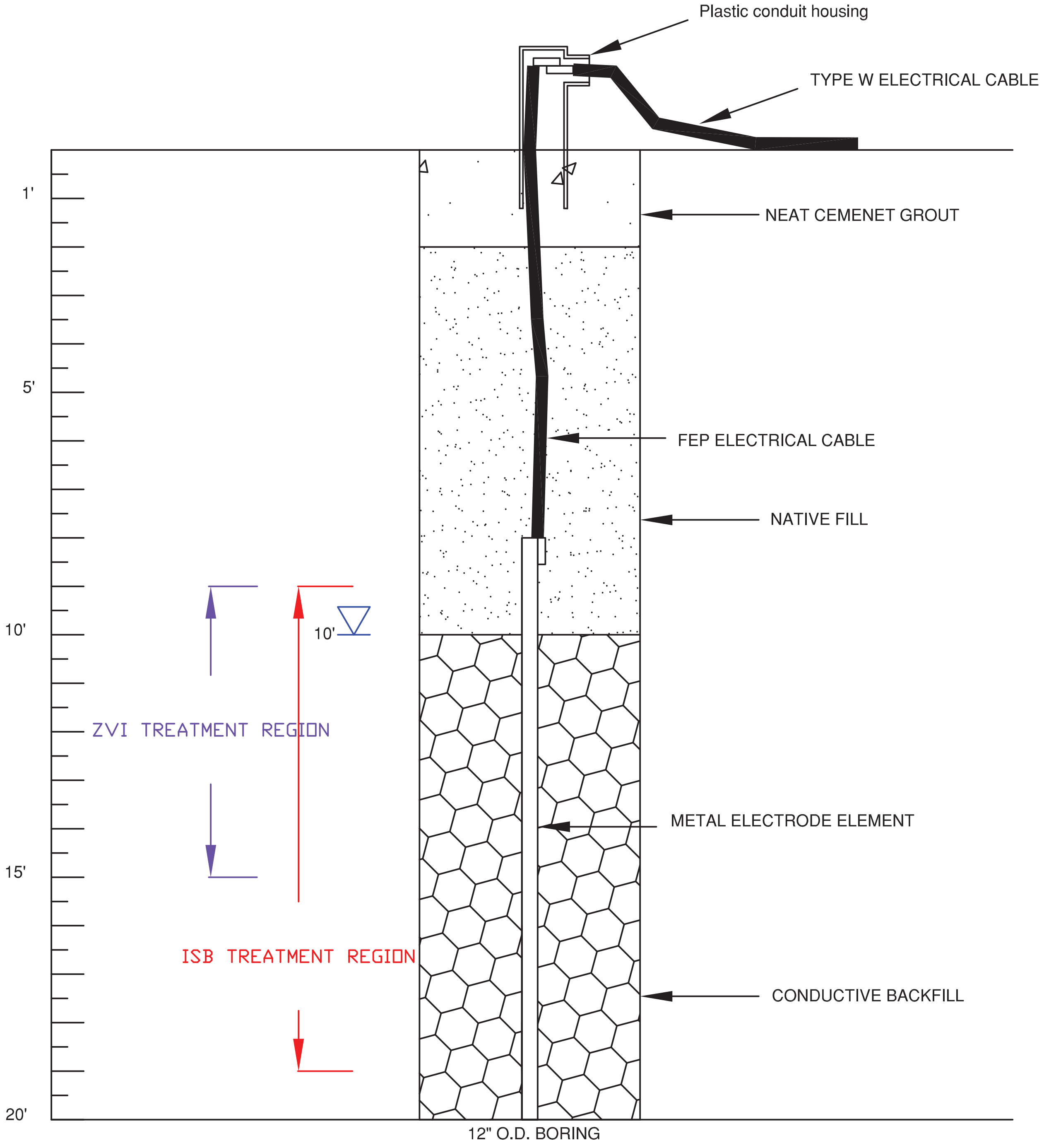

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Figure 5-16
ELECTRODE DETAIL

FORT LEWIS, WA

SCALE NONE
SHEET NO 1 SHEETS 1
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Heat loss includes conductive heating of the surrounding soils and groundwater flux through the treatment area.

Temperature Monitoring Points

Measurement of subsurface temperatures occurred at temperature monitoring point (TMPs) locations located upgradient, within, and downgradient of both of the ISB and ZVI test cells. These TMPs were used to track the heating process and ensure that the desired subsurface temperatures were achieved and maintained. In both the ZVI and ISB test cells, TMPs were installed within select groundwater MWs that were determined to best represent subsurface temperatures of each cell.

In the ZVI test cell the TMPs were located within the treatment region in MWs ZVI-MW1, ZVI-MW2, ZVI-MW5 and ZVI-MW7 as well as an upgradient location in ZVI-MW9 and a downgradient location in ZVI-MW8. Each TMP within the ZVI test cell consisted of 4 to 6 Type-T thermocouples spaced at 4 foot intervals from 1-ft bgs to the bottom of each MW. The upgradient and downgradient TMPs each contained only one Type-T thermocouple located at 9 ft bgs. **Table 5-11** displays the number of thermocouples and corresponding depths for each TMP in the ZVI test cell.

Table 5-11. ZVI TMP Thermocouple Numbers and Depths.

TMP Location	Number of Thermocouples	Thermocouple Depths (ft bgs)
ZVI-MW1	6	1, 5, 9, 13, 15, 19
ZVI-MW2	5	1, 5, 9, 13, 15
ZVI-MW5	4	1, 5, 9, 13
ZVI-MW7	4	1, 5, 9, 13
ZVI-MW8 (downgradient)	1	9
ZVI-MW9 (upgradient)	1	9

In the ISB test cell, the TMPs were located within the treatment region in MWs ISB-MW1, ISB-MW2, ISB-MW3 as well as an upgradient location in ISB-INJ and three downgradient locations in ISB-MW4, ISB-MW5, and ISB-MW6. Each TMP within the ISB test cell consisted of 6 Type-T thermocouples spaced at 5-foot intervals from 2-ft bgs to 27-ft bgs, which corresponded to the depths used for groundwater monitoring within the ISB treatment region. The upgradient TMP contained only one Type-T thermocouple located at 15 ft bgs. Two of the three downgradient TMPs, ISB-MW4 and ISB-MW6, contained two Type-T thermocouples located at 7 ft bgs and 17 ft bgs with the third downgradient TMP, ISB-MW5 containing four Type-T thermocouples located at 7 ft bgs., 12 ft bgs, 17 ft bgs and 21.5 ft bgs. Downgradient TMP ISB-MW5 contained more thermocouples compared to the other two downgradient TMPs as it was centered on the groundwater flow exiting the ISB test cell. **Table 5-12** displays the number of thermocouples and corresponding depths for each TMP in the ISB test cell. Individual TMP locations for both the ISB and ZVI test cells are shown above in **Figure 5-14** and **Figure 5-15**.

Table 5-12. ISB TMP Thermocouple Numbers and Depths.

TMP Location	Number of Thermocouples	Thermocouple Depths (ft bgs)
ISB-MW1	6	2, 7, 12, 17, 22, 27
ISB-MW2	6	2, 7, 12, 17, 22, 27
ISB-MW3	6	2, 7, 12, 17, 22, 27
ISB-INJ (up gradient)	1	15
ISB-MW4 (downgradient)	2	7, 17
ISB-MW5 (downgradient)	4	7, 12, 17, 21.5
ISB-MW6 (downgradient)	2	7, 17

5.5 Field Testing

5.5.1 Phase 2 and 3: ISB Injection Strategy

EOS® Injections

Between February and March 2009, two EOS® injections were completed at the ISB test cell through injection well ISB-INJ. The purpose of the injection was to establish reducing conditions in the aquifer conducive to ARD. In addition, EOS® was selected because it is a long-lived electron donor and the soybean oil sorbs onto the soil matrix once the emulsion breaks. This was intended to address the significant concern that the high groundwater flow system within the ISB test cell would “wash away” the added amendments before the biological reaction kinetics could degrade the carbon and stimulate the desired reducing conditions necessary to stimulate growth of *DHC* The injections were performed on February 5 and March 10, 2009. The injection volume of EOS® for each injection event is summarized in **Table 5-13**.

Table 5-13. Summary of amendment injections in the ISB test cell during Phase 2 and 3.

Phase/ Injection Event	Injection Type	Injection Date	Total Volume Injected (gallons)	Volume EOS (gal) or Mass whey (lb)	EOS (% v/v) or whey (% w/w)	% w/w bicarbonate
Phase 2/ Event 1	EOS	5-Feb-09	2678	61	1.36%	NA
Phase 2/ Event 2	EOS	10-Mar-09	930	54.5	3.50%	NA
Phase 2/ Event 3	Powdered whey/ bicarbonate	3-Jun-09	1400	200	1.72%	0.86%
Phase 2/ Event 4	Powdered whey/ bicarbonate	21-Jul-09	1343	200	1.79%	0.89%
Phase 3/ Event 1	Powdered whey/ bicarbonate	10-Sep-09	1224	200	1.96%	0.98%
Phase 3/ Event 2	Powdered whey/ bicarbonate	16-Oct-09	1212	200	1.98%	0.99%
Phase 3/ Event 3	Powdered whey/ bicarbonate	20-Nov-09	1212	200	1.98%	0.99%
Phase 3/ Event 4	Powdered whey/ bicarbonate	21-Dec-09	1401	200	1.71%	0.86%
Phase 3/ Event 5	Powdered whey/ bicarbonate	29-Jan-10	1776	200	1.35%	0.68%
Phase 3/ Event 6	Powdered whey/ bicarbonate	2-Mar-10	1345	200	1.79%	0.89%

The design for the EOS® injection included approximately 1600 gallons of an approximately 3.6% solution. However, during the January event, the pumping rate of the EOS® stock solution was much slower than anticipated through the injection equipment (Dosatron), attributed to cold temperatures (below 50 degrees Fahrenheit) during the injection. Therefore, the first injection event consisted of 2,678 gallons of an in-line concentration of 1.4% (v/v) EOS® solution. The EOS® stock solution was prepared by mixing 55 gallons of EOS® 598 concentrate, 1 gallon of EOS® Activator, and 5 gallons of EOS® AquaBupH (a pH buffering solution). Once the stock solution was thoroughly mixed, a Dosatron Model DI-210 water–driven proportional injector was used to inject the stock solutions for in-line mixing to achieve the target injection concentrations. The Dosatron mixing concentration was set to approximately 10% for a 10:1 feed-water to stock solution ratio. The total injection rate ranged from 5.5 to 6.5 gpm and was limited by the available flow and pressure of feed-water conveyed to the injection site.

The second injection event consisted of 930 gallons of an in-line concentration of 3.5 % (v/v) EOS® solution. The EOS® stock solution was prepared by mixing 55 gallons of EOS® 598 concentrate, 1 gallon of EOS® Activator, and 5 gallons of EOS® AquaBupH (a pH buffering solution). An EOS® stock solution was directly pumped into the injection well using a submersible pump and manifold. The target injection concentration was achieved using this revised approach.

Bicarbonate Buffered Whey Injections

Results of the EOS® injections suggested that the EOS® was not retained within the test cells following either EOS® injection in sufficient quantity to drive conditions anaerobic. Therefore, a decision to switch from EOS® to buffered whey injection was made. During the ER-0218 demonstration, whey powder was used and was successful at achieving sufficiently reducing conditions to stimulate growth of *Dehalococcoides* and achieve reduction of chlorinated ethenes (Lee et al 2008, 2012). However, fermentation of whey powder also significantly reduced pH, which resulted in a reduction in dechlorination rate and efficiency. Therefore, between June 2009 and September 2010, three sodium bicarbonate-buffered, whey injections were completed at the ISB-INJ well for Phase 2 (**Table 5-13**), and six sodium bicarbonate-buffered, whey injections were completed at the ISB-INJ well for Phase 3 between September 2009 and March 2010. The injection volume and mass of whey and sodium bicarbonate for each injection event is summarized in **Table 5-13**.

Each injection event consisted of approximately 1,000 gallons of whey solution; immediately followed by 200 gallons of sodium bicarbonate solution. At the end of each injection, 200 gallons of water were injected into the well to flush the screen and filter pack. The total target *in situ* amendment concentration was approximately 1.8% (w/w) whey and 0.9% (w/w) bicarbonate.

The whey injections consisted of first preparing a concentrated stock solution by mixing 200 lbs of cheese whey powder with 100 gallons of water. The stock solution was prepared and mixed in 55-gallon drums using mixing sticks and recirculation with a submersible sump pump. A Dosatron Model DI-210 water–driven proportional injector was used to inject the stock solution with a larger volume of water to achieve the target concentration. The Dosatron mixing concentration was set to approximately 10% for a 10:1 feed-water to stock solution ratio. The whey solution injection rate ranged from 5 to 6 gpm and was limited by the available flow and pressure of the feed-water conveyed to the injection site. The sodium bicarbonate injections consisted of preparing a concentrated stock solution by mixing a total of 100 lbs of No. 2 sodium bicarbonate with 200 gallons of water. The solution was prepared in 55-gallon drums and mixed via recirculation with a submersible sump pump. After the sodium bicarbonate was completely dissolved, the solution was injected into the well using the sump pump. Sodium bicarbonate injection rates ranged from 6 to 9 gpm.

5.5.2 Phase 2 and 3: ZVI Injection Strategy

A full description of the ZVI injection process is described in Truex et al. 2010 and is summarized here. Prior to ZVI injection, a sodium bromide (100 mg/L as bromide ion) solution was injected to evaluate the injection pressure, bromide distribution within the targeted test zone, and to enable monitoring of bromide elution to estimate the groundwater velocity at the test site. Tracer concentrations were monitored in the test cell wells using a downhole bromide ion selective electrode during and after injection to define the tracer breakthrough and elution responses within each of the MWs ZVI-MW1 through MW9. Tracer breakthrough (50% of injected concentration) was compared to the predicted radial transport for flow within a cylinder with a height equal to the well screen length and a porosity of the outwash material. Tracer elution (time for reduction to 50% of peak concentration) was evaluated for MWs ZVI-MW1 through -MW7 to estimate groundwater velocity based on advection of clean water upgradient of the well estimated based on a nominal injection radius of 3 m and a groundwater flow direction of 294 degrees.

The ZVI injection system described in **Section 5.4.2** was used to inject a solution consisting of 0.02 wt% SlurryPro™ (SlurryPro CDP, KB International, www.kbtech.com), 0.0008 wt% surfactant (Aerosol, Sigma Chemical, St. Louis, Missouri), 1.36 wt% S-3700 ZVI (Fe0 colloids with a diameter of 2 +/- 1 um, International Specialty Products, Wayne, New Jersey), and groundwater from the influent line of the Landfill 2 pump and treat system, which contained a nominal TCE concentration of 150 ug/L. The injection system was used to feed ZVI at a nominal rate of 1.1 kg/min into the injection water. Surfactant from a 1 wt% stock solution was metered into the wash down hopper portion of the ZVI solids feed system to disperse the ZVI particles and prevent clumping.

A 0.2 wt% SlurryPro™ stock solution (**Figure 5-17**) was metered into the injection water downstream of the ZVI/surfactant feed system. The SlurryPro™ component of the injection solution was selected because its rheological properties as a shear-thinning fluid facilitate ZVI transport through porous media (Oostrom et al. 2007). The injection system provided a continuous flow method for preparing a suitable, uniformly-mixed injection solution (**Figure 5-11**). **Figure 5-18** shows a picture of the ZVI injection solution and **Figure 5-19** shows groundwater samples containing ZVI collected from the MWs at the mid-point of ZVI injection.

5.5.3 Phase 3: ERH System Operations

The ERH operations period for Phase 3 of the ESTCP ER-0719 remediation includes site activities from system shakedown and start-up through ERH operations and system demobilization.

ERH System Start Up

ERH system shakedown and start-up testing began the week of June 8, 2009. With all electrical and temperature monitoring installations complete, proper operation of the internal and external interlocks for each system component was verified. TRS then applied power to the electrodes for start-up voltage testing on June 16, 2009.

Concurrent with the ERH system testing, step and touch voltage safety tests were also performed. These tests are done to evaluate surface conditions for the presence of induced voltages. Areas where personnel may walk or touch surfaces are measured for voltage potential.

Figure 5-17. Stock solution of SlurryPro™ (0.2 wt%).

Figure 5-18. Picture of ZVI injection solution during injection.

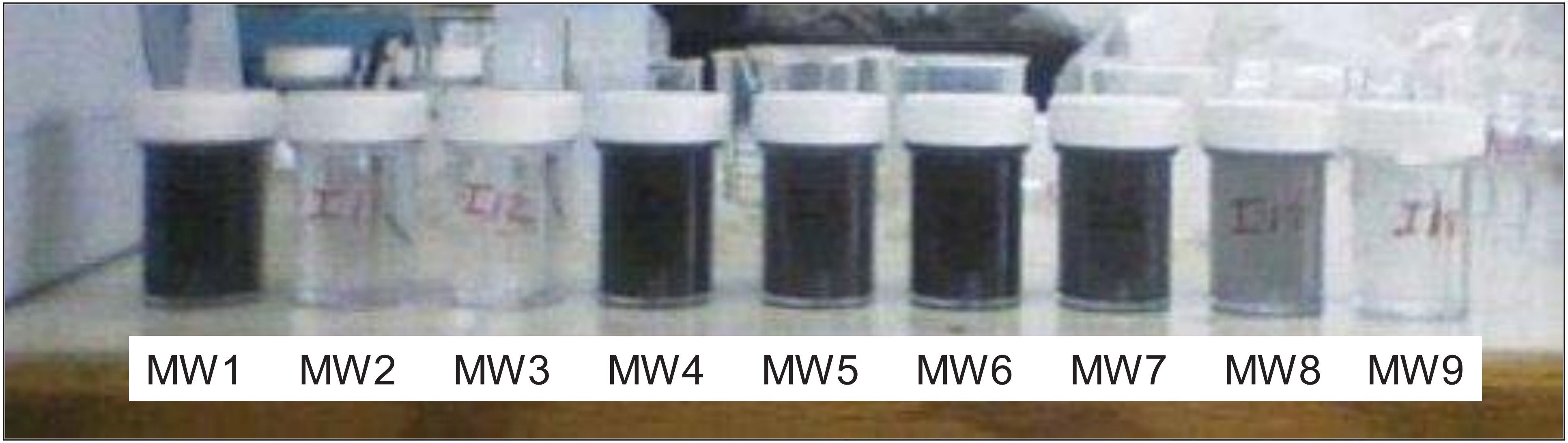


Figure 5-19. Samples at monitoring wells a the mid-point of ZVI injection.

Any areas with measurements of 15 volts are identified and the situation rectified by either isolation, or bonding. During this procedure the step and touch voltage testing verified that no locations exceeded the 15-Volt standard.

With the initial surface voltage survey complete, the applied voltage to the subsurface was slowly increased over the remainder of the start-up period. At each voltage increase, checks for surface voltage were performed and results recorded until the final start-up voltage of 325 volts was reached. In no instance did step-and-touch readings at the surface exceed the TRS 15-volt limit. The ERH system first operated overnight in unattended mode on June 17, 2009 and that date was set as the start of the operations period.

Safety and Security

During ERH start-up, and throughout system operation, step-and-touch voltage potentials in and around the electrode field were monitored frequently to ensure public and worker safety. At no time during ERH system start-up or operations were surface voltages above 15-volts measured at any location on or adjacent to the electrode field. During ERH operations the remediation area was also surrounded by security fencing and access to the remediation area was not permitted unless proper Lock-Out/Tag-Out (LOTO) procedures were followed prior to access by project team members.

A LOTO procedure was established by TRS during active ERH heating to ensure the safety of all ESTCP team members while conducting field work within the ER-0719 test cells during Phase 3 of operations. Prior to conducting any field activities within the treatment region ERH power application was ceased and zero energy application was verified by TRS. The PCU was locked out using a keyed LOTO device by on site personnel conducting the field work and was only unlocked after field work was completed and the treatment region was cleared of all personnel. Power was only able to be reapplied to the treatment region after all site personnel were verified out of the treatment region and the PCU LOTO device was unlocked.

ERH Operations

Treatment of the ZVI test cell began on June 17, 2009 with a target treatment temperature of 50°C, however, modification were made throughout the test based on analytical results. The actual average temperatures in the ZVI test cell ranged from 35 and 48°C from August 20, 2009 through December 31, 2009. From January 1, 2010 through the end of treatment on March 22, 2010 temperatures in the ZVI cell were maintained between 31 and 34°C. During this period a total of 60,038 kilowatt hour (kWh) of energy was applied to the ZVI treatment region.

Treatment of the ISB test cell began on September 26, 2009 with a target treatment temperature of 40°C. The ISB test cell achieved an average temperature of between 30 and 48°C from October 12, 2009 through January 3, 2010. From January 4, 2010 through February 10, 2010 temperatures in the ISB cell were maintained between 25 and 30°C. From February 11, 2010 through the end of treatment on March 22, 2010 temperatures in the ISB cell were maintained between 29 and 36°C. During this period total of 33,330kWh of energy was applied to the ISB treatment region.

ERH Operations System Optimization

The ERH system was continuously monitored which allowed operational adjustments to be made either remotely or by on-site staff. The ability to make changes to system operations remotely helped ensure that the remedial objectives of the project were met while the system remained safe and environmentally compliant. Through the use of remote monitoring of the temperature monitoring system and remote operating features of the power output control systems, operations personnel were able to respond rapidly to system changes and maximize energy input to both the ISB and ZVI test cells concurrently.

TRS used voltage adjustment and on-time as the two primary methods of optimization during the treatment of both test cells. The soil conductivity at each electrode was unique to that location. TRS overcame the unique conductivities at each electrode by varying the applied voltage. Conductivities changed throughout the treatment duration, so frequent monitoring and adjustments were necessary. TRS also used ERH power application “on-time” as a method to maintain optimal treatment temperatures for each cell. Once the target temperature range had been met, power could be turned off to prevent overheating the soils, and wasting energy or reducing treatment effectiveness. The amount of on-time necessary to maintain temperatures was adjusted by observing the daily temperature data.

Demobilization

The electrodes were de-energized and the electrical service was permanently locked out on March 22, 2010. Final system demobilization, equipment breakdown, and material packaging were complete by May 18, 2010 and the PCU was removed from the site on May 19, 2010.

The thermocouples were left in their associated MWs for continued monitoring until the wells are permanently abandoned. Post-Phase 3 temperatures were monitored using a hand held thermocouple reader.

The electrodes in both the ZVI and ISB test cells were decommissioned by removal of surface appurtenances upon completion of Phase 3.

5.6 Sampling Methods

Samples, including groundwater, soil gas and soils were collected from all three phases in the ZVI and ISB test cell. The total number of samples taken and the types of samples that were collected are summarized in **Tables 5-14** and **5-15**. Analytical methods are highlighted in **Table 5-16**.

Table 5-14. ZVI Sample Types and Quantities.

Phase	Matrix	Number of Samples	Analytes[a, b, c, d]	Location
Pre-Demonstration Design	Soil Gas (GORE^{TM})	15	VOC, hydrocarbon, ethane, ethene, acetylene	Grid pattern across potential Test Cell location
	Groundwater	3	VOC, field parameters	INJ, MW1, MW2
	Groundwater	Continuous until breakthrough	Sodium Bromide	
	Groundwater		Sodium Bromide	MW1-MW7
Phase	Matrix	Number of Samples	Analyte	Location
Phase 1, Baseline Conditions	Groundwater	20	VOC, dissolved gases, anions, Fe(II), field parameters	INJ, MW1-MW9
	Groundwater	2	Microbial Targets	MW2, MW4
	Soil Gas (Summa)	5	VOC, ethene, ethane, acetylene	MW2, MW4, MW5, MW6, MW7
	Soil Gas (GORETM)	6	VOC, hydrocarbon, ethane, ethene, acetylene	MW2, MW4, MW6, Flux A, Flux B, Flux C
	Soil	9	VOC	Soil Cores near INJ, MW1, MW2

Table 5-14. ZVI Sample Types and Quantities. (Continued)

Phase	Matrix	Number of Samples	Analytes[a, b, c, d]	Location
Phase 2, Ambient Temperature	Groundwater	40	VOC, dissolved gases, anions, field parameters	INJ, MW1-MW9
	Groundwater	20	Fe(II)	INJ, MW1-MW9
	Groundwater	2	Microbial Targets	MW2, MW4
	Soil Gas (Summa)	5	VOC, ethene, ethane, acetylene	MW2, MW4, MW5, MW6, MW7
	Soil Gas (GORETM)	6	VOC, hydrocarbon, ethane, ethene, acetylene	MW2, MW4, MW6, Flux A, Flux B, Flux C
	Soil	6	VOC	Soil Cores near INJ, MW1
Phase 3, High Temperature	Groundwater	160	VOC, dissolved gases, anions, field parameters	INJ, MW1-MW9
	Groundwater	30	Fe(II)	INJ, MW1-MW9
	Groundwater	10	Microbial Targets	MW2, MW4
	Soil Gas (Summa)	35	VOC, ethene, ethane, acetylene	MW2, MW4, MW5, MW6, MW7
	Soil Gas (GORETM)	18	VOC, hydrocarbon, ethane, ethene, acetylene	MW2, MW4, MW6, Flux A, Flux B, Flux C
	Soil	9	VOC	Soil Cores near INJ, MW1, MW2

(a) VOCs to be quantified include PCE, TCE, 1-1,-DCE, cis-DCE, trans-DCE, and VC.
(b) Dissolved gases include ethene, ethane, and acetylene.
(c) Anions include Cl-, Br-, SO_4^{2-}, F-, and NO_3-
(d) Field parameters include Br$^-$ and/or I$^-$ DO, oxidation reduction potential (ORP), conductance, and temperature.

Table 5-15. ISB Sample Types and Quantities.

Phase	Matrix	Number of Samples	Analytes[a, b, c, d]	Location
Pre-Demonstration Design	Soil Gas (GORE™)	16	VOC, hydrocarbon, ethane, ethene, acetylene	Grid pattern across potential Test Cell location
	Groundwater	9	VOC, field parameters	MW1, MW2, MW3
	Groundwater	Continuous until breakthrough	Sodium Bromide	MW4, MW5, MW6
	Groundwater	88	Sodium Bromide	MW1-MW6
Phase 1, Baseline Conditions	Groundwater	16	VOC, dissolved gases, FE (II), COD, anions, field parameters	INJ, MW1-MW6
	Groundwater	4	Microbial Targets	MW1, MW2, MW3, MW5
	Soil Gas (Summa)	3	VOC, ethene, ethane, acetylene	MW1, MW2, MW3
	Soil Gas (GORE™)	6	VOC, hydrocarbon, ethane, ethene, acetylene	MW1, MW2, MW3, Flux A, Flux B, Flux C
	Soil	9	VOC	Soil Cores near INJ, MW1, MW2
Phase 2, Ambient Temperature	Groundwater	78	VOC, dissolved gases, anions, COD, field parameters	INJ, MW1-MW6
	Groundwater	52	Fe(II)	INJ, MW1-MW6
	Groundwater	8	Microbial Targets	MW2, MW4
	Soil Gas (Summa)	6	VOC, ethene, ethane, acetylene	MW1, MW2, MW3
	Soil Gas (GORE™)	24	VOC, hydrocarbon, ethane, ethene, acetylene	MW1, MW2, MW3, Flux A, Flux B, Flux C
	Soil	9	VOC	Soil Cores near INJ, MW1

Table 5-15. ISB Sample Types and Quantities. (Continued)

Phase	Matrix	Number of Samples	Analytes[a, b, c, d]	Location
Phase 3, High Temperature	Groundwater	88	VOC, dissolved gases, anions, COD, field parameters	INJ, MW1-MW6
	Groundwater	78	Fe(II)	INJ, MW1-MW6
	Groundwater	6	Microbial Targets	MW2, MW4
	Soil Gas (Summa)	11	VOC, ethene, ethane, acetylene	MW1, MW2, MW3
	Soil Gas (GORE^{TM})	18	VOC, hydrocarbon, ethane, ethene, acetylene	MW1, MW2, MW3, Flux A, Flux B, Flux C
	Soil	9	VOC	Soil Cores near INJ, MW1, MW2

(a) VOCs to be quantified include PCE, TCE, cis-DCE, trans-DCE, and VC.

(b) Dissolved gases include ethene, ethane, and methane.

(c) Anions include Cl-, Br-, SO_4^{2-}, and NO_3-.

(d) Field parameters include Br^- and/or I^- and DO, ORP, conductance, temperature, pH and alkalinity.

Table 5-16. Groundwater Sample Analysis Summary.

Matrix	Analytes	Sample Container	Preservative	Analytical Method	Holding Time	ZVI and/or ISB Test Cell
Groundwater	Bromide	One 125-mL HDPE	Cool to 4ºC	Ion-specific electrode	24 hours	ZVI and ISB
	VOCs (TCE, DCE isomers, VC)	Three glass 40-mL VOA vials	No headspace, HCl pH<2, cool 4ºC,	SW846-8260b	14 days	ZVI and ISB
	Dissolved gases (ethene, ethane, methane, acetylene)	Three glass 40-mL VOA vials	HCl pH<2, cool to 4ºC	RSKSOP-175	14 days	ZVI and ISB
	COD	Glass	H_2SO_4 pH<2	EPA 410.2	28 days	ISB
	Ferrous Iron	60 ml HDPE	-	HACH Field Test Kit	-	ZVI and ISB
	Water Levels	In situ	-	Contractor specific SOP	-	ZVI and ISB
	Anions (sulfate, nitrate, chloride, sulfide)	Glass or plastic	Cool to 4ºC	Ion chromatography EPA300.0	28 days	ZVI and ISB
	Purge parameters, (Temperature, pH, Specific Conductivity, ORP)	Collect during purging in flow-through cell	-	Direct Measurement Water Quality Probe	-	ZVI and ISB
	Microbial Parameters	1 L HDPE	Cool to 4ºC	qPCR	24 hours before filtering	ZVI and ISB
Soil Gas (Summa)	VOCs, dissolved gases	Summa Canister	-	EPA TO14A	30 day	ZVI and ISB
	Dissolved gases	Summa Canister	-	ASTM D1946	30 day	ZVI and ISB
Soil Gas (GORE™)	VOCs, dissolved gases, hydrocarbons	GORETM Modules	-	Modified EPA 8260/8270	-	ZVI and ISB
	VOCs	Glass	Cool to 4ºC	EPA 8260B	14 days	ZVI and ISB

5.6.1 Tracer Test

A tracer test was conducted in both the ZVI and ISB demonstration cells during the pre-characterization phase as discussed in **Section 5.2.4** and **5.2.5**.

5.6.2 Groundwater Sampling Methods

Low-flow groundwater sampling (micropurging) was used for all events to minimize the drawdown on the aquifer. Groundwater samples included water quality parameters (temperature, pH, specific conductivity, oxidation-reduction potential (ORP) and DO), ferrous iron, VOCs, dissolved gases, anions, COD (ISB only) and microbial targets. Water quality parameters were collected and recorded after purging parameters were met (stabilization or purged to dryness twice). The water quality meter was properly calibrated per manufacturer prior to sampling. Ferrous iron was collected and analyzed in field using the HACH field kit. For VOC, dissolved gas, anions and COD, the appropriate sample container, as outlined in **Table 5-16**, was filled, placed in a cooler with ice and sent to Test America-Tacoma or Idaho State University for analysis. To minimize volatilization during Phase 3 heating, groundwater was passed through stainless steel cooling coils at 20˚C before samples were collected.

5.6.3 Soil Gas Sampling Methods

GORE^{TM} modules were installed in the pre-characterization phase to identify TCE hot spots in the proposed test cells. The modules were placed in the soil using a rotary hammer drill at a depth of 3-4 ft bgs and deployed for a total of 5 days. Results of the soil gas survey were used to finalize ZVI and ISB demonstration cell locations.

During Phase 1, 2 and 3, soil gas samples were collected using Summa Canisters and/or GORE^{TM} modules. All soil gas samples were analyzed for VOCs, ethane, ethene and acetylene. To correlate the Summa and GORE^{TM} data, the SV port was purged, GORE^{TM} modules were placed in the screened portion of the SV port, the port was sealed from the atmosphere and the module was left for approximately 24 hours. To accommodate for the GORE^{TM} modules not fitting into the ZVI SV ports an alternative sampling technique was established. Teflon tubing was inserted into the SV port to a depth of 5 ft bgs. A 500 mL polybottle was attached to the tubing above ground. The GORE^{TM} module was placed in the polybottle, the lid was sealed with tape and the module was left for approximately 24 hours. Summa soil gas samples were collected following manufacturer recommendations immediately after the GORE^{TM} modules were removed.

GORE^{TM} modules were also installed 6” below the soil surface to monitor soil gas flux. Soil gas flux chambers consisted of a 4” diameter PVC pipe approximately 4” long filled with clean sand. The GORE^{TM} modules were placed in the flux chamber for a duration of 24 hours during the same time that modules were emplaced in the SV wells. Modules were collected and sent to GORE for analysis of VOCs and dissolved gases.

Following the removal of the GORE™ modules, Summa soil gas samples were collected. For the ISB test cell, the Summa canister tubing was inserted into the screened portion of the port, the top of the port was sealed and the canister was allowed to collect a sample for approximately one hour. In the ZVI test cell, the Summa canister was attached to the dedicated tubing, sealed and sample was collected for approximately one hour.

5.6.4 Soil Sampling Methods

Soils were collected in each test cell 3 times, once during borehole installation and once each at the end of Phase 2 and Phase 3. Samples were collected near the same location and depth for every phase to maximize consistency and comparability. The samples were screened on site using a PID probe, visually inspected for NAPL and assessed via oil-in-soil dye test kits and sheen tests. Based on the screening results, three samples were selected from each borehole and sent to the laboratory for VOC analysis.

5.6.5 EEH Sampling Methods

Subsurface Temperature Monitoring

Subsurface temperatures were measured using thermocouples placed in TMPs located within the ISB and ZVI test cells. The PCU system control program was utilized to continuously monitor each thermocouple temperature value and automatically record all the temperature values three times per day.

Thermocouple design is based on the change of electrical resistance between the connection of dissimilar metals when introduced to a specific range of heat. All thermocouples regardless of the temperature range they are designed for, or Type, are unable to be calibrated. In the rare event of a thermocouple failure the thermocouple will not read a correct value if a value is able to be read at all.

To verify the correct operation of the thermocouples used in both the ZVI and ISB test cells a hand-held thermocouple reader was used to validate and verify that the temperatures recorded using the automated data collection system matched those read using the hand held meter. Thermocouples were verified for correct operation after initial installation, when recorded temperatures appeared to be incorrect, and randomly throughout Phase 3 of operations.

ERH Power Output and Control Monitoring

PCU output and control data acquisition was performed on a dedicated computer running the Windows^{TM} operating system. Remote data acquisition software was used to collect and store power, voltage, current, and operational status data three times per day during Phase 3 of operations. Operations personnel accessed the data acquisition system to download data, or monitor and control the ERH process either directly or by remote connection.

Table 5-17 summarizes all temperature and power output sampling frequency and locations associated with the application of ERH low temperature heating for both the ZVI and ISB treatment regions.

Table 5-17. ERH Temperature and Power Sampling Frequency.

Component	Matrix	Number of Samples	Analyte	Location
Phase -3 ERH Monitoring	Soil (ZVI Cell)	21 Locations, recorded three times daily	Subsurface Temperature	All ZVI TMP (Thermocouple) locations
	Soil (ISB Cell)	27 Locations, recorded three times daily	Subsurface Temperature	All ISB TMP (Thermocouple) locations
	PCU output Voltage	6 independent outputs, recorded three times daily	Voltage (V)	Each PCU output buss bar used for ERH subsurface heating
	PCU Output Current	6 independent outputs, recorded three times daily	Current (I)	Each PCU output buss bar used for ERH subsurface heating
	PCU Output Power	6 independent outputs, recorded three times daily	Power (kW)	Each PCU output buss bar used for ERH subsurface heating
	PCU Input Voltage	3 independent outputs, recorded three times daily	Voltage (V)	PCU Primary Power connection buss bar
	PCU Input Current	3 independent outputs, recorded three times daily	Current (I)	PCU Primary Power connection buss bar
	PCU Input Power	3 independent outputs, recorded three times daily	Power (kW)	PCU Primary Power connection buss bar

5.7 Sampling Results

5.7.1 Phases 2 and 3: ISB

During Phase 2 operations, two EOS® injections and two buffered whey powder injections within the ISB test cell were conducted. The area of influence of these nutrient injections includes a lateral radius of approximately 20 ft., a downgradient extent of approximately 36 ft., and a vertical depth of approximately 10 ft. Groundwater monitoring results indicated that the high groundwater velocities resulted in inefficient retention of the EOS® substrate to establish reducing conditions and that high-frequency injections were required. In order to operate the system more cost-effectively, the decision was made to switch from high-frequency EOS® to buffered whey injections.

Following Phase 2 EOS® and whey injections, geochemical conditions were established that are favorable to reductive dechlorination. Redox conditions shifted in accordance with the nutrient distribution. The conditions within the ISB test cell were methanogenic from approximately four months after the first EOS® injection. In addition, sulfate-reducing to methanogenic conditions were established approximately 36 ft downgradient of the ISB test cell.

5.7.1.1 Groundwater Monitoring

Groundwater monitoring was performed to evaluate the performance of the ISB test at ambient temperature. Samples were collected from the injection well (ISB-INJ) and six MWs (ISB-MW1 though ISB-MW6) using low-flow sampling techniques to ensure that discrete intervals of the aquifer were measured and to aid in keeping atmospheric oxygen out of the collected water.

During well purging, the purge water was directed through a flow-through cell containing the field meter probe that measured DO, pH, temperature, ORP, and conductivity. Hach kits were used in the field to measure the biodegradation indicator parameter ferrous iron, which were analyzed within 60 minutes of sampling. Offsite analytical laboratories analyzed samples for chemical oxygen demand (COD), VOCs, (PCE, TCE, cis-1,2- and trans-1,2-DCE, 1,1-DCE, and VC), dissolved gases (methane, ethene, and ethane), sulfate, nitrate, chloride, and DHC. DHC was measured using qPCR, which was used to estimate the concentration of DHC and the DHC reductase genes *tceA*, *bvcA*, and *vcrA*.

Gradient

The design of the test cell layout was based on evaluation of the previous year (2008) results of the site-wide gradient for Landfill 2 (see **Figure 5-5**) during which time the Landfill 2 pump and treat system was operating. However, at the beginning of the ESTCP demonstration, the Landfill 2 pump and treat system well PW-1 was shut down. Actual gradient magnitudes are shown on **Table 5-7**.

Carbon Distribution

The addition of an EOS® and whey was intended as a source of essential nutrients, including carbon and electrons, for indigenous microorganisms. The challenge at the Fort Lewis EGDY was to add sufficient carbon to drive conditions from generally aerobic to methanogenic, which has been demonstrated to be conducive to dechlorination reactions at the site (Lee 2008). The distribution of electron donor injected (EOS® and whey) was monitored by measuring the COD concentrations at the injection and MWs.

The COD concentrations are shown in **Table 5-19** and **Figure 5-20** within the ISB test cell during the Phase 1 -3 sampling events. Considerable increases in COD concentrations were observed approximately one week following the first EOS® injection (EOS®11) (**Table 5-18**).

Table 5-18. Concentration of COD during baseline and post-Phase 2 EOS and whey injections.

Well (distance from INJ)	Depth (bgs)	COD (mg/L)						
		Baseline	Post-EOS 1		Post-EOS 2		Post-Whey 1	Post-Whey 2
			1 week	1 month	1 month	2 month	1 month	1 month
ISB-INJ (0 ft)	15	12	58	30	910	1000	1300	890
ISB-MW1 (20 ft)	12	14	49	14	41	13	42	73
	17	9	71	19	60	24	72	255
	22	12	170	30	48	26	86	270
ISB-MW2(14 ft)	12	11	100	23	100	32	44	120
	17	9	46	23	100	47	65	120
	22	0	160	35	92	45	61	150
ISB-MW3 (6 ft)	12	9	370	26	260	68	99	89
	17	0	320	26	94	49	100	180
	22	12	360	26	64	34	76	170
ISB-MW4 (36 ft)	15	12	20	12	16	0	0	15
ISB-MW5 (36 ft	15	0	22	12	48	3	0	15
ISB-MW6 (35 ft)	15	12	18	12	34	6	32	15

Table 5-19. Concentration of COD during Phase 2 and 3.

Days After 1st Injection[a]	CMT Depth (ft bgs) Sampled	COD (mg/L)						
		ISB-INJ[b]	ISB-MW1	ISB-MW2	ISB-MW3	ISB-MW4[b]	ISB-MW5[b]	ISB-MW6[b]
-8.00	12	12	14	11	0	12	0	12
	17		9	9	9.3			
	22		12	0	12			
6.00	12	58	49	100	370	20	22	18
	17		71	45.5	320			
	22		170	160	360			
32.00	12	30	14	23	26	12	12	12
	17		19	23	26			
	22		30	35	26			
67.00	12	910	41	100	260	16	48	34
	17		60	100	93.5			
	22		48	92	64			
92.00	12	1000	13	32	68	0	0	6.4
	17		24	47	49			
	22		26	45	34			
147.00	12	1300	42	44	99	0	6.4	32
	17		72	65	100			
	22		86	61	76			
193.00	12	890	73	120	89	15	0	15
	17		257.5	120	180			
	22		270	150	170			
252.00	12	90	58	88	150	25	15	28
	17		85	92.5	70			
	22		50	130	60			
287.00	12	370	50	110	160	13	15	10
	17		130	140	60			
	22		120	170	55			
315.00	12	240	21	130	155	16	10	14
	17		92	180	65			
	22		160	160	60			
355.00	12	23	14	79	68	23	16	0
	17		39	120	0			
	22		79	160	39			
383.00	12	88	7	92	52	9	0	0
	17		47	103.5	24			
	22		47	110	20			
411.00	12	90	30	170	80	20	7	33
	17		76.5	240	90			
	22		83	180	43			
438.00	12	17	0	72	26	6	27	6
	17		9	100	9			
	22		17	72	9			

[a] Sampling times vary with 1-2 days

[b] INJ, MW4, MW5 and MW6 were all sampled at 15 ft bgs.

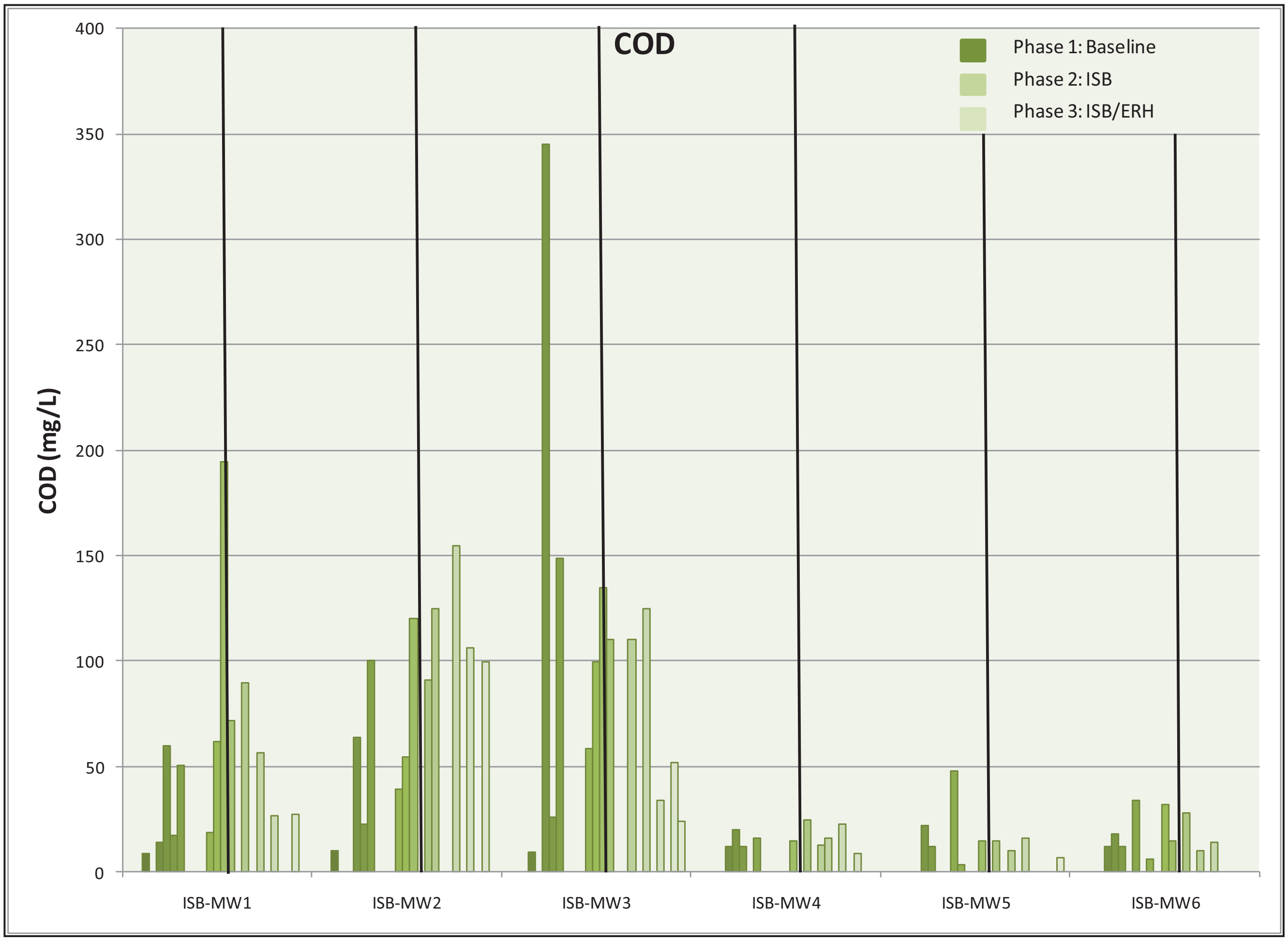


Figure 5-20. Concentrations of carbon during Phase 1, 2 and 3 in the ISB wells. Vertical black lines indicate transition from Phase 2 to Phase 3.

In addition, relatively high concentrations were observed within the ISB test cell (ISB-MW1 through ISB-MW3) approximately 6-20 ft downgradient of ISB-INJ within concentration ranging from approximately 49-370 mg/L. COD concentrations in downgradient MWs ISB-MW4 through –MW6 were slightly greater than baseline. COD concentrations were generally depleted in all of the monitored wells one month post-EOS®11 injection with concentrations ranging from 12-35 mg/L.

Following the EOS®22 injection, measured COD concentrations were sustained between 900-1000 mg/L one and two months post-injection within the ISB-INJ. Elevated levels of COD were also observed 1 month post –EOS®22 injection within the test cell with concentrations ranging from 41-260 mg/L). Two months post-EOS®22, however, concentrations in all monitored wells, except ISB-INJ, were generally depleted with concentrations ranging from 0-68 mg/L). The inability to sustain concentrations of COD for longer than approximately 1 month post-EOS® injections led to the decision to switch the amendment to bicarbonate buffered whey. This was largely due to the necessity to conduct much more frequent injections with EOS® than is cost-effective. For high-frequency injections, bicarbonate-buffered whey is much more cost effective compared to EOS®.

Following Phase 2 injection with whey, COD concentrations were maintained at approximately 42-270 mg/L within the ISB test cell (MW1 through MW-3) one month post-whey 1 and whey 2 injections. Concentrations at downgradient locations ISB-MW4 through-MW6 remained low (0-32 mg/L).

During Phase 3, whey/bicarbonate injections continued and concentrations were initially slightly lower overall (**Table 5-19**) with values varying from 50-170 mg/L during the first 3 months of operations and continuing to decline to with values ranging from 0-160 the last 3 months of heating within the heated zone. Similarly, concentration declined slightly in the injection well. COD concentrations at downgradient locations ISB-MW4 through-MW6 remained low (0-33 mg/L).

Geochemical Response

Chlorinated hydrocarbons serve as electron acceptors in microbially-mediated redox reactions during reductive dechlorination. Therefore, they have to compete with naturally occurring electron acceptors in groundwater. During bioremediation, injection of nutrients in sufficient quantities drives redox conditions from aerobic → nitrate reducing → iron reducing → sulfate reducing → methanogenic. For reductive dehalogenation, dechlorination of PCE and TCE to cis-1,2-DCE generally occurs under iron-reducing to sulfate-reducing conditions. Complete dechlorination to ethene typically occurs under sulfate-reducing to methanogenic conditions. Thus, understanding redox conditions provides key insight into the potential for reductive dechlorination to occur at a site. The concentrations of various electron acceptors are discussed below to assess the accurate redox conditions within the ISB test cell. **Figure 5-21** illustrates the typical response in redox conditions during progression of the ISB demonstration.

Dissolved Oxygen. DO concentration of less than 0.5 mg/L is considered optimal for dechlorination (data presented in **Appendix A**). During the baseline sampling event the DO concentrations were observed between 1.8 mg/L to 3 mg/L at all the wells except ISB-MW3 (0.5 mg/L). Immediately following donor injection the DO concentrations decreased and were observed below 0.5 mg/L indicating that the donor injection has successfully created anoxic conditions within and downgradient of the ISB test cell.

Nitrate. Nitrate concentration of less than 1 mg/L is desirable for efficient dechlorination (data presented in BA). During the baseline sampling event the nitrate concentrations were observed near 2 mg/L at all the MWs. Immediately following donor injection the nitrate concentrations decreased to non-detect, which has been sustained throughout Phase 2 and 3 operations. These results indicate that within and downgradient of the ISB test cell, nitrate reduction was occurring following the donor injections.

Ferrous Iron. Ferrous iron is the product of ferric iron reduction. Ferrous iron concentration of greater than 1 mg/L is considered optimal for dechlorination. **Figure 5-21** illustrates typical dissolved (ferrous) iron concentrations for the ISB test cell. During the baseline sampling event near zero concentrations of ferrous iron were observed at all the wells except well ISB-MW2 (0.4 mg/L). Increase in ferrous iron concentrations have been observed at all the wells following Phase 2 nutrient injections with concentrations ranging from 2 mg/L to 4 mg/L during August 2009 sampling event. During Phase 3, elevated dissolved iron concentrations were observed within the test cell with concentrations generally above 3 mg/L for all sampling events. The results indicate that iron reducing conditions were developed within and downgradient of the ISB test cell during Phases 2 and 3.

Sulfate. Optimal dechlorination rates are supported by sulfate concentration of less than 1 mg/L. **Figure 5-21** illustrates typical sulfate concentrations for the ISB test cell. The sulfate

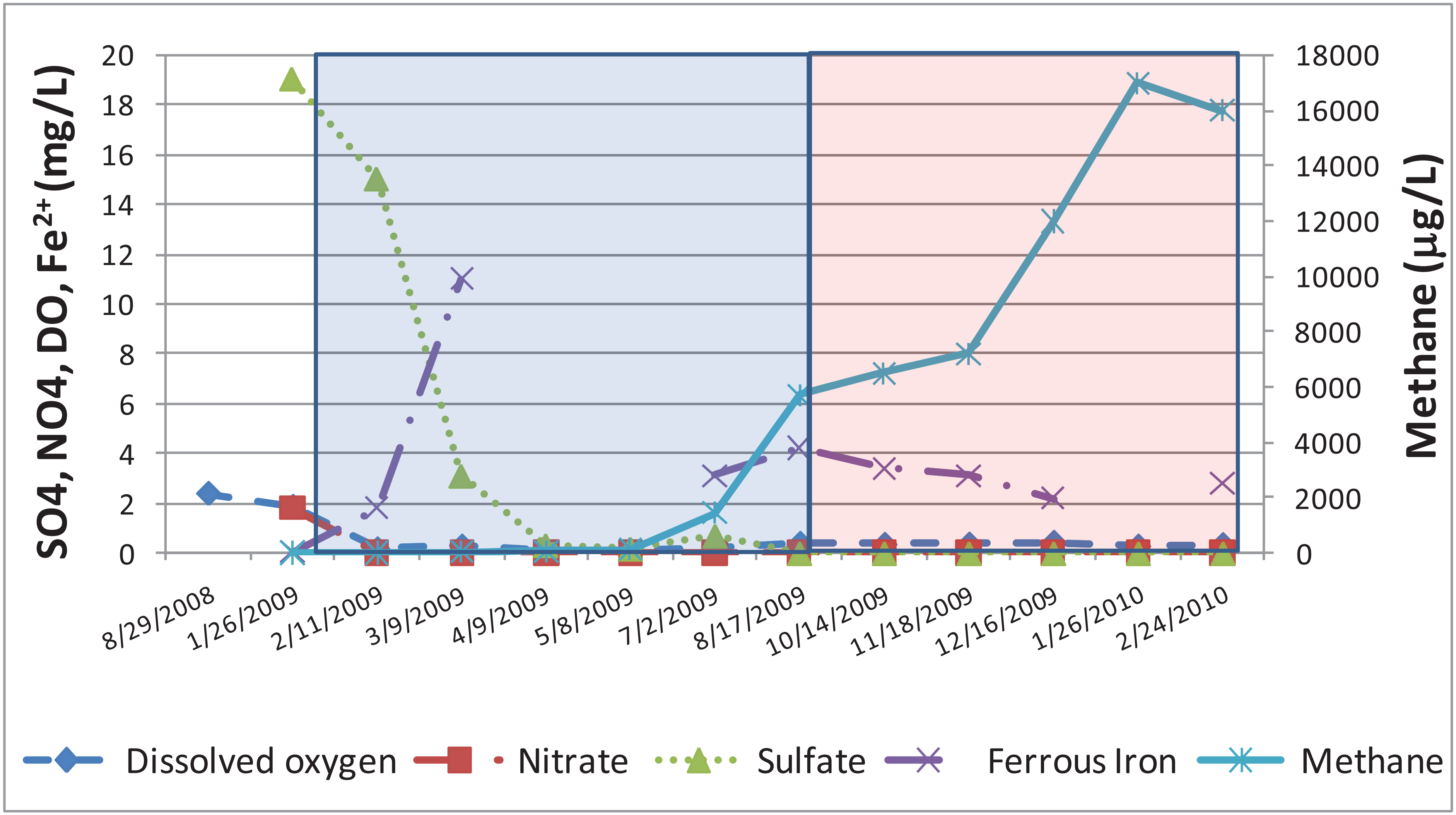


Figure 5-21. Typical progression of redox parameters during Phase 2 and 3.

concentrations ranged from 14 mg/L to 22 mg/L during the baseline sampling event. Sulfate concentration started decreasing immediately following donor injection at all the MWs. Concentrations of sulfate were substantively depleted (concentrations <0.5 mg/L) from April through July 2009 and were depleted (nondetect) at ISB-INJ and within the test cell (ISB-MW1 through –MW3) at the end of Phase 2. At downgradient wells ISB-MW4, ISB-MW5, and ISB-MW6 sulfate concentration have remained low (concentrations near 3 mg/L). Sulfate concentrations within the ISB test cell remained less than 1 mg/L through Phase 3. Depletion of sulfate at all the MWs indicated establishment of sulfate reducing conditions within and downgradient of the ISB test cell during Phases 2 and 3.

Methane. Methane provides an indication of conditions most conducive to complete reductive dechlorination of TCE to ethene. Methane concentration above 500 µg/L is considered optimal for dechlorination. **Figure 5-21** illustrates typical methane concentrations over time for the ISB test cell. Methane was generally either very low (<2 µg/L) or non-detect during baseline sampling. Methane concentrations were observed to increase following nutrient injection, with substantial concentration (>250 µg/L) observed at all the MWs and ranged from 4100 µg/L to 6300 µg/L within the ISB test cell (ISB-INJ and ISB-MW1 through ISB-MW3) and ranged from 340 µg/L to 720 µg/L downgradient of the test area (ISB-MW4 through ISB-MW6) during August 2009 sampling event. During Phase 3, methane concentration continued to dramatically increase with concentrations greater than 10,000 ug/L observed at ISB-INJ and ISB-MW1 through ISB-MW3. These data indicate that strongly methanogenic conditions were developed during Phase 2 and 3.

pH. The pH of the groundwater plays an important role in the activity of dechlorinating bacteria, DHC. Activity of DHC decreases significantly in aquifers with pH less than 5.5, and they are completely inactive below pH of 5.0. In addition, the relatively low buffering capacity of the Fort Lewis aquifer necessitated buffering to maintain pH at sufficient levels during acid production as a result of anaerobic fermentation. Therefore pH was adjusted using buffers (activator and AquaBupH during EOS® injections and sodium bicarbonate during whey injections). pH during all Phase 2 and 3 sampling events was maintained above 6.0 for all monitoring locations within and downgradient of the ISB test cell. The pH at the ISB test cell MWs ranged from 6.2-7.9 during EOS® injection and 5.73-6.8 during Phase 2 and 3 whey injections.

Contaminant Degradation

Carbon and redox parameters are only indicators of conditions favorable for reductive dechlorination at the site. The concentrations of parent compounds (TCE) and reductive daughter products (DCE, VC, ethene, ethane and chloride) were used as direct evidence of treatment of contaminants of concern at the site. Molar concentrations are used in the figures so that an evaluation of mass balance can be made (1 mole of DCE is produced from reductive dechlorination of 1 mole of TCE, 1 mole of VC is produced from 1 mole of DCE, and so on).

The total chloroethenes were primarily comprised of TCE and DCE during the baseline sampling event. The baseline concentrations of TCE ranged from 1,800 µg/L to 6,300 µg/L and 1,2-DCE ranged from 94 µg/L to 530 µg/L at wells ISB-MW1 through ISB-MW3. Some decrease in TCE and increase in DCE concentrations were observed at these wells immediately following Phase 2 EOS® and whey donor injections. The total chloroethene concentrations (primarily TCE and DCE) increased considerably at these wells as observed during the April 2009 sampling event, one month following donor injection and ranged from 5,600 µg/L to 16,000 µg/L (TCE) and 2,550 µg/L to 16,000 µg/L (1,2-DCE). The TCE concentrations continued to decrease and the concentrations range from 73 µg/L to 750 µg/L during the August 2009 sampling event (day 193). The 1,2-DCE concentrations range from 1,100 µg/L to 6,400 µg/L as of August 2009 (day 193). VC was periodically observed during Phase 2, although concentrations were generally very low (2 µg/L to 54 µg/L when observed). In addition, low levels of ethene were also observed with maximum concentration at 1.2 ug/L.

During Phase 3, the concentration of DCE, VC and ethene dramatically increased, as did chloride. In, October 2009 (day 251), one month after heating began, DCE ranged from 110 to 11,000 µg/L, VC 9 to 780 µg/L and ethene non-detect to 530 µg/L, at wells ISB-MW1 through -MW3. These trends continued in November 2009 (day 286) with DCE concentration 39 to 22,000 µg/L, VC 35 to 4,100 µg/L and ethene non-detect to 300 µg/L. However, along with significant increases in daughter products, large increases in TCE were also observed with concentrations ranging from 4.6 to 13,000 µg/L in October (day 251) and 0.265 to 26,000 µg/L in November, 2009 (day 286). The maximum concentrations observed corresponded to the time when the maximum temperatures were observed in the test cell, December, 2009 (day 314). TCE concentrations ranged from 360 to 42,000 µg/L in ISB-MW1 and ISB-MW2 sampling locations, DCE ranged from 1,300 to 33,000 µg/L, VC ranged from 44 to 1,000 µg/L and ethene ranged from non-detect to180 µg/L.

The concentrations at the injection well ISB-INJ and the downgradient wells ISB-MW4 through ISB-MW6 were one to three orders of magnitude lower compared to the MWs ISB-MW1 through ISB-MW3. During Phase 2, the TCE concentrations ranged from 32 µg/L to 38 µg/L and 1,2-DCE concentrations ranged from 13 µg/L to 29 µg/L. At well ISB-INJ the TCE concentrations were observed to decrease with corresponding increase in 1,2-DCE concentrations with little to no VC or ethene production. The downgradient wells ISB-MW4 through ISB-MW6 showed decrease in TCE concentration but without corresponding increase in the daughter products.

During Phase 3, however, a significant shift in products was observed at the downgradient wells ISB-MW4 through –MW6. Initially, a large increase in DCE was observed at ISB-MW4 (2,300 µg/L) on October, 2009 (day 251), but were much lower by the November, 2009 (day 286) sampling event (480 µg/L). By March and April, a combination of TCE (7.5 µg/L), DCE (180 µg/L), VC (43 µg/L) and ethene (10 µg/L) were observed at ISB-MW4. This well generally had the highest concentrations of the downgradient locations due to its location relative to ISB-MW2.

Figure 5-22 presents the percentage of total mass of VOCs (sum of TCE, cis-1,2-DCE, VC and ethene) and daughter products (DCE, VC, and ethene) as TCE for small volumes around each MWs ISB-MW1, ISB-MW2, and ISB-MW3 during Phases 2 and 3. For the analysis, the figure

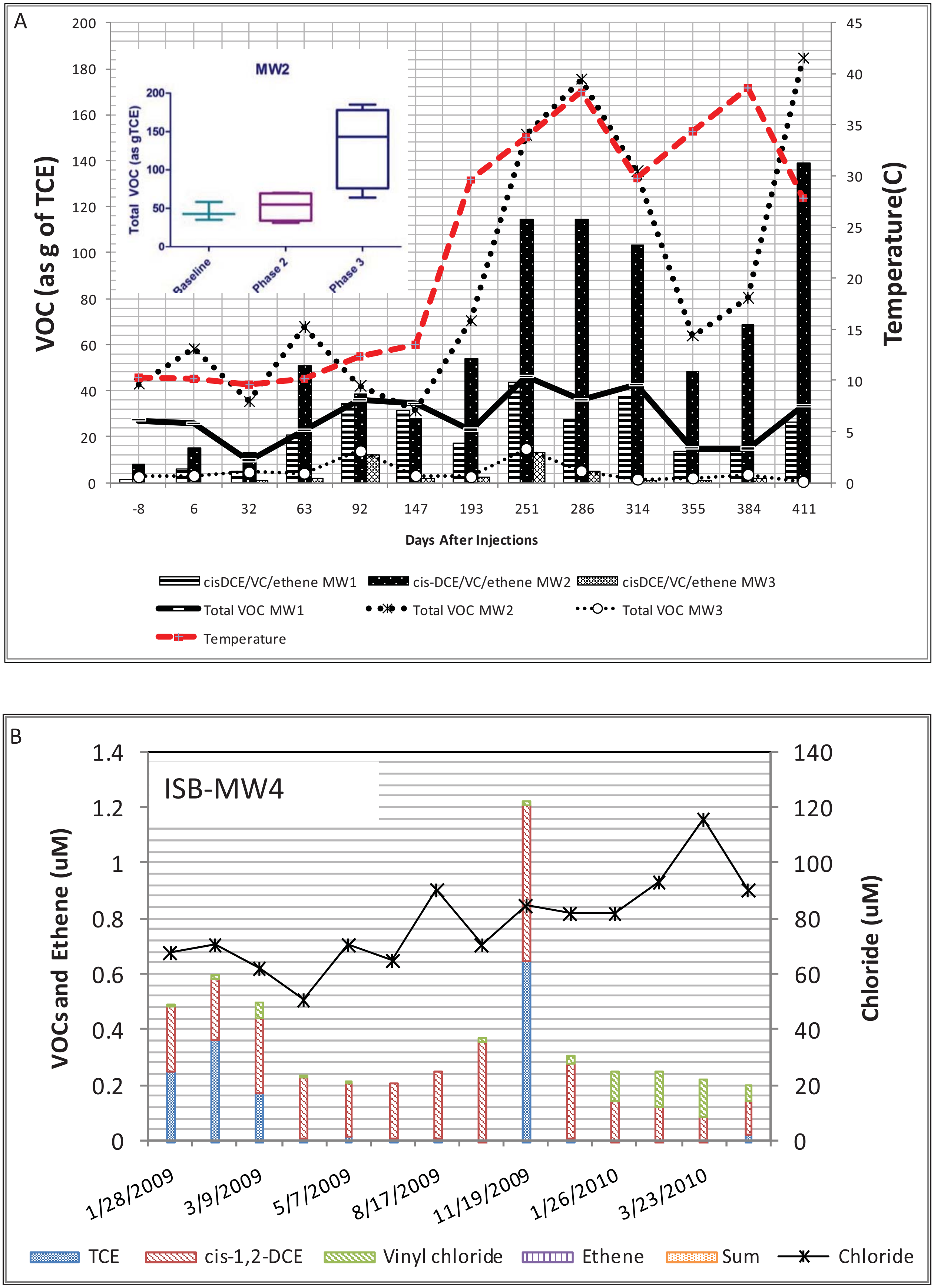


Figure 5-22. Phase 2 and 3 total molar VOC mass in ISB test cell (A) and downgradient concentration at ISB-MW4 (B).

assumes the total contaminant mass within a volume approximately 1 meter from the sampling well (r= 1 m, depth= 25 ft). This figure represents discrete points in time and illustrates the increase in total mass in groundwater observed after heating began, especially at ISB-MW2, which was the hot spot well. Total concentrations increased by a factor of 3-4 after heating began compared to concentrations observed just prior to heating. The inset of **Figure 5-22** illustrates the range, mean (at depths 12, 17 and 22 ft bgs), and one standard deviation from the mean of total VOCs at ISB-MW2.

Figure 5-23 illustrates the average chlorine number calculated for each well (for ISB-MW1 through –MW3, averaged concentrations are for depth intervals 12, 17, and 22 ft bgs). The chlorine number is a useful approach for evaluating the relative TCE and reductive daughter products at a given location at a given time.

The chlorine number is calculated by:

$$N_{cl} = \frac{\sum w_i C_i}{\sum C_i}$$

Where wi is the number of chlorines on the compound (i.e. TCE is 3, DCE is 2, VC is 1) and Ci is the molar concentration of the compound. In a system where TCE predominates the chlorine number will be close to 3, in a system dominated by DCE, the chlorine number is 2 and in a system dominated by VC the chlorine number is 1. During baseline sampling, TCE comprised an average of 89% with a range between 75 and 97% of the total VOC molar mass for the test cell wells (ISB-MW1 through ISB-MW3) with DCE comprising the remaining mass, as illustrated by average chlorine numbers between 2.87 and 2.96. By the August 2009 sampling, TCE comprised an average of 9% of the total VOC molar mass and cis-1,2-DCE comprised an average of 89% as and the chlorine number ranged from 2.05-2.12 for ISB-MW1 through –MW3. Therefore, efficient conversion of TCE to DCE within the high concentration source area was achieved within the test cell.

During Phase 3, the total molar mass went up, as did the concentrations of TCE and DCE, as contaminant mass was driven into groundwater. However, the chlorine numbers only increased slightly to 2.09-2.13 indicating that rapid TCE dechlorination was occurring. The chlorine number subsequently declined as VC became more predominant (the analysis does not take into account ethene) with numbers ranging from 1.50-2.10. More striking, however, was the effect of Phase 3 on downgradient wells ISB-MW4 through –MW6. Similar to the treatment area wells, the chlorine number dramatically declined during Phase 2 from 2.47-2.52 to 1.97-2.01. During Phase 3, an initial increase in the chlorine number was observed to 2.0-2.7, but rapidly declined and by the end of the heating phase (March 2010), the chlorine number was 1.39-1.48. This indicates that additional dechlorination is occurring once contaminants are discharged from the treatment cell, with chlorine numbers close to 2 reduced to less than 1.5 approximately 15 ft downgradient of the treatment area.

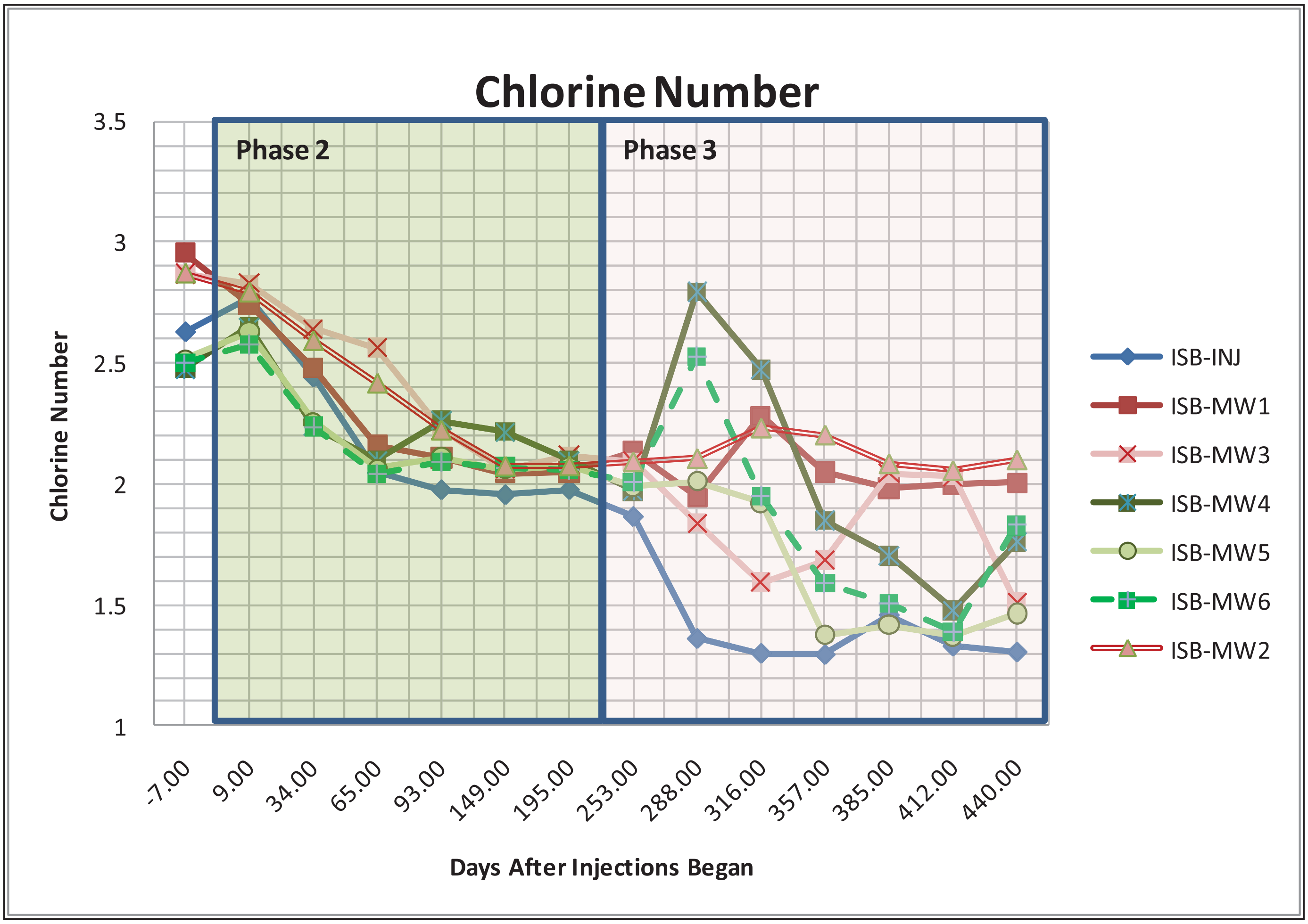


Figure 5-23. Chlorine numbers calculated for wells ISB-INJ, ISBMW-1 through-MW3 (average of depths 12, 17, and 22 ft bgs) and downgradient wells ISB-MW4 through –MW6 during the demonstration.

Mass Flux And Discharge Modeling

Groundwater hydraulic and contaminant data were input into the Mining Visualization System (MVS) Version 9.52 software to evaluate mass discharge from the test cell over time during Phase 2, after reducing conditions had been established, and Phase 3. The model utilizes a constant rectilinear grid at a 121x121x35 (X, Y, Z) resolution. Effective porosity was set at 18% and hydraulic conductivity was set to 434 ft/day from 6.5-15 ft bgs, from 464 ft/d from 15-20, and 564 ft/d from 20-25 ft bgs in X, Y direction and half this value in the Z direction (i.e. Kz= ½ [Kx, Ky]).

The seepage velocity module was used to compute a vector groundwater flow field. The module outputs vector data representing X, Y, and Z components. The seepage velocities were calculated from interpolated water levels, hydraulic conductivity and effective porosity in to arrive at a vector seepage velocity (Vx, Vy, Vz) at each node, by taking the gradient of (kriged) head (without any z-exaggeration) and multiplying each component of head gradient by the component of conductivity at that node (based on its material) (Kx, Ky, Kz) and dividing by the Effective Porosity (Ne) for that material.

$$Vx = dH/dx * Kx / Ne \qquad \textbf{[Equation 1]}$$

$$Vy = dH/dy * Ky / Ne \qquad \textbf{[Equation 2]}$$

$$Vz = dH/dz * Kz / Ne \qquad \textbf{[Equation 3]}$$

Head data (dH/dx, dy or dz) in the form of water levels were first kriged in three-dimensional space based on water levels as measured in the well screens corresponding to each sampling event. This data was then processed to create streamlines only for a visual representation.

A formula to evaluate mass flux in three dimensions was input into the software that used the calculated seepage velocity data and kriged analytic concentrations for each date range to calculate the moles/sq ft per-day. The results were a vector-based mass flux calculation at a nodal level throughout the model. At each node, mass flux was calculated using the following formula:

$$Mf = Vs*Ct*n_e$$

The mass flux nodal calculation (in moles per square foot [sqft] per day [d]) were then integrated over a cross section between the observation wells ISB-MW1 and ISB-2 (approximately 16 ft wide and 18.5 ft deep), which were nearly transect to groundwater flow direction (**Figure 5-24**), this transect was used to evaluate discharge of contaminants over time during Phases 2 and 3.

Figure 5-24 represents the total molar VOC and degradation daughter product mass flux and discharge during the last three sampling events of Phases 2 and all of Phase 3. These data were used to evaluate the relative change in mass flux and discharge, used to infer treatment rates, as a result of increasing temperatures. The total VOC flux in millimole (mmol) per sqft per d is

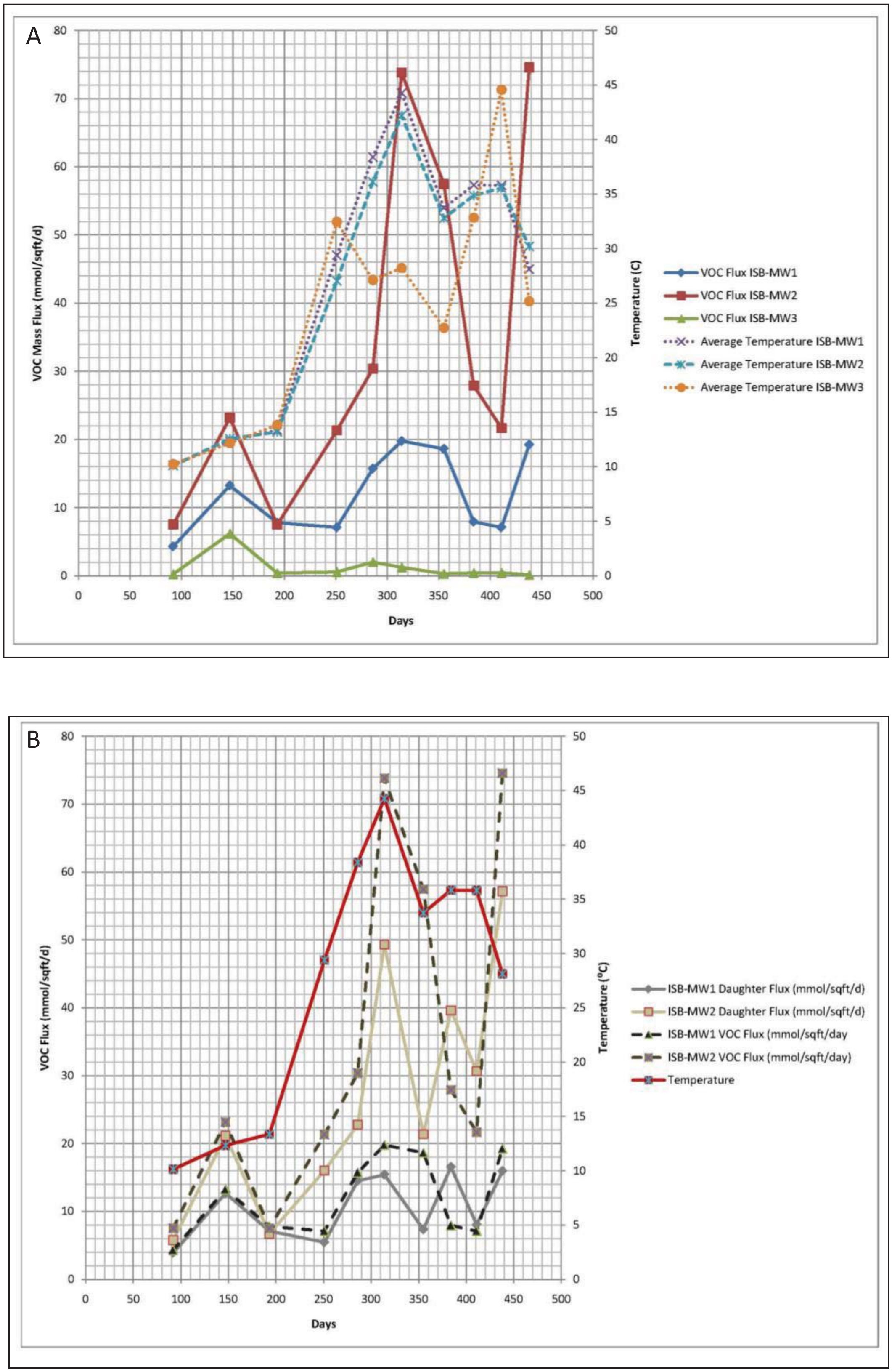


Figure 5-24. Phase 2 and 3 total VOC mass flux (A) , reductive daughter product mass flux (B) and VOC, daughter product and chloride discharge (C) as a function of temperature across the ISB-MW1 and ISB-MW2 transect.

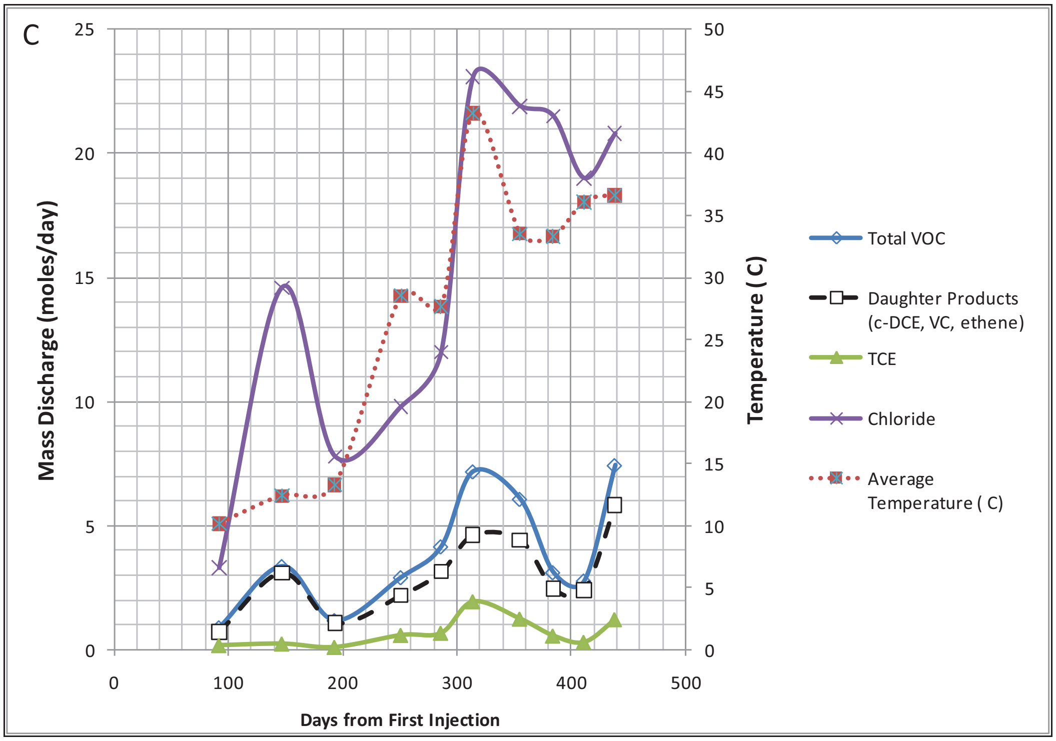


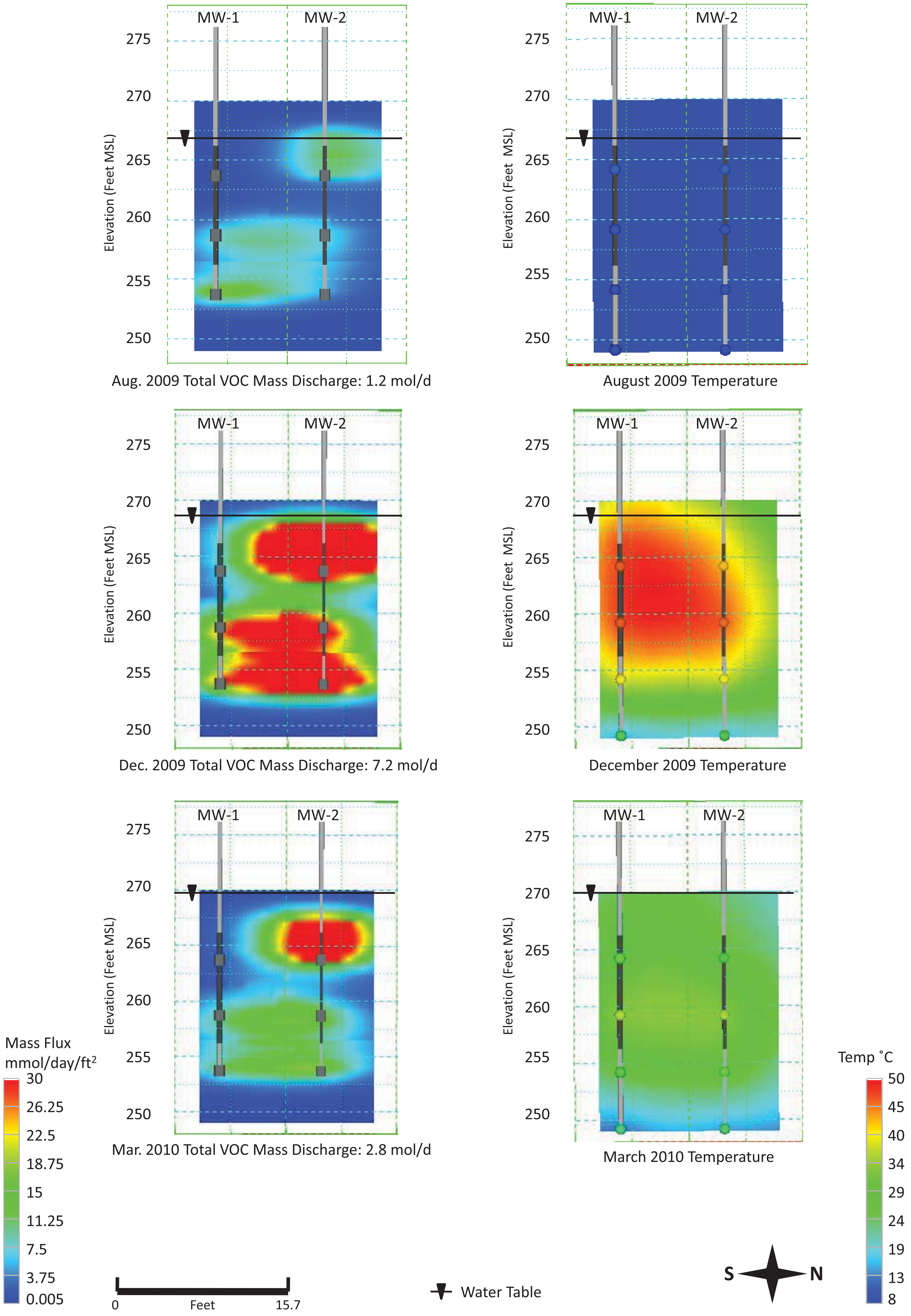
Figure 5-24 CONT'D. Phase 2 and 3 total VOC mass flux (A) , reductive daughter product mass flux (B) and VOC, daughter product and chloride discharge (C) as a function of temperature across the ISB-MW1 and ISB-MW2 transect.

illustrated in **Figure 5-24A**. The mass flux and mass discharge observed at point ISB-MW3 generally declined during the field demonstration. The VOC concentrations at this location were the lowest of the source wells, and it was generally on the upgradient periphery of the source area. In addition, due to preferential heating at this location, the electrode nearest ISB-MW3 was disconnected shortly after the heating system was started, and temperatures were generally 10-15°C lower, on average, compared to ISB-MW2 and ISB-MW1 (**Figure 5-24A**). Two MWs located downgradient within the source area ISB-MW2 and ISB-MW1 had much higher overall VOC concentrations, especially ISB-MW2. Overall, mass flux increased with temperature, especially at temperatures greater than 35°C (**Figure 5-24A** and **B**). The maximum temperature achieved in the test cell was an average of 43°C in December, approximately 314 days after initiation of the demonstration, 90 days after initiation of heating. The VOC mass flux at these locations generally increased during heating with the average increase in mass flux from approximately 8 mmol/sqft/d for both ISB-MW1 and –MW2 during the August (day 193) just before initiating heating to the maximum flux of approximately 74 mmol/sqft/d at ISB-MW2 and 20 mmol/sqft/d at ISB-MW1 in December (day 314) (**Figure 5-24A**).

The proportion of reductive daughter product mass flux observed is used to determine what percentage of TCE is biologically degraded along the source area ISB-MW1 and -2 transect. **Figure 5-24B** illustrates the total VOC flux compared to flux of reductive daughter products. During the end of Phase 2, reductive daughter product flux accounted for 81-97% of the total flux, an average of 7.1 and 6.7 mmol/sqft/d at ISB-MW1 and –MW2, during the August (day 193) sampling event before initiating heating on. During the maximum mass flux observed December (day 314), the daughter product flux increased to approximately 15 and 49 mmol/sqft/d average for the three depths at ISB-MW1 and ISB-MW2. This accounted for 41-97% of the total mass flux. This suggests that the rate of reductive dechlorination also increased to reduce the increased mass of contaminants. The mass flux outputs for the nine sampling points within the test cell are presented in **Appendix D**

The mass flux values calculated using the MVS model were integrated across an area extending from the water table (at 267.5 feet mean sea level [ft msl]) to the bottom of the sample zone (249 ft msl) or approximately 18.5 ft, and extending 16 ft from ISB-MW2 to ISB-MW1. **Figure 5-25** illustrates the MVS-modeled temperature profile and VOC, daughter product and chloride mass flux and discharge across the ISB-MW2 and –MW2 transect at three timepoints, one at the end of Phase 2 August (day 193), one a maximum temperature during Phase 3 December (day 314) and one at the end of the heating March (day 411). This figure provides a visual representation of the MVS-modeled analysis and results.

The MVS-modeled discharge from the ISB-MW1 and –MW2 transect prior to heating (n=3 sampling events May, July, and August 09), was 1.8 mole/day corresponding to approximately 240 g of TCE/day (**Table 5-20**). After heating, the average mass discharge for all 7 post-heating events was 4.8 mole/day corresponding to 633 g/day of TCE, a factor of 2.6 increase in mass discharge. The maximum mass discharge observed during the sampling event corresponding to maximum temperature observed in the test cell (December, day 314) was 7.2 mol/d



Aug. 2009 Total VOC Mass Discharge: 1.2 mol/d

August 2009 Temperature

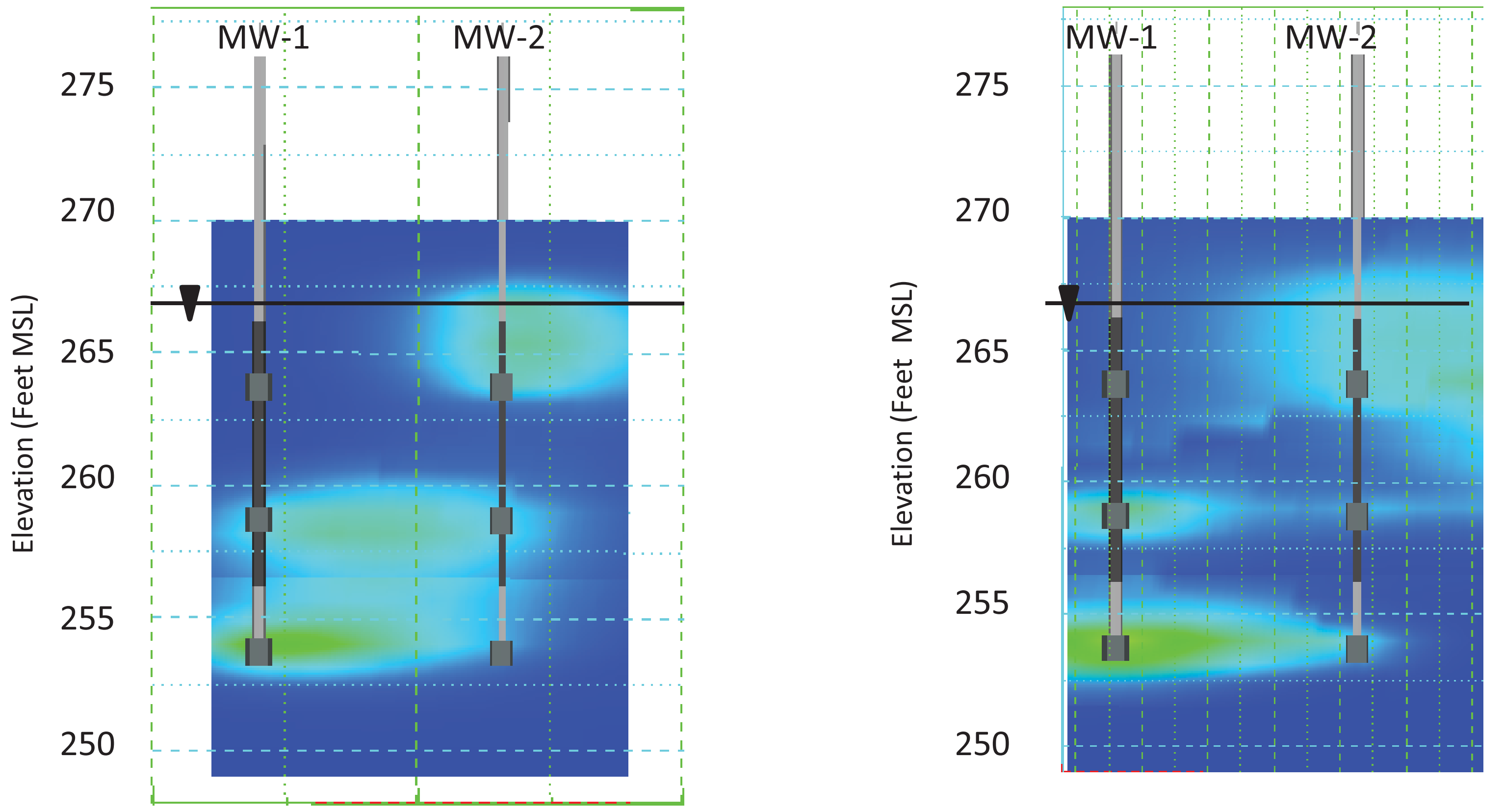
Dec. 2009 Total VOC Mass Discharge: 7.2 mol/d

December 2009 Temperature

Mar. 2010 Total VOC Mass Discharge: 2.8 mol/d

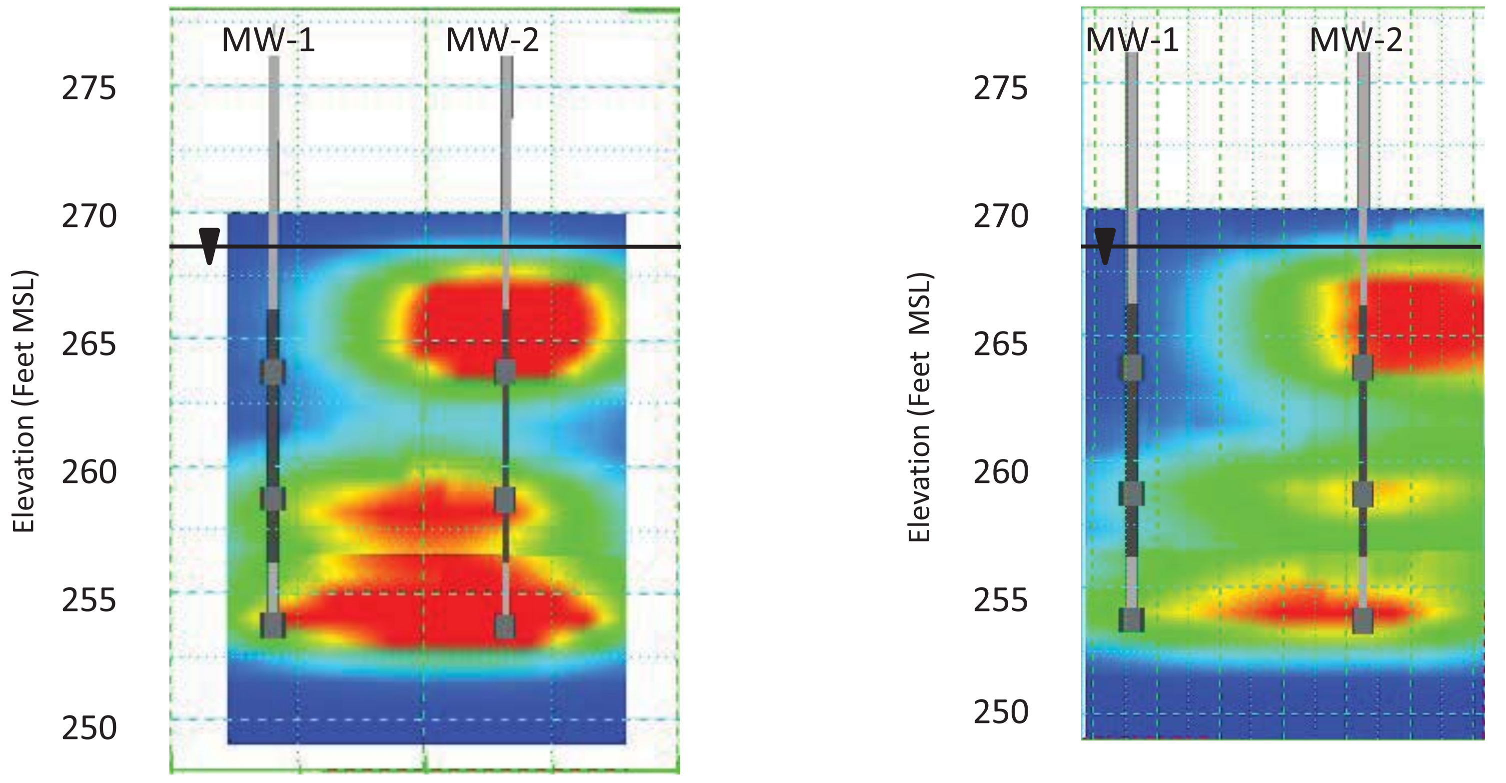
March 2010 Temperature

Figure 5-25. MVS-modelled mass flux and discharge versus temperature from the ISB test cell at three timepoints during Phase 2 and 3.



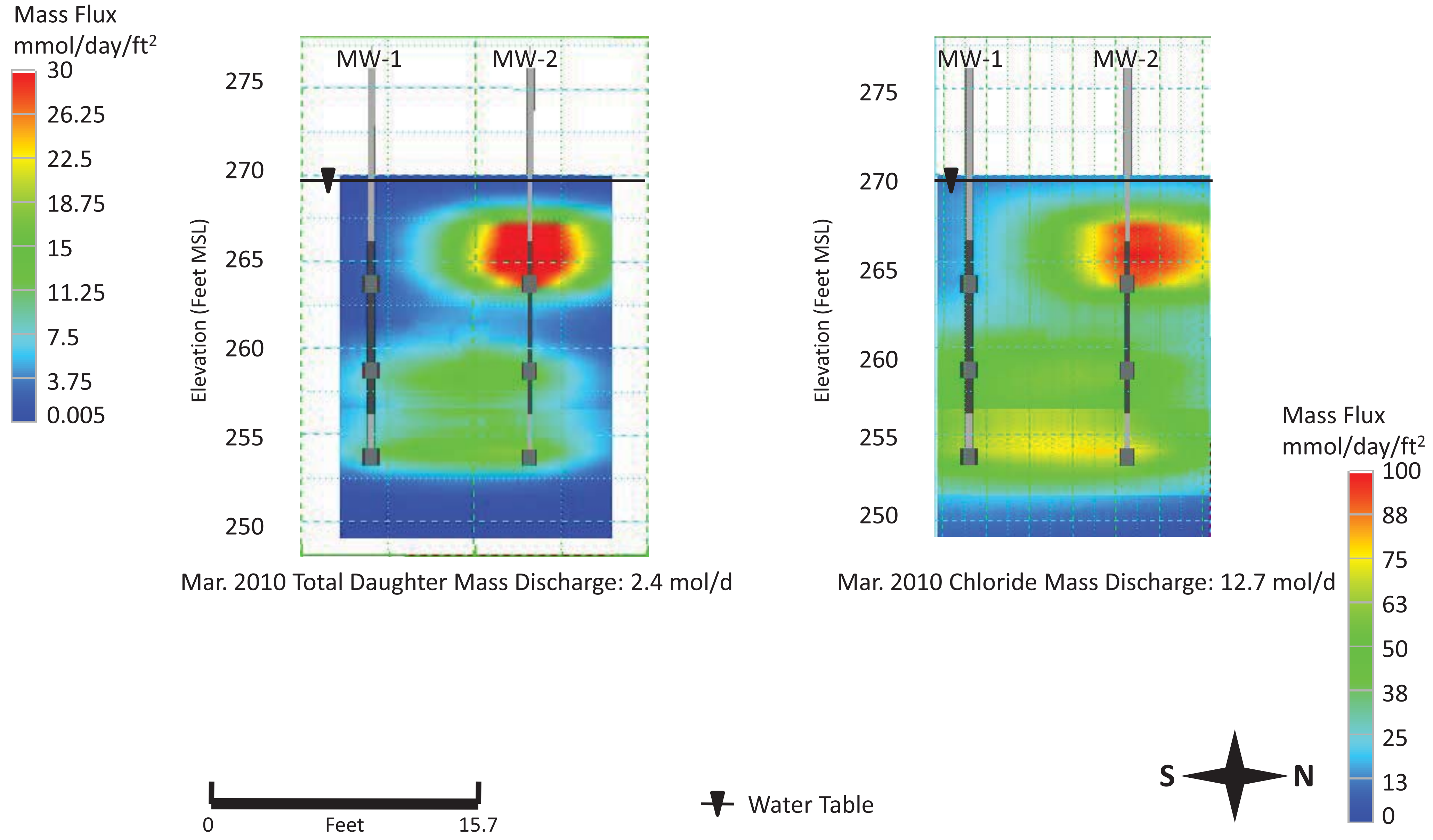
Aug. 2009 Total Daughter Mass Discharge: 1.1 mol/d

Aug. 2009 Chloride Mass Discharge: 3.3 mol/d



Dec. 2009 Total Daughter Mass Discharge: 4.6 mol/d

Dec. 2009 Chloride Mass Discharge: 11.6 mol/d



Mar. 2010 Total Daughter Mass Discharge: 2.4 mol/d

Mar. 2010 Chloride Mass Discharge: 12.7 mol/d

Figure 5-25 (Continued). MVS-modelled mass flux and discharge versus temperature from the ISB test cell at three timepoints during Phase 2 and 3.

Table 5-20. Summary of mass discharge estimates for Phase 2 and 3.

	Phase 2				Phase 3			
MD_{out}	Average mole/day (n=3) [a]			gTCE/day[b]	Average mole/day (n=7) [a]			gTCE/day[b]
Total VOC	1.8	+/-	1.3	240	4.8	+/-	2.0	633
Products (cis-DCE, VC, ethene)	1.6	+/-	1.3	214	3.6	+/-	1.4	471
Chloride	6.1	+/-	5.7	798	10.7	+/-	3.8	1403

Notes:

[a] Concentrations from all of the monitoring wells were kriged to determine a 3D contaminant plume. Mass discharge was evaluated through a transect 15.8 feet across through ISB-MW1 and -MW2 and 21 feet deep.

[b] g of TCE per day was evaluating by multiplying the molar concentration of Total VOCs or the sum of cis-DCE, VC and ethene by the molecular weight of TCE. TCE dechlorinated based on chloride data was evaluated by taking the chloride molar concentration and subtracting the background chloride (2.5 moles) and then multiplying by the molecular weight of TCE. It was assumed that 1 mole of chloride corresponded to 1 mole of TCE dechlorinated as cis-DCE was the predominant by-product.

corresponding to approximately 943 g/d of TCE, a factor of 3.9 increase in mass discharge. This enhanced mass transfer occurred in the test cell during heating and is primarily attributed to the heating effects (i.e. accelerated dissolution and kinetics). It is assumed that contaminant flux coming into the test cell is negligible since VOC concentrations at ISB-INJ upgradient of the test cell were generally 2-4 orders of magnitude lower than concentration observed at ISB-MW1, -MW2 or -MW-3. Therefore, it was assumed that all of the contaminants were derived from residual source material within the test cell itself.

In addition to total VOCs, mass discharge of daughter products from the test cell was evaluated to determine the biodegradation efficiency within the heated zone. Of the 240 g/day of TCE-equivalent VOC mass discharged from the test cell 214 g/day or 89% was observed as daughter products during Phase 2. This was primarily DCE (89-99% of the molar mass of daughter products DCE, VC and ethene during the August 09 event). During Phase 3, total molar daughter products increased to an average of 471 g/d TCE-equivalent treated, a factor increase of 2.2. Again, DCE was the primary degradation product (13-98%), although significant quantities of VC and ethene were also observed at many locations. The maximum discharge of daughter products occurred during the December (day 314) event, which increased to 607 g/d as TCE, or 64% of the total VOC discharge.

In addition to daughter products, mass discharge using chloride was also evaluated. If applicable, chloride is generally more conservative compared to a molar mass balance using organic degradation by products in groundwater because chloride is conserved in groundwater, while organic VOCs can be degraded (especially VC and ethene/ethane which are very transient within the Landfill 2 shallow aquifer once generated), can partition to the soil, and/or can volatilize to the vadose zone. Biodegradation and volatilization can result in underestimating organic VOC concentrations, and ultimately TCE reactions, when only groundwater data are considered. At Landfill 2, background chloride around the test cell was averaged 70.6

micromoles per liter (uM)(average of ISBINJ, ISB-MW4 through –MW6 during baseline, February and March 2009 samplings n=12). This was used as the background and subtracted from the concentrations observed during the active portion of Phase 2 and Phase 3. The adjusted chloride concentrations were input into the MVS model to evaluate TCE dechlorination. Based on an evaluation of chloride flux from the test cell, the average chloride flux during Phase 2 was 6.2 moles/day compared to 15.8 moles/day during heating. This corresponded to an average of 798 g/d of TCE dechlorinated to DCE during Phase 2 and 2078 g/d of TCE dechlorinated to DCE during Phase 3.

Microbial Community

Dehalococcoides. The dechlorinating bacteria, DHC, have been found to be very important for achieving complete dechlorination of PCE to ethene in groundwater. **Figure 5-26** presents the DNA data over time for the ISB test cell. Only wells ISB-MW1, ISB-MW2, ISB-MW3, and ISB-MW5 were sampled for DNA during the baseline sampling event. The DHC numbers were observed to be > 10^2 gene copies/L at wells ISB-MW1 through ISB-MW3 and > 10^3 gene copies/L at well ISB-MW5. Low detection of all three functional genes tceA, bvcA, and vcrA were also observed at some of the wells during the baseline sampling event. During Phase 2, concentrations increased by one to two orders of magnitude to approximately 10^5 cells/L. Large increases were also observed in functional gene *vcrA*. Following the onset of heating (days 280 and 385), an additional one to two order of magnitude increase in *DHC* was observed, along with reductase genes *vcrA*, *bvcA*, and *tceA*.

Methanogens/Sulfate Reducers/Iron Reducers.

Other anaerobic members of the microbial community were monitored using molecular tools, including methanogens, sulfate reducers and iron reducers. For methanogens 4 genes were targeted for analysis targeting orders *Methanomicrobiales (MMIC)*, *Methanosarcina (MSAR)*, *Methanobacteriales (MBAC)*, and *Methanococcales (MCOC)*. Of these, only the first three were amplified in samples collected during the demonstration (data presented in **Appendix A**. Initially, all methanogens were non-detect during the Phase 1, baseline sampling event. By Day 149 and 195 after amendment injections began, increases to 10^6 to 10^8 genes/L of groundwater were observed indicating significant growth during Phase 2. During Phase 3, total concentrations of MMIC and MSAR increased to approximately 10^7 to 10^9 genes/L of groundwater, indicating an additional one order of magnitude increase. MBAC concentrations, however, were similar or slightly lower during Phase 3 than observed during Phase 2.

For iron-reducing bacteria, average concentrations (ISB-MW1, -MW2 and -MW3) increased from approximately 10^4 to a maximum of 10^7 genes/L of groundwater by day 195. However, concentrations declined to an average of 10^6 by day 288 and to 10^5 genes/L of groundwater by the end of Phase 3 (day 386).

Molecular analysis of sulfate reducing bacteria, targeting the dsrA gene, was unsuccessful in amplifying this target.

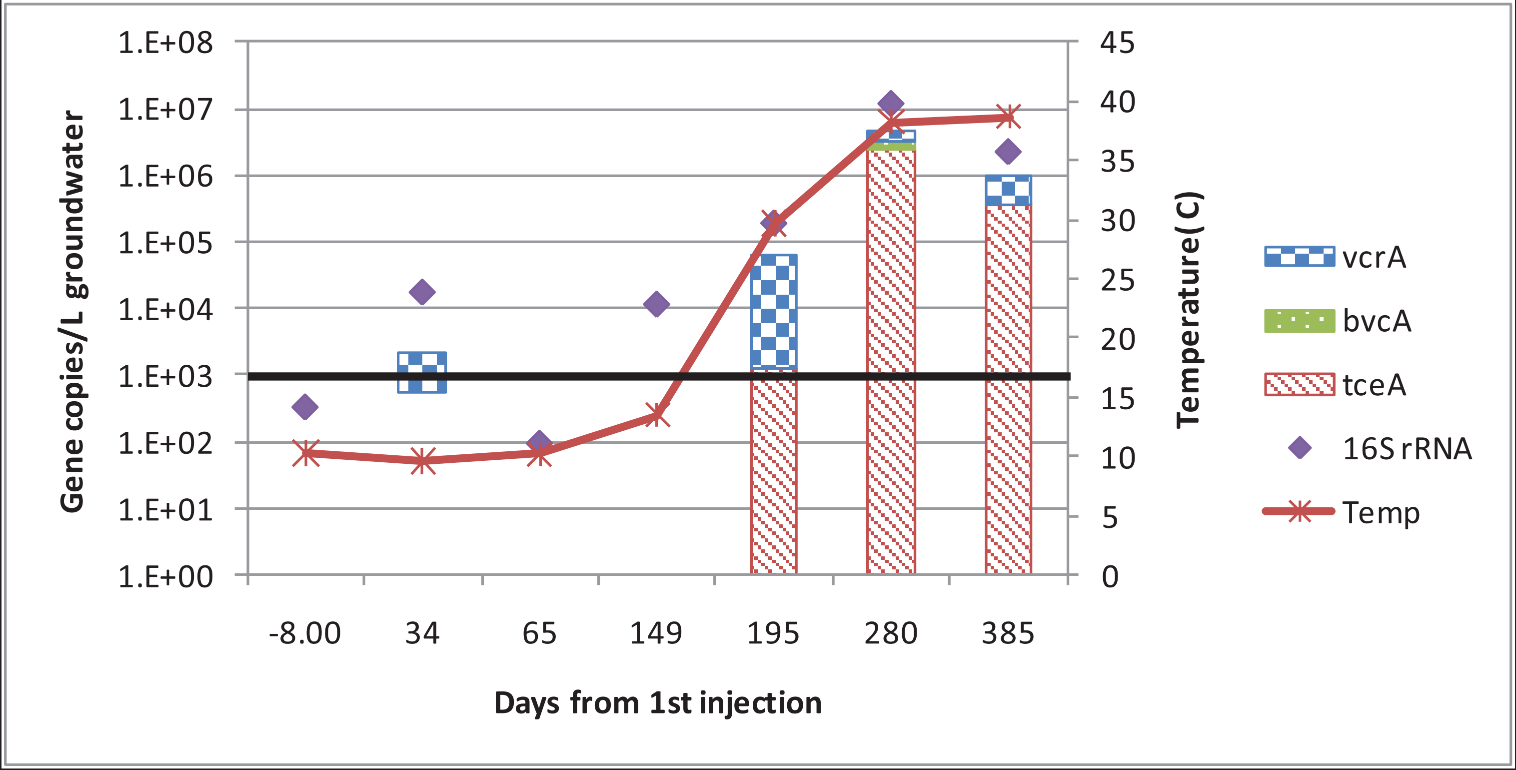


Figure 5-26. Results of molecular DNA Analysis for DHC during Phase 1, 2 and 3 of operations.

5.7.1.2 Soil Vapor Monitoring

As part of the mass balance approach, an evaluation of heating on increased volatilization of contaminants to the vadose zone and ultimately to the ground surface and potential overlying buildings was conducted. The increase in volatilization was modeled and compared to site-specific shallow soil gas measurements to quantify and confirm contaminant flux to the vadose zone caused by heating.

The model used is a modification of EPA's Johnson-Ettinger Model (EPA 2004) based on the analytical evaluation of diffusion from groundwater source to ground surface and included a one-dimensional analytical solution for discrete monitoring points. Assumptions used within the model included 1) no advective mechanism for vapor migration and 2) no lateral migration of contaminant by diffusion. Although simplistic, the model correlates well with measured soil gas concentrations at the ground surface and therefore is believed to offer a useful tool to gauge increased flux caused by ERH-enhanced bioremediation.

The model involved analytical derivation of two phenomena: the solubility of the contaminant at various temperatures (i.e., Henry's Law) and the diffusive flux of contamination from the groundwater source through the vadose zone (i.e., Fick's First Law of Diffusion). The following site-specific empirical data were used to build and calibrate the model: groundwater temperature, dissolved-phase contaminant concentrations, soil classification, soil porosity, soil temperature, and soil gas contaminant concentrations. The model evaluated flux of TCE, DCE, and VC from groundwater to the ground surface at three discrete points in the project area, MWs MW-1, MW-2, and MW-3, for five discrete sampling events in 2009, January (Baseline), July (Phase 2), August (Phase 2), November (Phase 3), and December (Phase 3).

First, the vapor source concentration, C_{source} was estimated at the groundwater interface using Henry's Law and measured contaminant concentration in groundwater. Henry's constant was determined for each contaminant and adjusted based on measured groundwater temperatures using EPA's OSWER method (EPA 2001). Second, a derivation of the effective diffusion coefficient, Deff, for the specific lithology of each MW was determined. All three wells were assumed to have two distinct soil horizons. The first was the capillary fringe above the groundwater interface, and the second was the unsaturated zone above the capillary fringe to the ground surface. The diffusion coefficient for each soil horizon was derived using the process detailed in **Section 2.3** of EPA 2004 assuming a sandy soil texture to account for both the silt and gravel component of the soil. The diffusivity in air and water of each contaminant was determined at measured soil temperatures, moisture content, and porosity using EPA's onsite assessment tools (EPA 2011). As noted earlier, **Section 2.3** of EPA 2004 provides the details for calculating diffusion coefficients for soil horizons using the Millington and Quirk model and additional soil characteristics provided by Hers (2002). Assumptions or simplifications included in the model were a consistent groundwater level, consistent capillary fringe, and static moisture content of the soil. Deff represents the harmonic mean of the diffusion coefficients for each soil horizon. Also, as noted earlier, the flux model assumed no contaminant concentration at the ground surface, thereby maximizing the modeled flux rate.

Third and final, the flux to ground surface was calculated using Fick's First Law of Diffusion, Csource and the derived Deff. The model was simplified to assume a full concentration gradient through the vadose zone, or in other words, there were no assumed pre-existing soil gas contaminant concentrations which would limit diffusion from the groundwater source. Therefore, the model should be conservative in evaluating risk by overestimating flux.

Lastly, the model was calibrated using flux extrapolated from measured soil gas concentrations at depths of 7 ft bgs and ground surface. The performed calibration was not an independent operation because the empirical flux was derived using the modeled Csource and Deff; however, the calibration is a relative check to verify that the modeled flux at 7 ft bgs and ground surface would yield soil gas concentrations similar to the measured soil gas concentrations.

Modeling Results

Table 5-21 presents an example model input for TCE and temperatures profiles for MW-1 during the January, August, and December sampling events, which coincide with the beginning of the project, mid-point at which basic bioremediation ended and ERH-enhanced bioremediation began, and a monitoring point four months into ERH-enhanced bioremediation, with the highest recorded average *in situ* temperatures.

Table 5-21. TCE and Temperature Profiles for ISB-MW1.

Month	TCE GW Conc (µg/L)	GW Temp (°C)	Temp of Capillary Fringe (°C)	Temp of Unsaturated Zone (°C)
January	14,000	10.1	10	7
August	27	11.6	13	17
December	1,600	45.2	41	18

Using these data as a starting point, the following steps are calculated for each sample event: TCE C_{source}, TCE Deff for the entire soil column, and finally the TCE flux from groundwater to ground surface. **Table 5-22** presents the modeled results. This procedure was repeated for all of the test cell MWs.

Table 5-22. Modeled Results for TCE for ISB-MW1.

Month	C_{source} (µg/L)	Deff (cm^2/sec)	Flux (µg/sec/cm^2)
January	2,870	1.05e^{-4}	9.87 e^{-7}
August	5.99	1.06 e^{-4}	2.08 e^{-9}
December	1,514	1.16 e^{-4}	5.78 e^{-7}

Figures 5-27, **-28**, and **-29** illustrate the change in flux for TCE, DCE, and VC, respectively, based on bioremediation treatment from during Phase 2 (July and August 2009) and Phase 3 (August to December 2009). The figures also include groundwater temperatures for the modeled flux rates. The figures illustrate how flux varies during the two stages of the study. For the

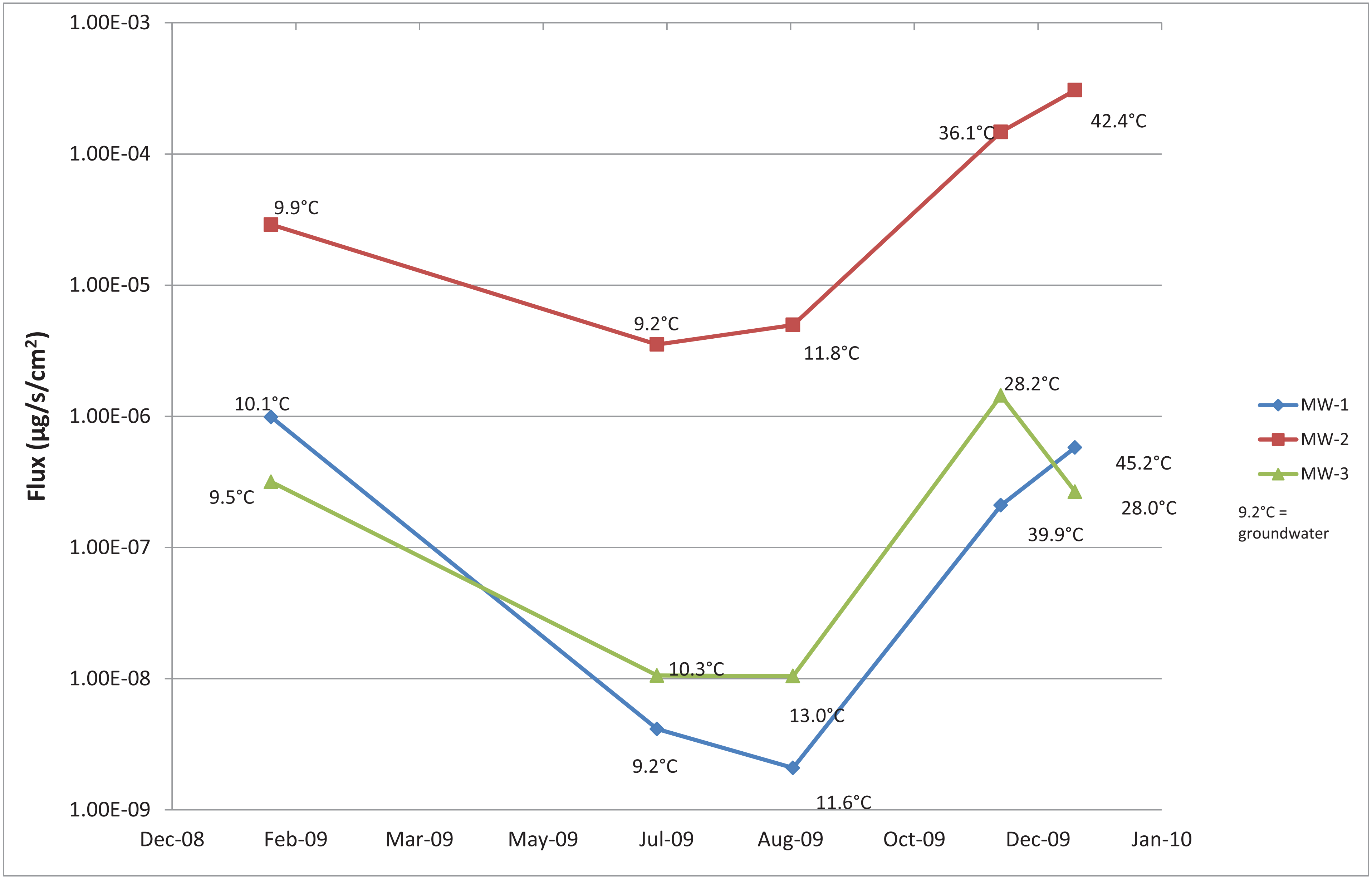


Figure 5-27. TCE vapor flux during Phase 1, 2, and 2 for the ISB test cell.

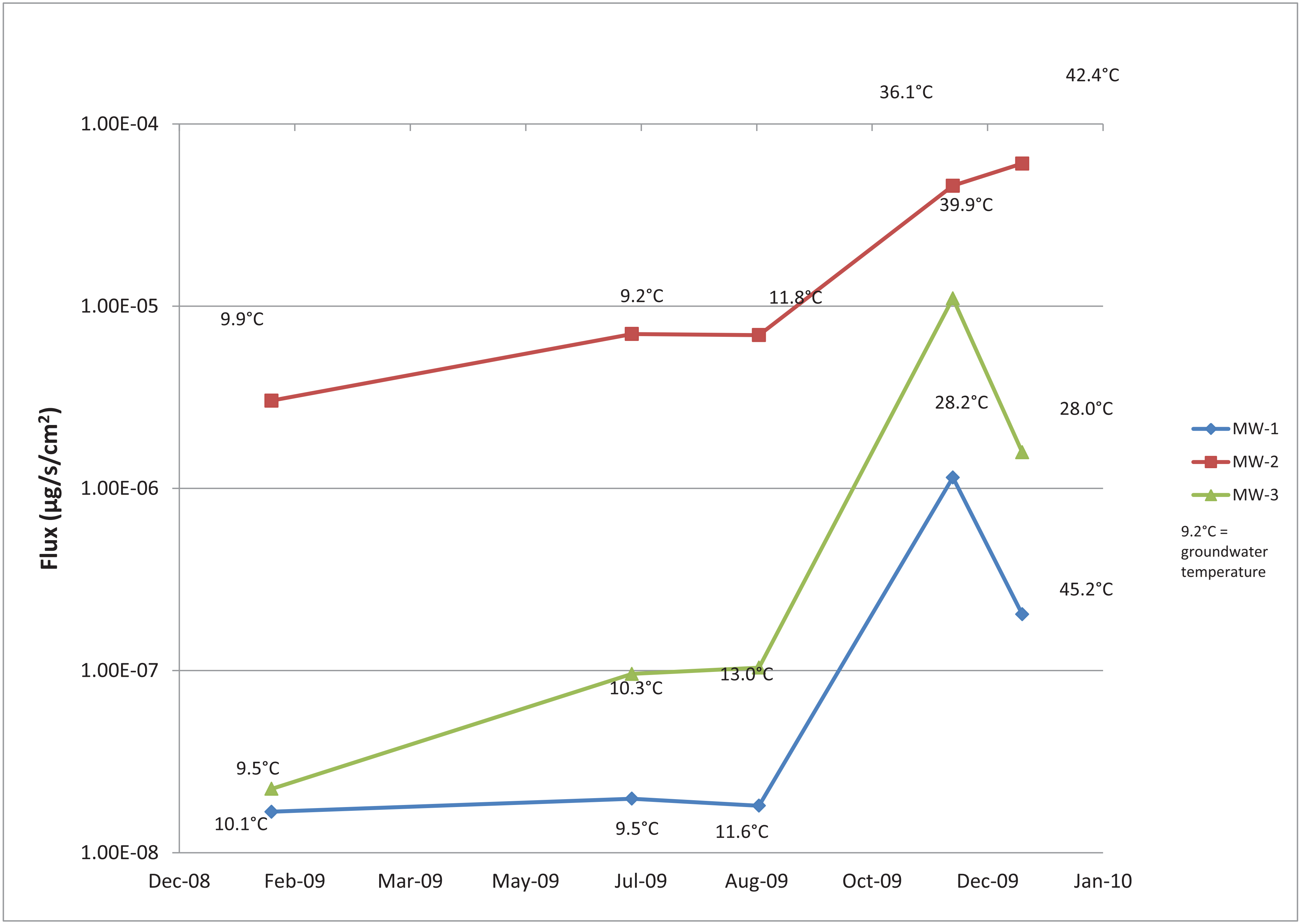


Figure 5-28. cis-DCE vapor flux during Phase 1, 2, and 2 for the ISB test cell.

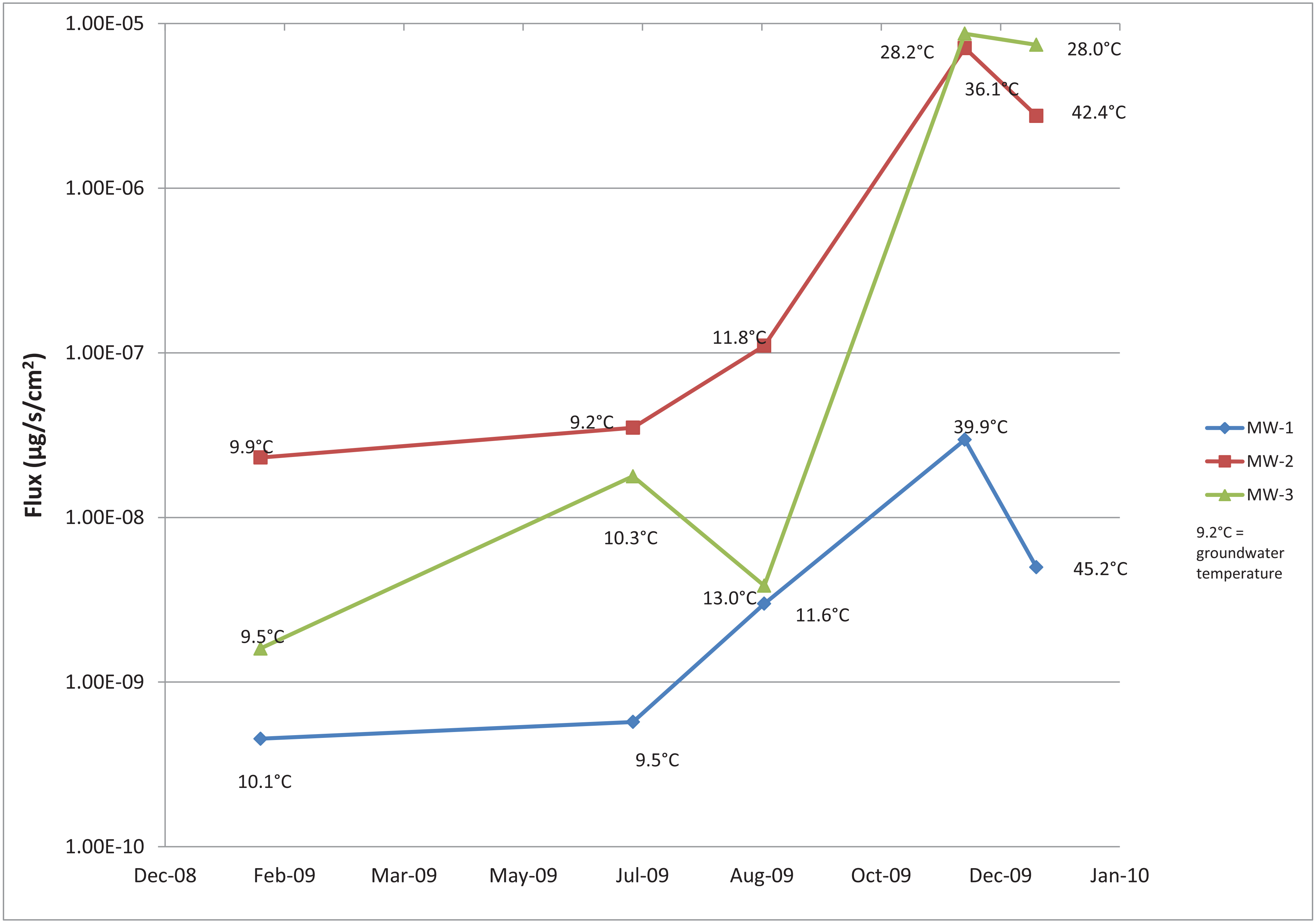


Figure 5-29. VC vapor flux during Phase 1, 2, and 2 for the ISB test cell.

January to August timeframe when basic bioremediation was conducted, TCE flux generally declined by two orders of magnitude as reductive dechlorination reduced the mass of TCE, and fluxes of DCE and VC increased by less than an order of magnitude as the mass of daughter compounds increased during reductive dechlorination. During Phase 3, the flux of TCE and DCE increased by approximately two orders of magnitude as increases in system temperature increased dissolution and volatilization of the contaminants. The flux of VC increased by as much as three orders of magnitude for similar reasons as TCE and DCE and also because VC was almost non-existent in the system prior to bioremediation, and therefore reductive dechlorination greatly increased the mass of VC more so than another daughter compound like DCE.

Increases in mass flux to the vadose zone were most dramatic after the onset of heating (November 2009), but generally declined over time. For instance, modeled fluxes for December were slightly less than the modeled fluxes for November even though the system temperatures generally were greater in December. These results indicate dechlorination rates may have increased to a level sufficient to reduce contaminant flux to the vadose zone.

A one-dimensional analytical model was developed to estimate changes in flux caused by diffusion from increased solubility and volatilization of contaminants during ERH-enhanced bioremediation. The model was mostly developed using site-specific data to estimate chemical conditions and physical characteristics at the site, but it also included assumptions and generalizations to minimize the complexity of modeling the capillary fringe and unsaturated zone, especially in relation to deriving diffusion coefficients.

Flux was modeled for TCE, DCE, and VC for five sampling events during 2009: one baseline, two during basic bioremediation efforts, and two during ERH-enhanced bioremediation. The modeled results were expected in that TCE flux decreased during Phase 2 and DCE and VC flux increased due to higher concentration of these compounds in groundwater. During Phase 3, however, TCE, DCE and VC increased by at least two orders of magnitude during ERH-enhanced bioremediation initially during the November sampling event. By the December sampling event, however, it appears that flux beginning to decrease as ERH-enhanced biodegradation rates increased.

The model was calibrated with extrapolated flux measurements derived from analytical concentrations of soil gas samples collected during the sample events. Although about 25% of the extrapolated flux estimates were negative because measured concentrations exceeded Csource, the modeled flux estimates overall correlated very strongly with the extrapolated flux estimates, especially for the flux estimates at the ground surface where many of the uncertainties associated with modeling diffusion through the capillary fringe are muted by the length of the unsaturated zone.

Calibration Of Model

Soil gas samples were collected from 7 ft bgs and at ground surface during the same five sampling events: January, July, August, November, and December 2009. These data have been used to evaluate the general accuracy of the modeled flux rates by extrapolating a flux rate based on soil gas contaminant concentrations. As noted previously, the calibration is not an independent evaluation because modeled C_{source} and D_{eff} must be used to extrapolate flux for the soil gas concentrations; however, if the model is a valid tool then the modeled flux should exhibit some degree of consistency with the extrapolated flux.

For the 7 ft bgs depth, 28 out of the 45 extrapolated flux measurements were realistic in that they were a positive number. The 17 cases involving negative flux measurements occurred because the measured soil gas concentration at 7 ft bgs was greater than the modeled C_{source}. This result is not unexpected for the 7 foot depth given the following reasons: 1) uncertainty in the soil and water characteristics of the capillary fringe which greatly impedes diffusive migration, 2) depressurization of the capillary fringe, and hence an increase in the diffusion coefficient, was not modeled, 3) potential entrainment of contaminant residual source in the capillary fringe and bottom of unsaturated zone, which was not assumed in the model, and 4) greater dissolved groundwater concentrations could be located near to the discrete MW points, which would increase soil gas concentrations near the MW by lateral diffusion. Regardless of these 17 instances where the extrapolated flux was negative, the data set of paired modeled and extrapolated flux rates yields a strong correlation ($r^2 = 0.996$) as demonstrated in **Figure 5-30**.

The results of the soil gas samples from the ground surface indicate an even better performance of the model. In this case, only 5 of the 45 extrapolated flux measurements yielded a negative flux measurement. All five instances were for TCE in either July or August 2009 at which point bioremediation had decreased TCE mass in the groundwater, but it is possible that soil gas concentrations in the vadose zone had not reached a steady state with the decreasing mass of contaminants in groundwater. **Figure 5-31** shows the strong correlation ($r^2 = 0.999$) for the data set of paired modeled and extrapolated flux rates at the ground surface.

The calibration testing indicates that the one-dimensional analytical model generally performs well for estimating flux to the vadose zone during ERH-enhanced ISB and that the predictability of the model improves with increasing distance from the source.

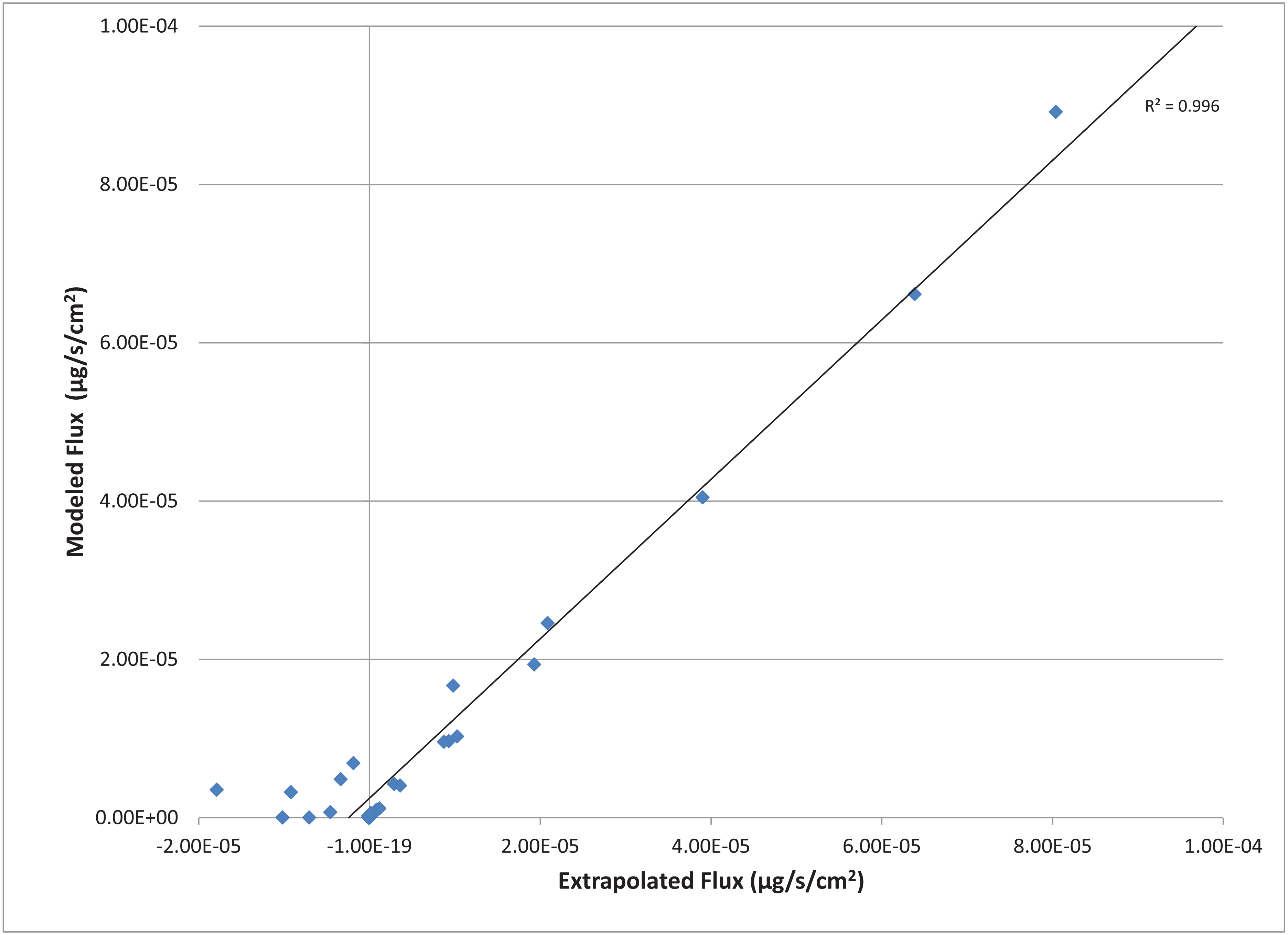


Figure 5-30. Model and extrapolated vapor flux at 7 feet bgs in the ISB test cell.

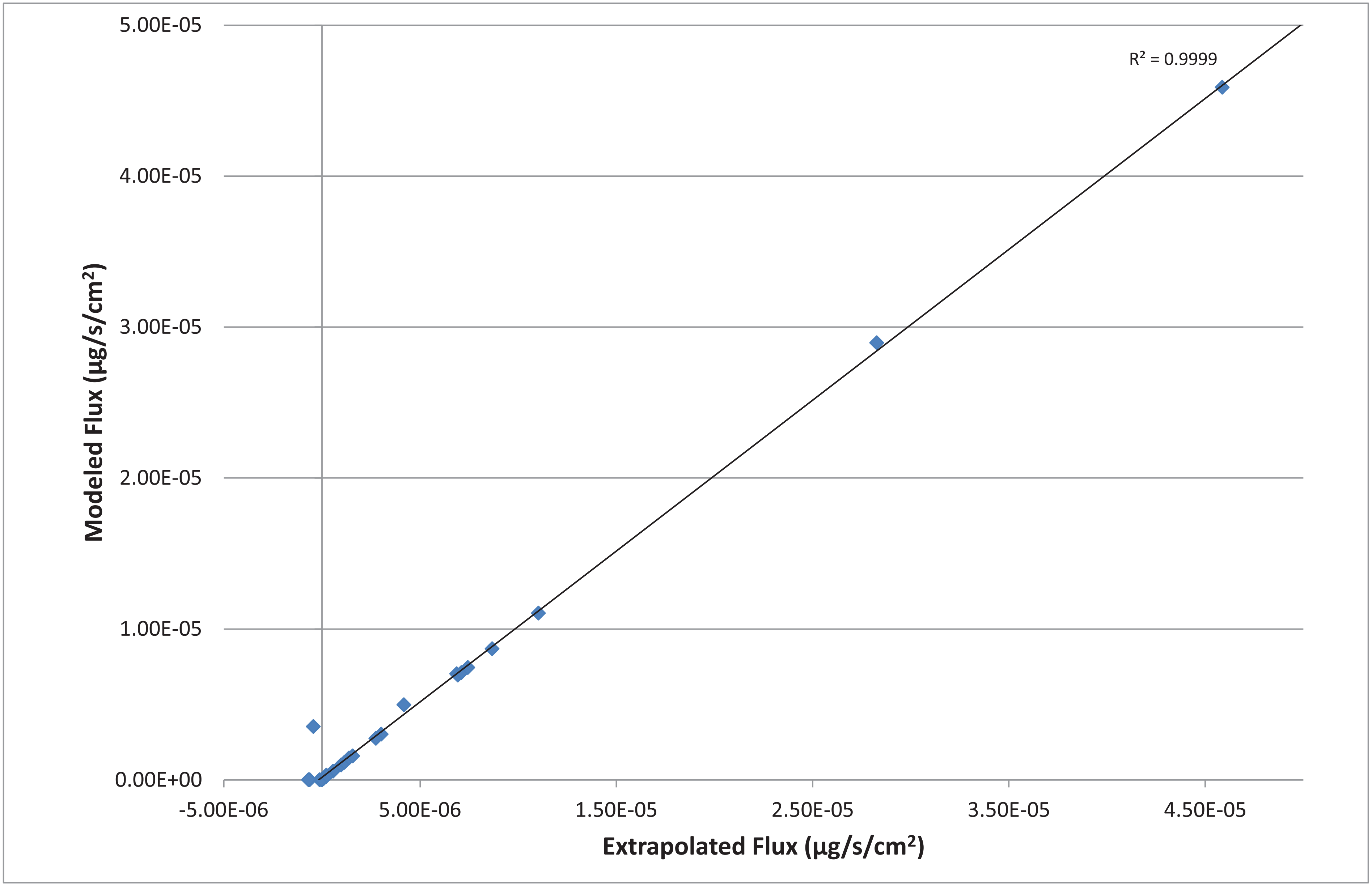


Figure 5-31. Modeled and extrapolated vapor flux at ground surface in the ISB test cell.

Soil Monitoring

Soil concentrations of TCE, DCE, and VC were measured during Phase 1, Baseline, following Phase 2 ambient treatment, and following Phase 3 heated treatment. Soil samples were generally collected within the borehole (Baseline) or within one foot of ISB-MW1, -MW2 and –MW3. **Figure 5-32** illustrates results of the Baseline post-Phase 2 and post-Phase 3 soil monitoring. DCE and VC soil concentrations were much lower than the TCE concentrations and are presented only in **Appendix E**. High concentration of TCE were observed at all monitoring locations, but were generally highest at ISB-MW2 during baseline sampling (5.1-130 mg/kg). Generally soil concentrations decreased following Phase 2 with an average 27% reduction in soil concentrations (n=3). Following Phase 3, average soil concentrations again decreased at ISB-MW1 and ISB-MW2, but dramatically increased in ISB-MW3, indicating that a significant source was still present in this well after Phase 3. However, generally temperatures were much lower at this location than at ISB-MW1 and ISB-MW2 because the electrode nearest this well was turned off shortly after startup because of preferential heating.

Three soil samples were collected from each soil boring and the average concentration was 48.5 mg/kg during baseline (range 4.9-130 mg/kg), 60.0 mg/kg following Phase 2 (range 0.36-220 mg/kg) and 17.5 mg/kg following Phase 3 (range 0.29-100 mg/kg) for an average reduction of 64% compared to baseline and 70% compared to Phase 2 (see **Appendix A**). However the variability in concentration results, and the high uncertainty in the total mass present within the test cell, limits the ability to interpret the soil results. These data generally support that treatment of TCE in soil was occurring during the test.

5.7.2 ZVI Injection Results

Details of the ZVI injection are described by Truex et al. (2010) and summarized below. A tracer test was conducted prior to ZVI injection to evaluate the subsurface flow system and finalize the injection parameters. **Table 5-23** shows the comparison of observed tracer breakthrough and the calculated arrival time based on a radial flow assumption and an effective porosity estimate of 0.18. Tracer reached full injected concentration at all wells except ZVI-MW2 (80%), ZVI-MW3 (75%), ZVI-MW6 (85%), and the upgradient well ZVI-MW9 (25%). Tracer arrival at different MWs indicated several preferential pathways from the injection point with the most significant to wells ZVI-MW6 and ZVI-MW8 as indicated by substantially shorter actual arrival times compared to calculated estimates. Overall, however, tracer arrival to the other six MWs was consistent with calculated estimates, indicating that the radial flow assumption was appropriate. Tracer elution evaluation resulted in an estimated average groundwater linear velocity of 16 m/d with a standard deviation of 6.5 m/d. Thus, prior to injection, there was a relatively high groundwater velocity across the test site.

Table 5-24 summarizes the ZVI injection parameters. During injection of the ZVI solution, pressures at the injection well and MWs were higher than observed during the tracer test as expected due to the higher viscosity of the injection solution (**Figure 5-33**). However, the pressure did not become a limiting factor for injection at the target flow rate. These figures show moderate pressure at the injection well (~1.5 m of head with the SlurryPro™ compared to 0.75 m

Table 5-23. Summary of tracer arrival and ZVI distribution results.

Well	Radial Location from Injection Well (m)	Measured Tracer Breakthrough (h)[1]	Calculated Tracer Breakthrough (h)	Comparison of Measured to Calculated Arrival	Average ZVI Concentration During Injection (% of injection concentration)
MW1	1.22	0.13	0.28	early	26
MW2	2.10	0.87	0.84	OK	1
MW3	2.07	0.75	0.82	OK	1.5
MW4	1.04	0.15	0.20	OK	17
MW5	2.23	0.70	0.94	OK	5
MW6	2.04	0.20	0.79	very early	14
MW7	2.07	0.50	0.82	OK	8
MW8	4.05	0.67	3.12	very early	2.6
MW9	4.27	>2.5	3.46	OK	None

based on time to reach 50% of injected concentration using down-hole bromide probe data.

Table 5-24. Summary of ZVI injection parameters.

Item	Value
Water injection rate(average)	20.5 gpm
SlurryPro™ injection rate(average)	2.2 gpm
Surfactant injection rate (average)	76 mL/min
Total solution injection rate (average)	22.7 gpm
Total injection solution volume	13,660 L
SlurryPro™ stock solution injection volume	1300 L
Injected ZVI mass	187 kg
SlurryPro™ concentration (average)	0.019 wt%
Surfactant concentration (average)	0.0008 wt%
ZVI concentration in injection solution	1.36 wt%
Injection duration	158 min

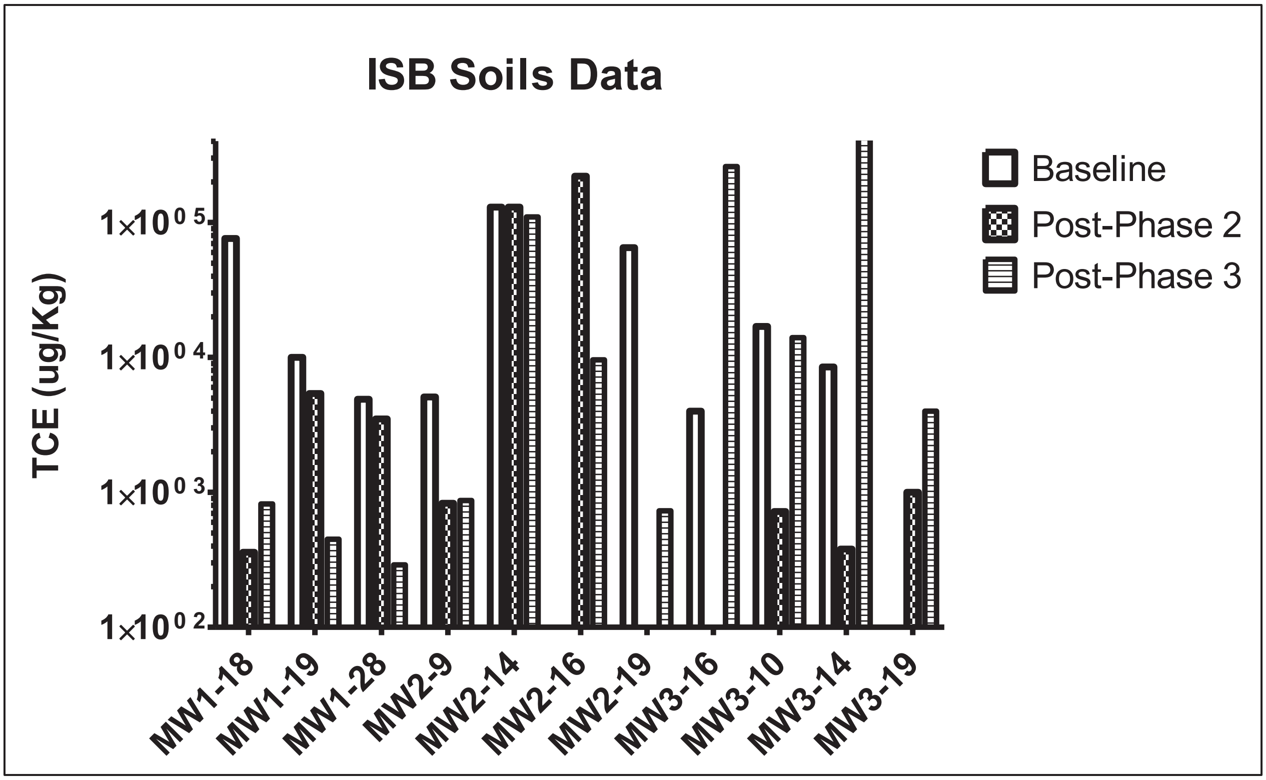
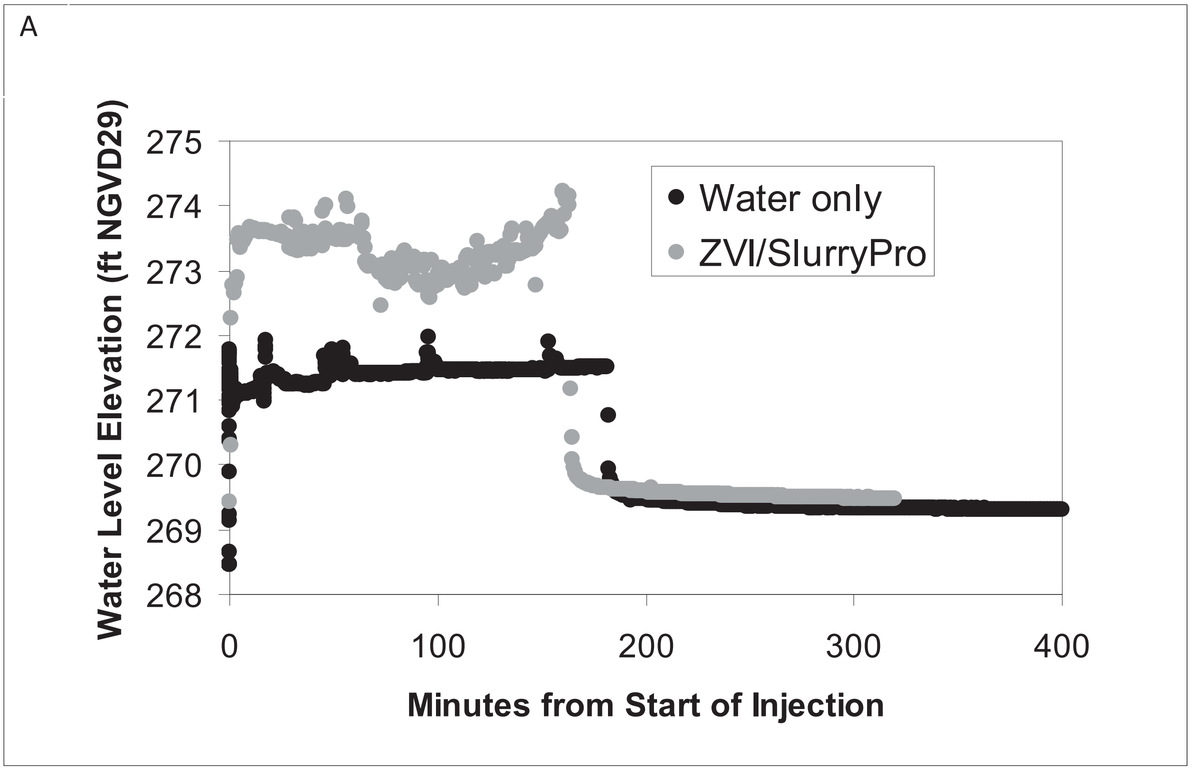


Figure 5-32. Summary of soil concentration results for Phases 1, 2 and 3 for the ISB test cell.



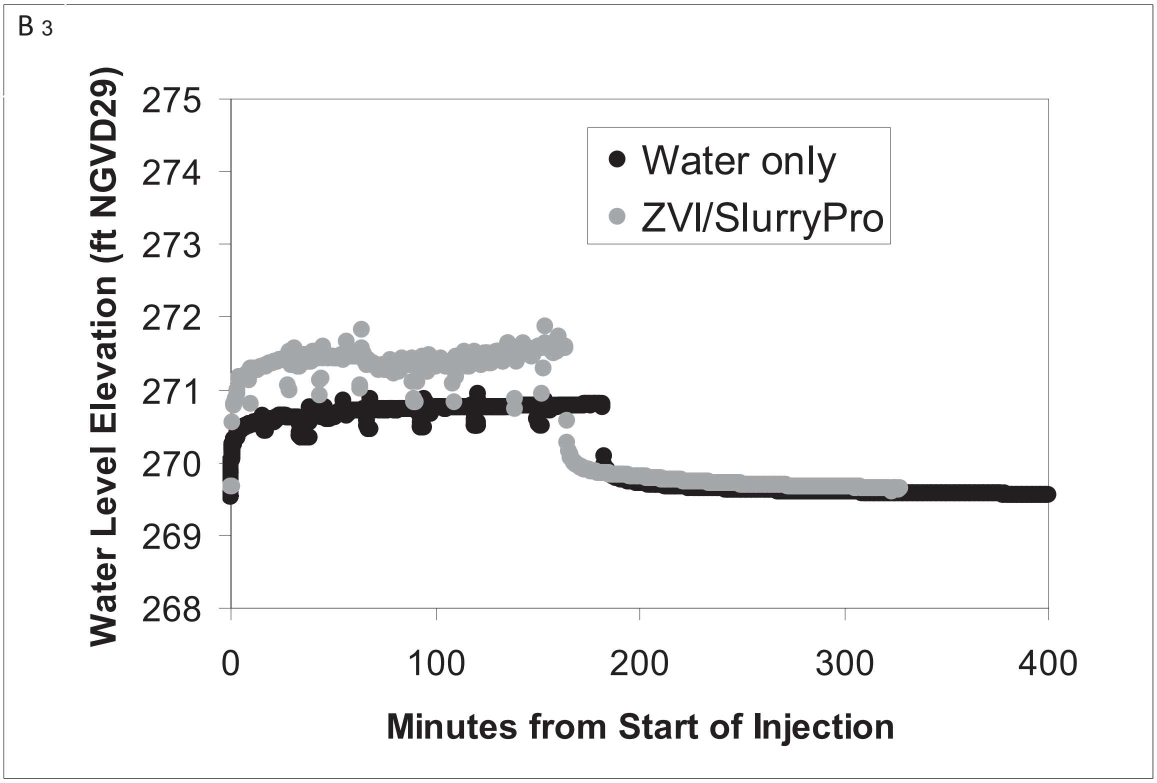


Figure 5-33. Pressure response at (A) the injection well, (B) monitoring well MW1 located at a radial distance of 1.22 m from the injection well, and (C) monitoring well MW5 located at a radial distance of 2.23 m from the injection well.

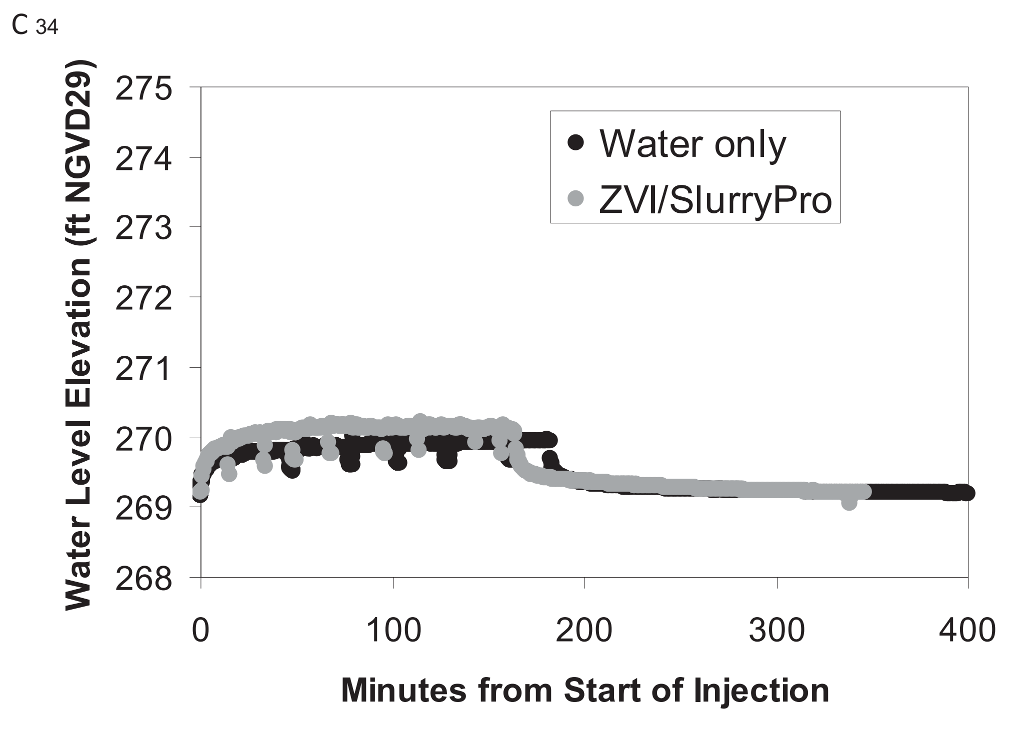


Figure 5-33. (Continued) Pressure response at (A) the injection well, (B) monitoring well MW1 located at a radial distance of 1.22 m from the injection well, and (C) monitoring well MW5 located at a radial distance of 2.23 m from the injection well.

of head for water injection) and then pressure decreasing with radial distance from the injection well as would be expected with development of a water table mound around the injection point. These pressures suggest normal groundwater flow with no fracturing of the formation.

Table 5-23 shows the ZVI concentration in the MWs as a function of radial distance from the injection well. Decreasing concentration of ZVI with radial distance from the injection well was observed, consistent with the occurrence of some filtration and gravitational settling of ZVI during injection (Oostrom et al. 2007). These results represent measurement of ZVI particles that reached each MW and could be retrieved in the sampling system. The correlation of these data to actual ZVI concentration in the aquifer at these locations is not known. As an additional indication of ZVI distribution, the groundwater chemistry and dechlorination reactions at each monitoring location showed indications of the reductive processes expected with ZVI as discussed in the next section.

5.7.3 Phase 2 and 3: ZVI

Analysis of the ZVI treatment results is presented in Truex et al. (2010 and 2011) and summarized below. Data were collected periodically for 345 days after ZVI injection, with the highest data density during the first 150 days. Seasonal water table variation occurred over this test timeframe and the water level decreased such that the test cell screens were below 90% saturated after day 121 with increasing water levels starting around day 184 (**Figure 5-34**). For this reason, the mass-discharge analysis presented in **Section 6** focused on the first 120 days of treatment, 60 days under ambient conditions (Phase 2), and 60 days of heated treatment (Phase 3). The data presentation below provides data for the full duration of the test. However, data past day 121 should be considered in light of the water table variations. Additionally, most of the data analysis focuses on data from the injection well and MWs other than ZVI-MW3. Well ZVI-MW3 was screened in the top 0.6 m of the aquifer and due to the water level variations, having a well screen interval different from other test well, and the proximity of ZVI-MW3 to ZVI-MW2, ZVI-MW3 was not included in most of the data analyses.

Groundwater Monitoring

Constituents in groundwater were monitored over time in the ZVI test cell to evaluate the geochemical conditions and the contaminant and dechlorination product concentrations as part of evaluating the ZVI treatment process and the impact of elevated temperature.

Geochemical Response

ZVI reactions in groundwater cause a decreased oxidation-reduction potential (ORP) and an increase in pH. The ORP substantially decreased in the test cell upon addition of ZVI and remained low, generally between -100 and -200 mV for the first 150 days of the test, spanning both ambient temperature and elevated temperature conditions (**Figure 5-35**). The ORP is not a direct measure of dechlorination reactions, but provides an indication that the ZVI was active in chemically reducing the groundwater system over time. When the ORP increased again toward starting ORP conditions it is an indication of the ZVI losing its ability to maintain chemically reducing conditions either through being expended or passivated to an extent that rate of reductive ZVI processes were slower than the rate of oxidizing species into the monitored

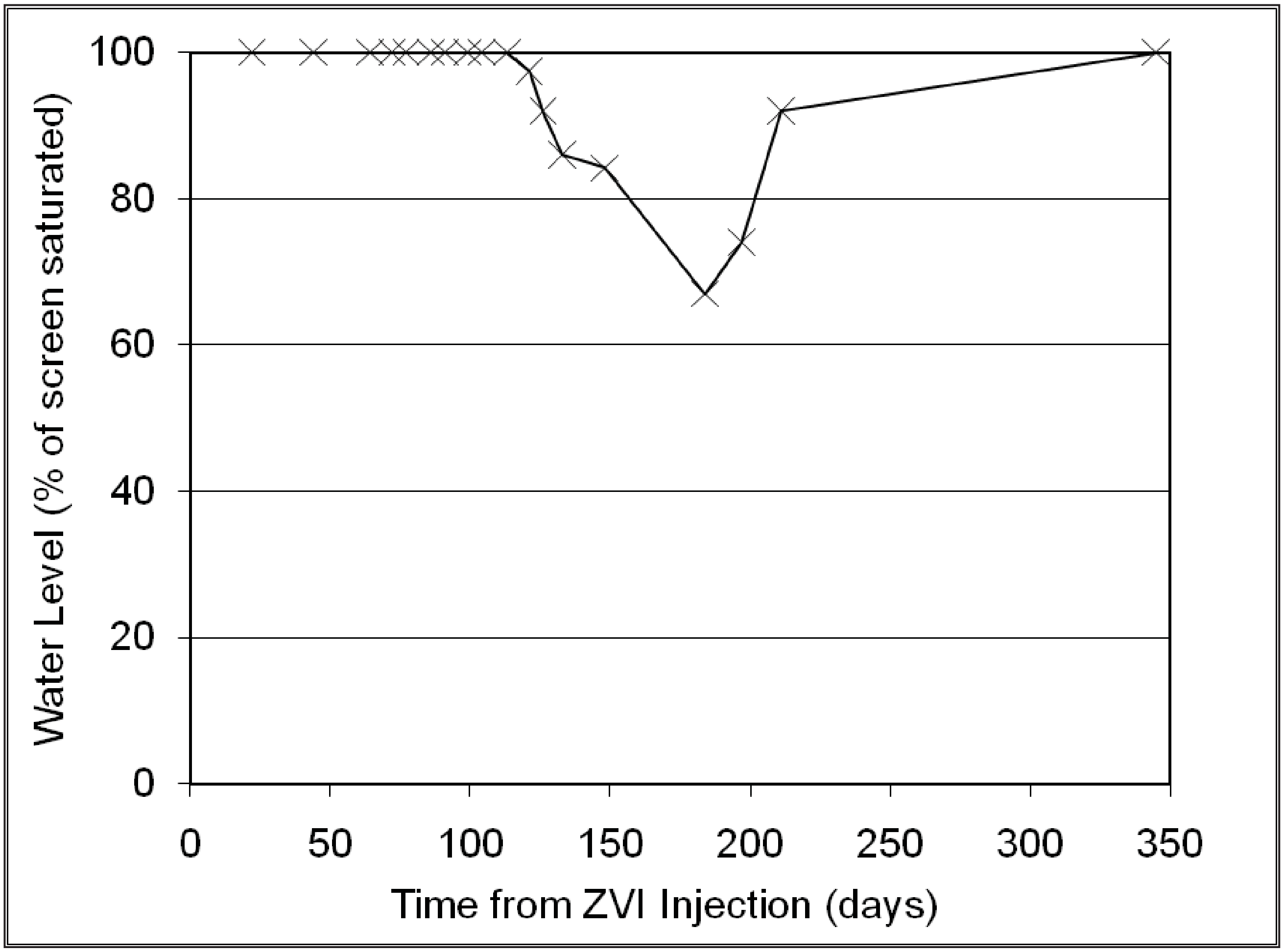


Figure 5-34. Water level variation during the field test.

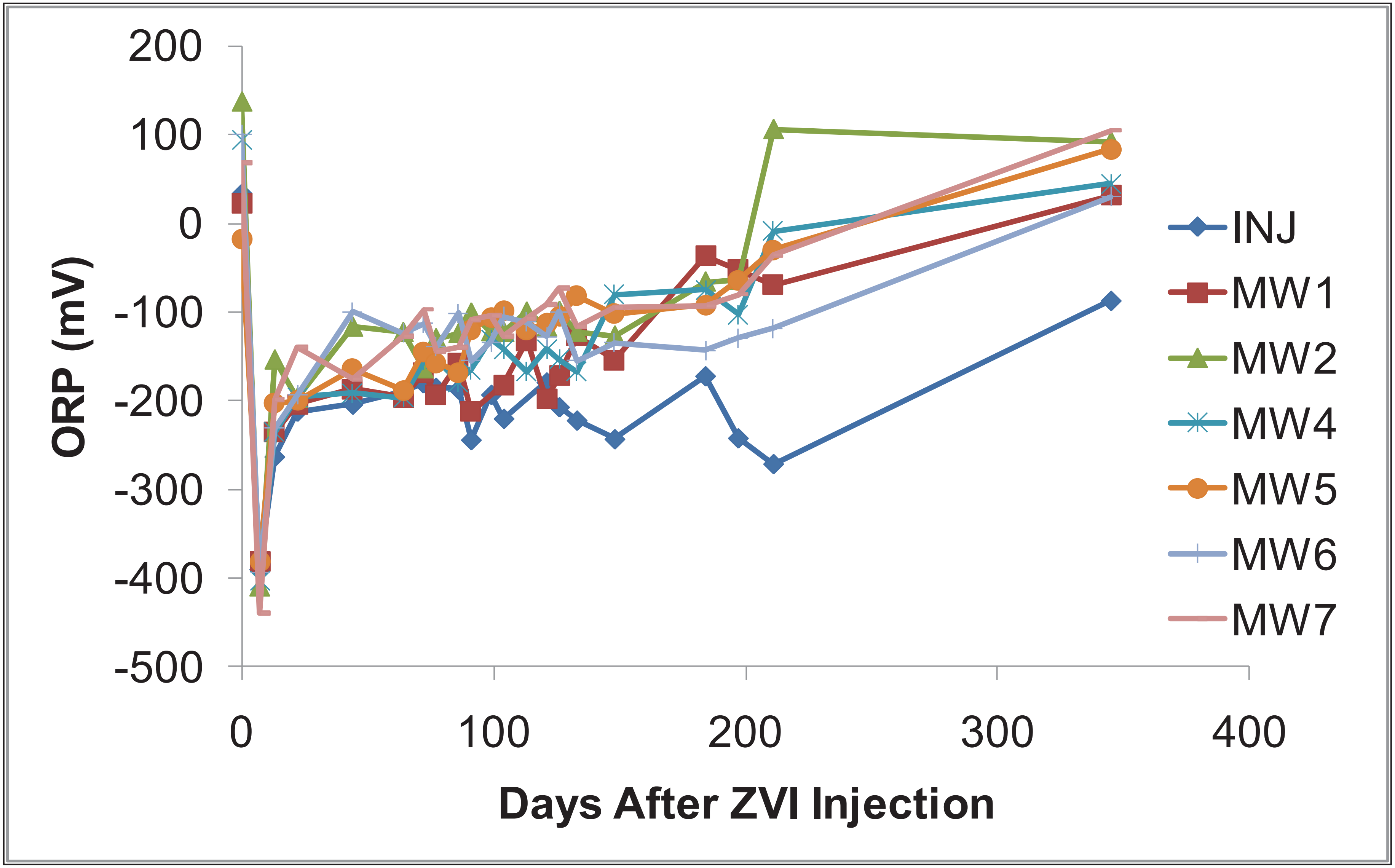


Figure 5-35. Oxidation-reduction potential over time in the test cell.

interval. The low ORP conditions were maintained longest at the injection well were the highest concentration of ZVI was present in the aquifer. Changes in pH (increased due to ZVI reactions with water) showed similar trends in terms of the timeframe of ZVI reactions at the monitoring locations (**Figure 5-36**).

Contaminant And Dechlorination Product Concentrations

The concentrations of TCE (target contaminant) and dechlorination products in the groundwater are the central data need to evaluate treatment over time because the reactions occur in the aqueous phase and collecting and measuring concentrations in groundwater is a robust process. Soil contaminant data are important, but do not provide significant temporal information. Vapor data is important because TCE and its dechlorination products are volatile. However, vapor data can be impacted by interferences in the unsaturated zone where samples are collected (see discussion in next section) and data represent concentrations after transport out of the groundwater and potentially through zones of further degradation processes (e.g., oxidation reactions not present in the groundwater).

The TCE concentration over time is expected to be impacted by dissolution from sediment-associated or DNAPL TCE, dechlorination reactions, and volatilization. Likewise, dechlorination products are impacted by these same processes, although dissolution is expected to be minimal, and potentially by sorption. However, the sorption of the TCE dechlorination products is expected to be low at the test site (Truex et al. 2006). Evaluation of these processes is described in Section 6 using a mass-discharge approach based on the groundwater data presented here. While most of the results interpretation requires a mass-discharge analysis, some general conclusions about contaminant dechlorination can be drawn directly from the contaminant data and are presented below.

The temporal variation in TCE and dechlorination concentrations in the groundwater at each monitoring location are shown in **Figures 5-37** through **5-46**. At all interior test cell wells, dechlorination daughter products appeared within one week of ZVI injection and showed primarily dechlorination products present by 44 days and continuing through about 120 days after injection. The total organic dechlorination products show a sharp increase during the first 60 days of heating, days 60 – 120 after injection, and then begin to decline. The dominant organic dechlorination daughter products observed were cis-1,2-DCE, ethene, and ethane, indicative of both beta elimination and reductive dechlorination mechanisms. The increases in cis-1,2-DCE concentrations suggest that incomplete biological dechlorination of TCE to cis-1,2-DCE was stimulated rapidly, potentially induced by hydrogen produced by the ZVI. In the absence of VC concentration increases (less than 0.2 uM at all wells within the test cell during the test), the complete biological reductive dechlorination pathway is unlikely and the ethene and ethane concentration increases suggest that beta elimination dechlorination reactions catalyzed by the ZVI were occurring. Acetylene is a transient product of the abiotic reactions and was observed at concentrations ranging up to 0.4 uM at the injection well and wells ZVI-MW3 through -MW7 ranging up to 1.2 uM. Note that dechlorination products were observed in ZVI-MW3 even though this well was screened within a till feature at the top of the aquifer. Data after

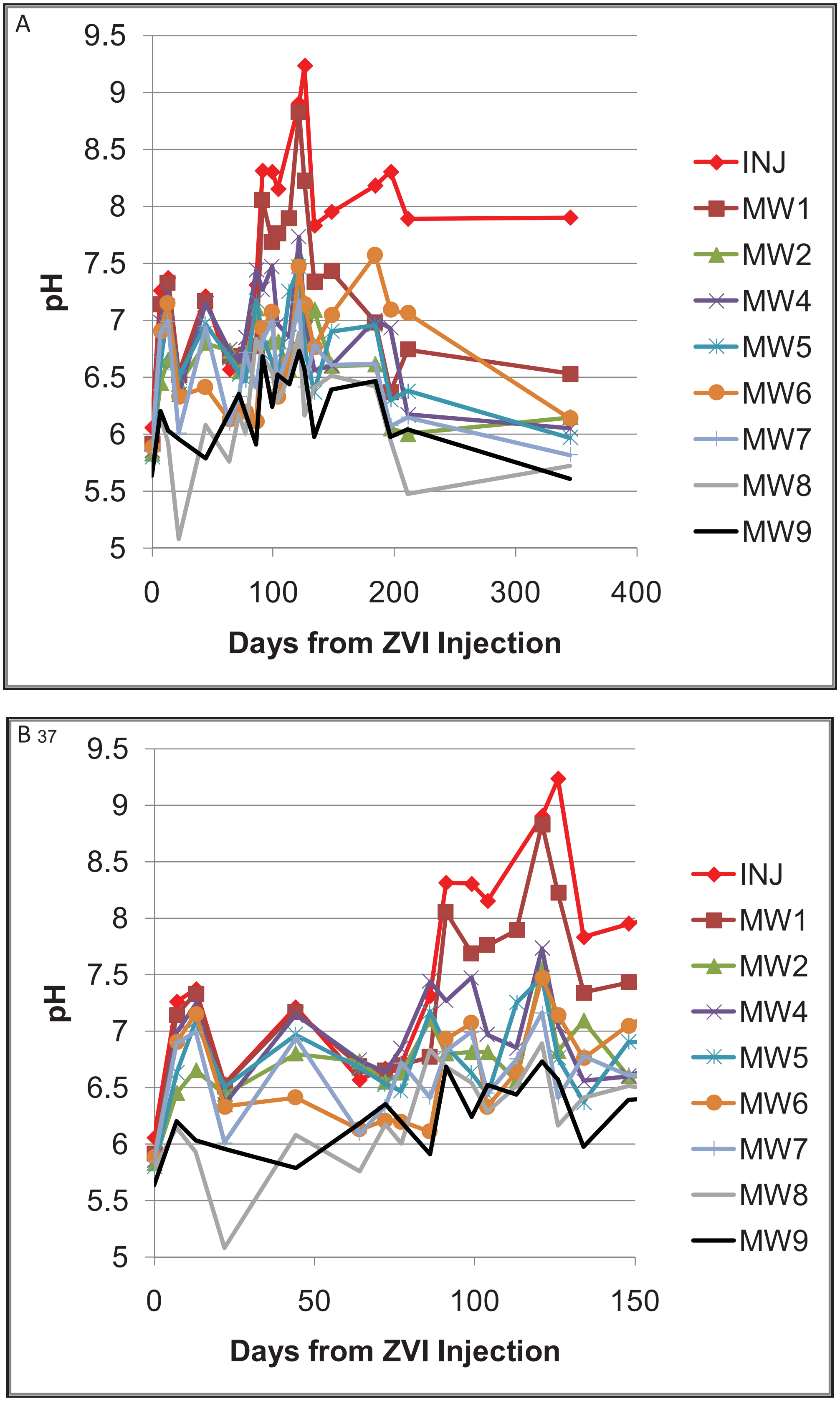


Figure 5-36. Measured pH response during ZVI demonstration (A) and for first 150 days (B).

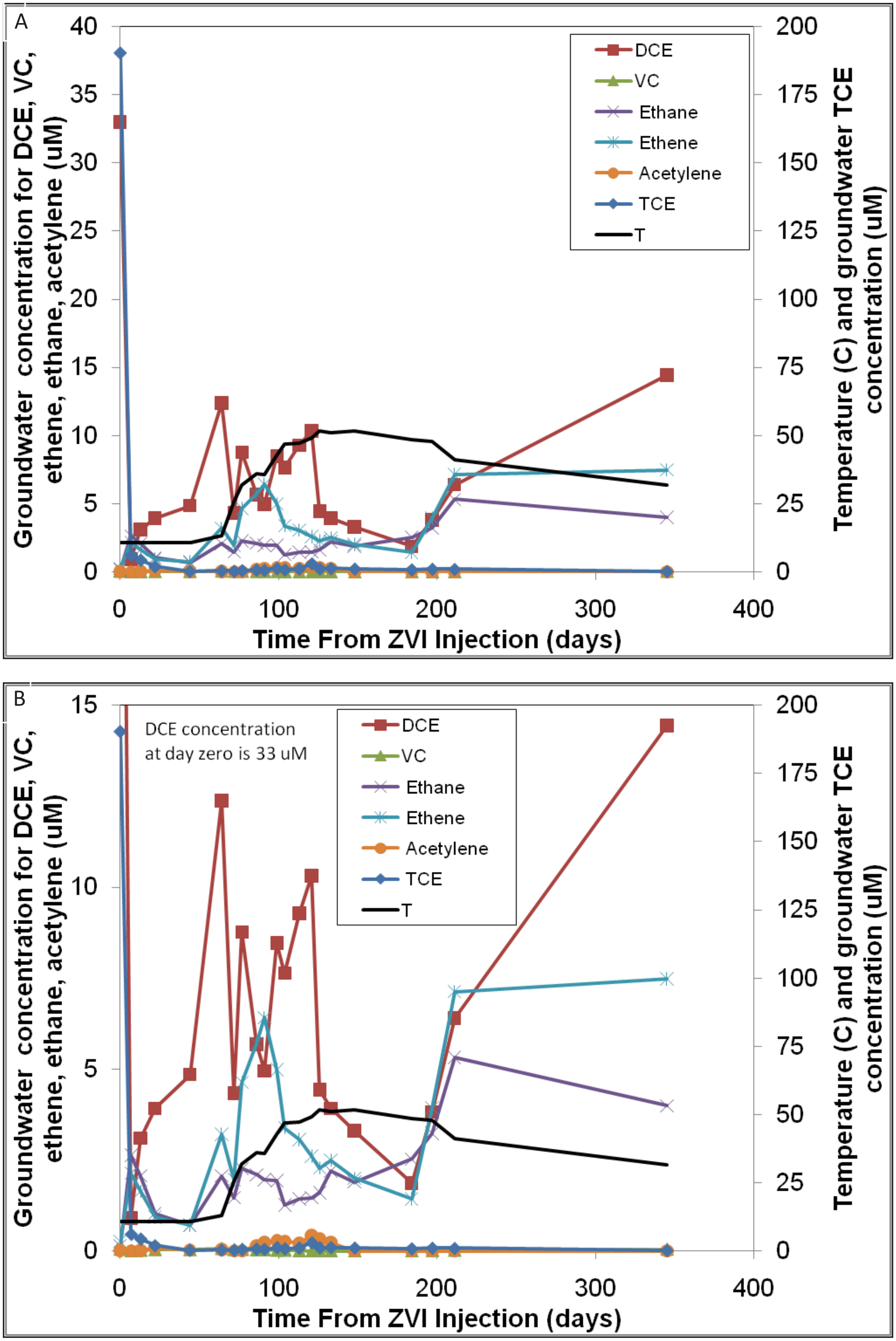
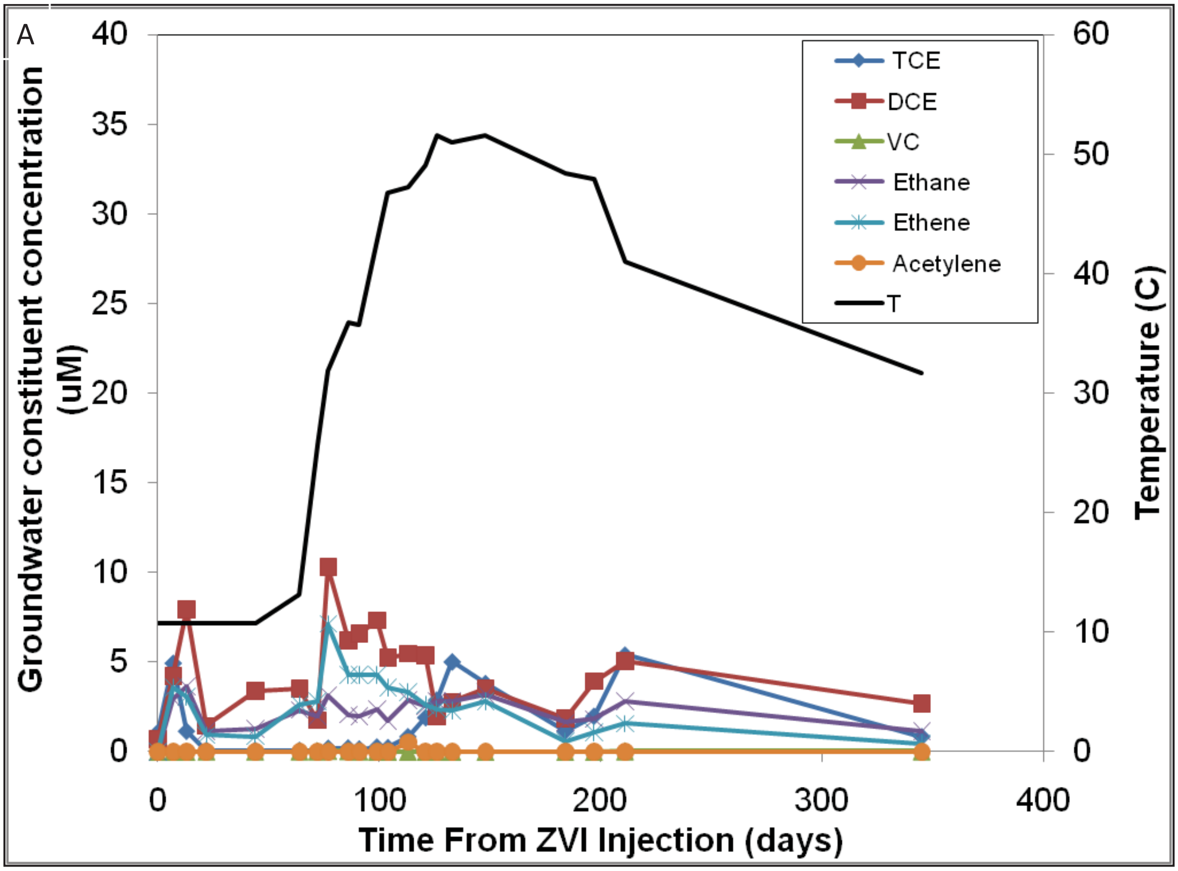


Figure 5-37. Groundwater concentrations at well INJ. (B) graph presents groundwater constituents at a refined scale to show details.



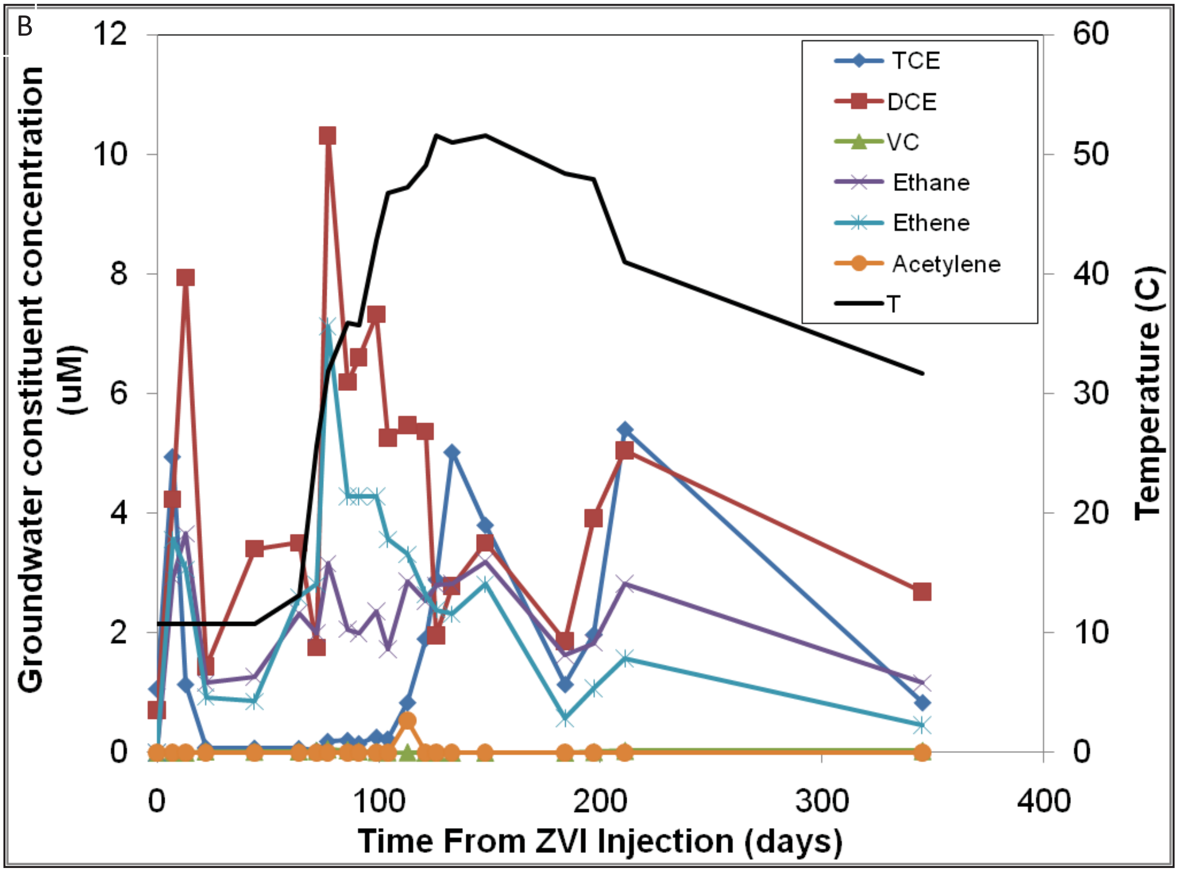


Figure 5-38. Groundwater concentrations at well MW1. (B) graph presents groundwater constituents at a refined scale to show details.

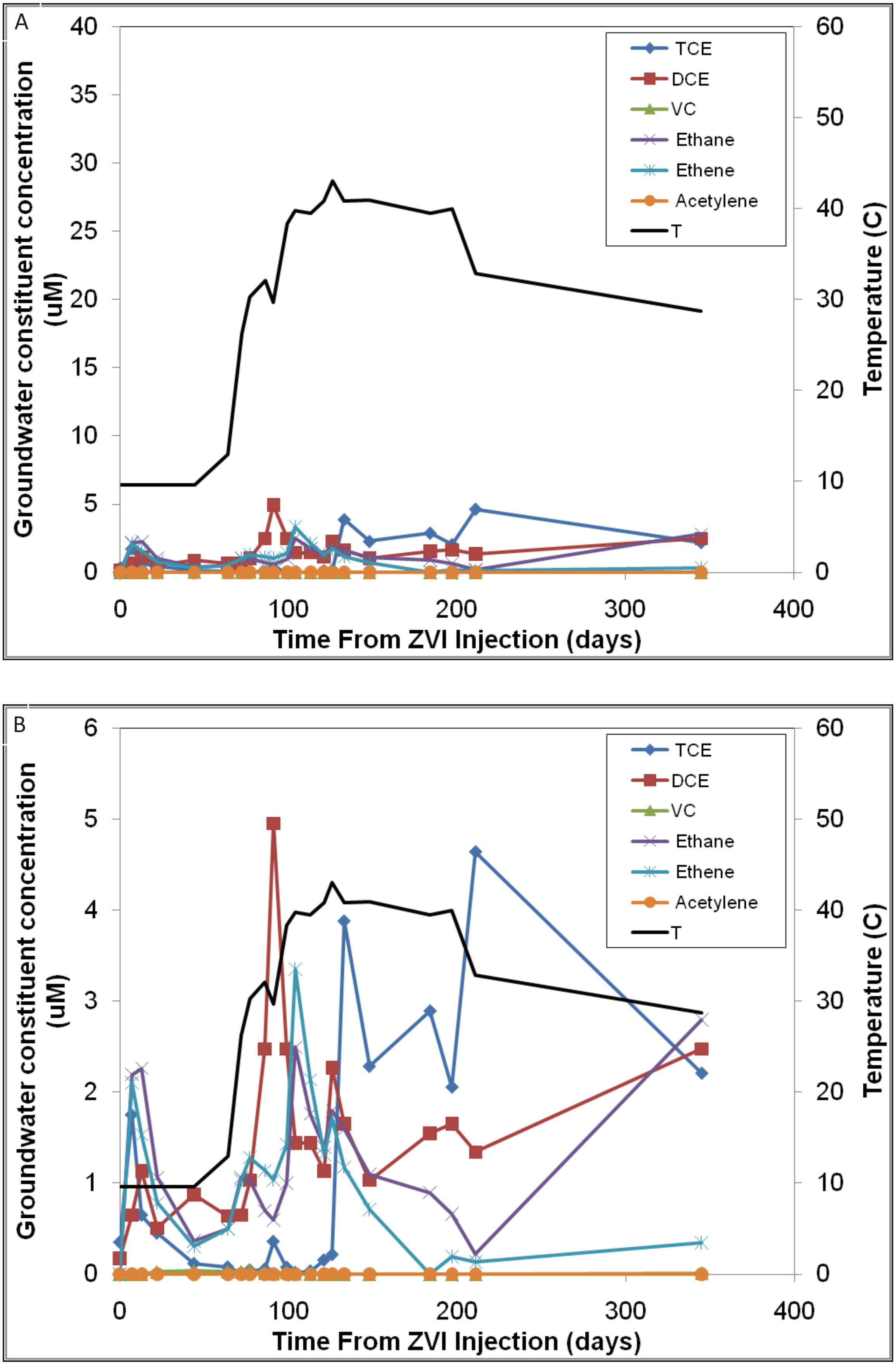


Figure 5-39. Groundwater concentrations at well MW2. (B) graph presents groundwater constituents at a refined scale to show details.

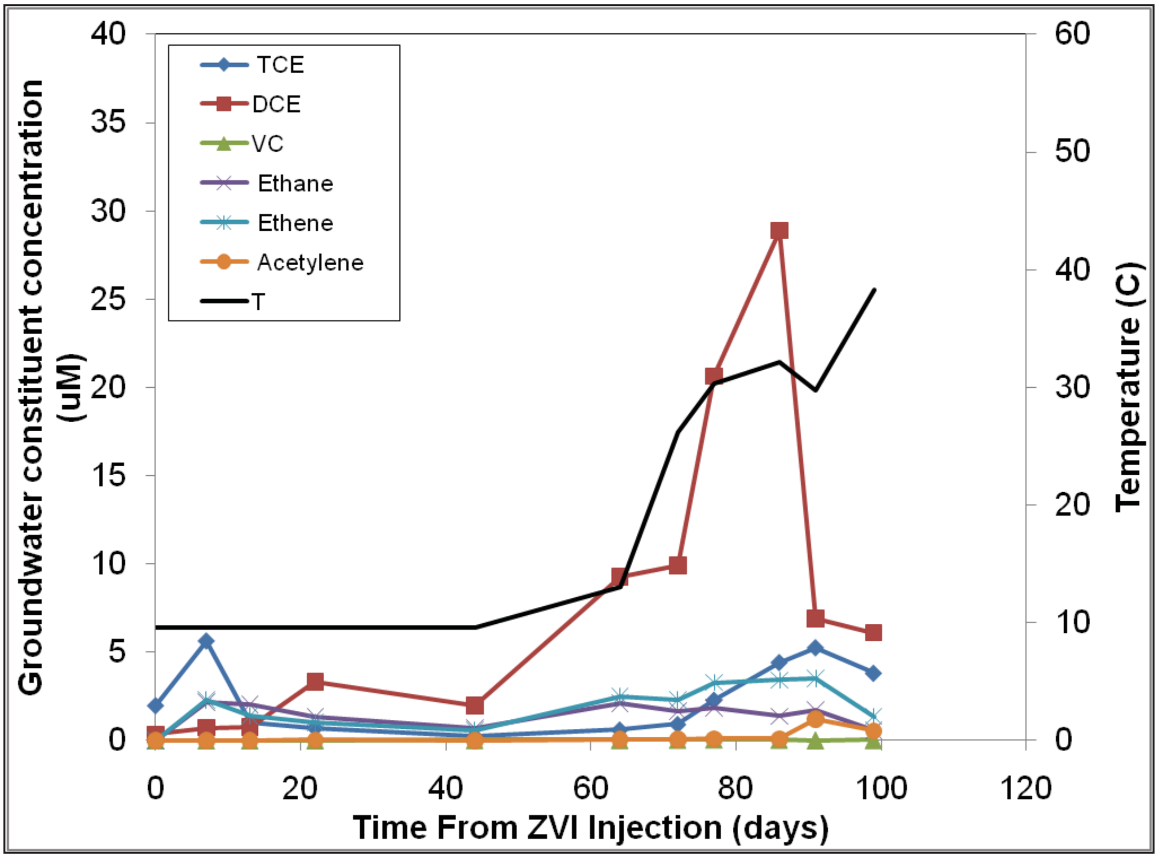


Figure 5-40. Groundwater concentrations at well MW3.

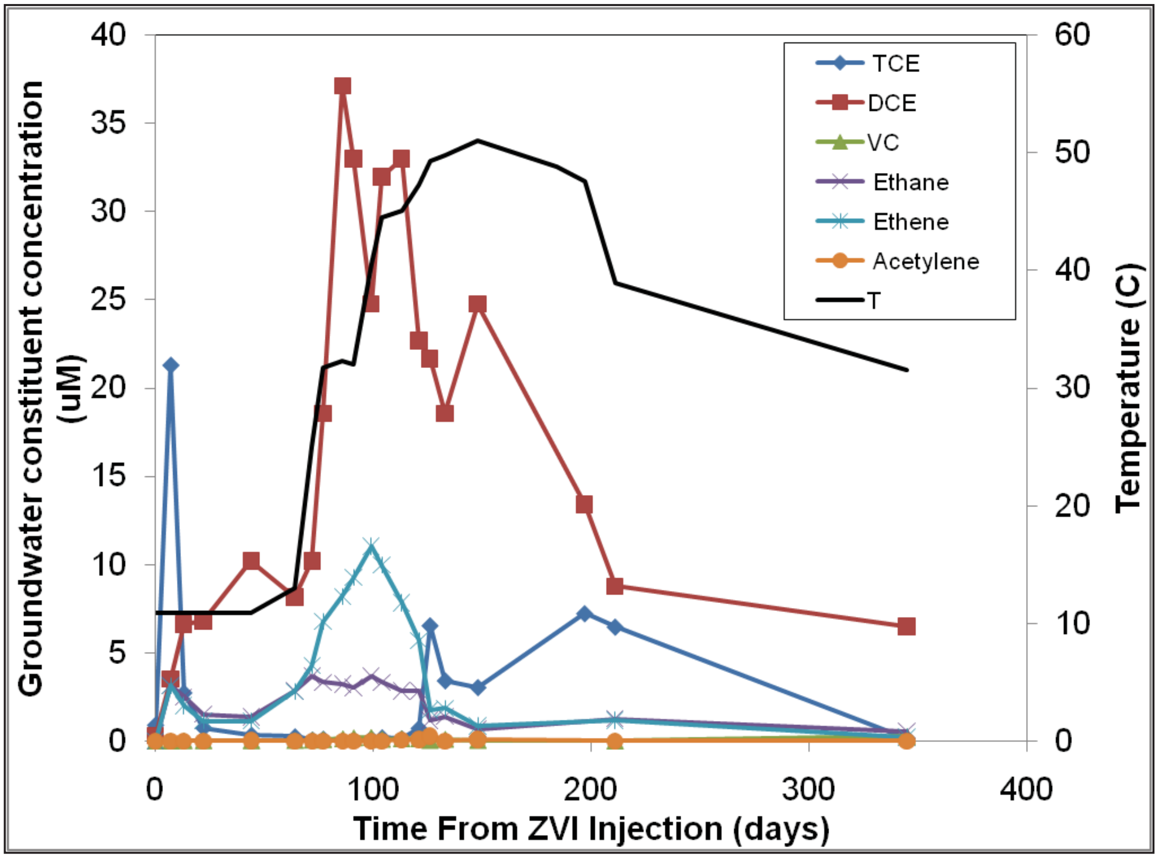


Figure 5-41. Groundwater concentrations at well MW4.

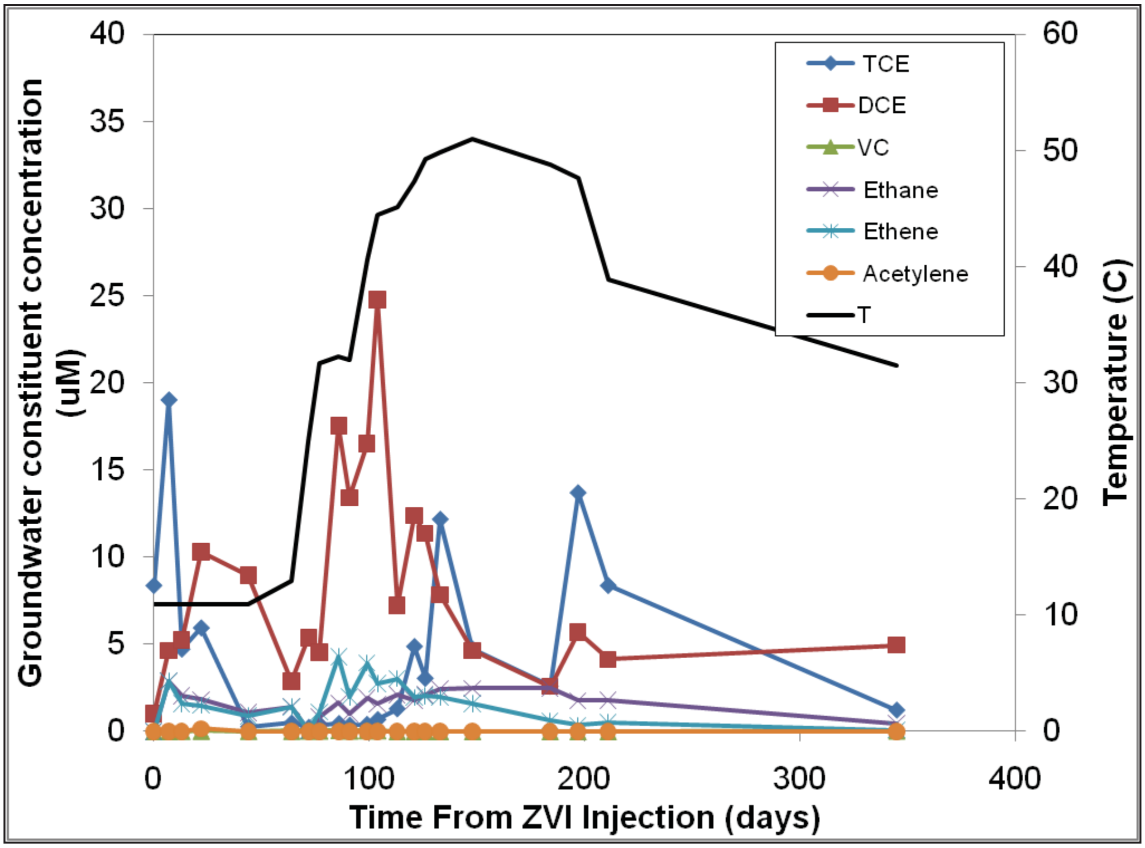


Figure 5-42. Groundwater concentrations at well MW5.

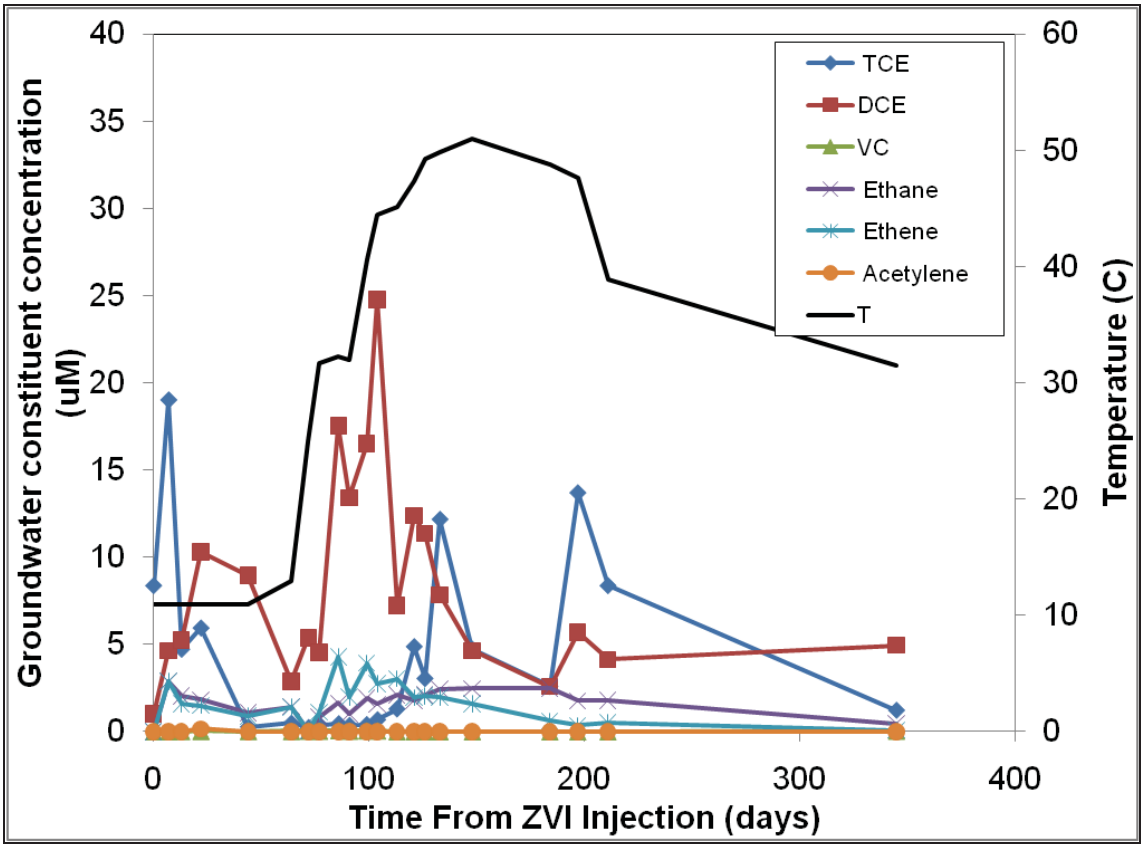
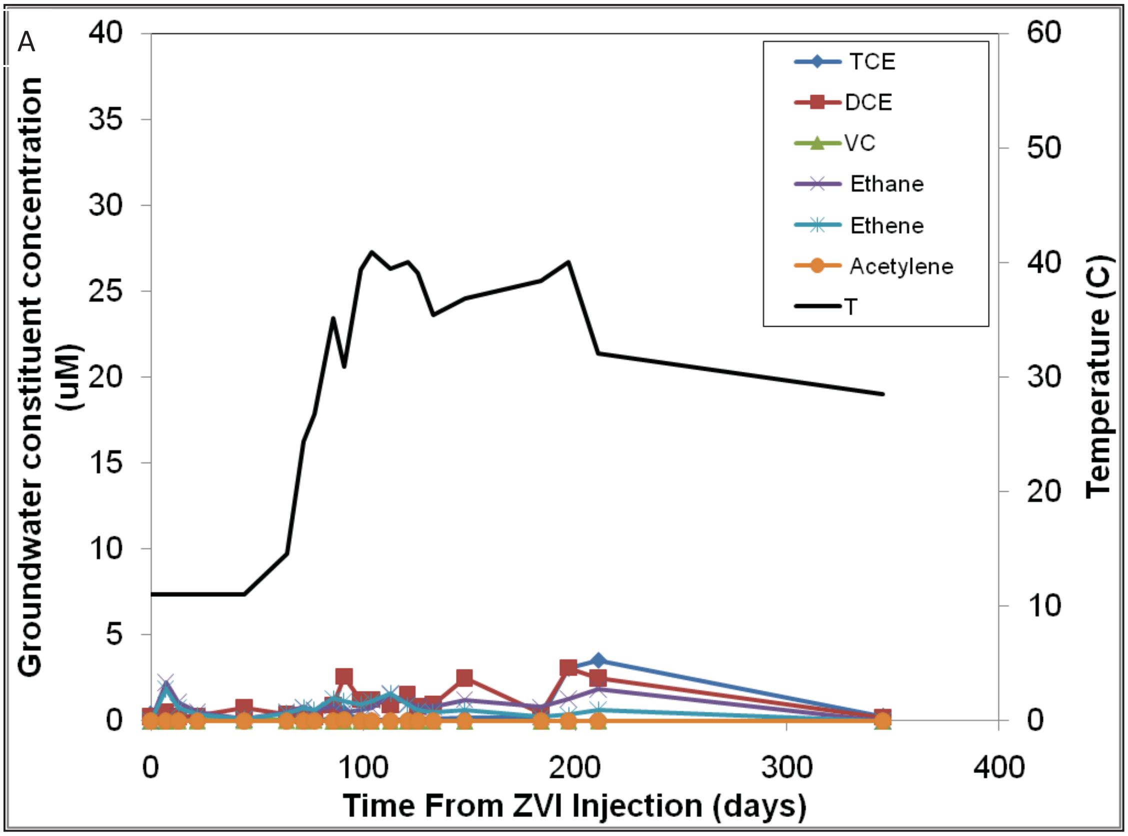


Figure 5-43. Groundwater concentrations at well MW6.



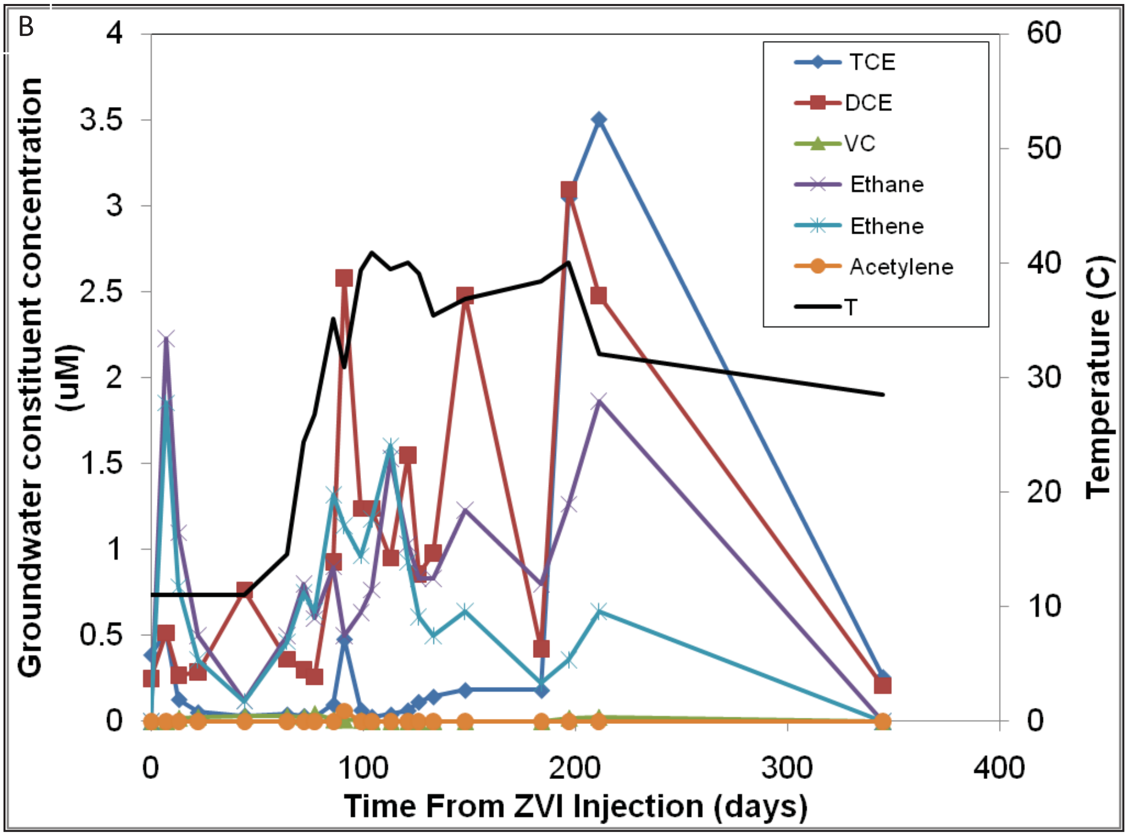
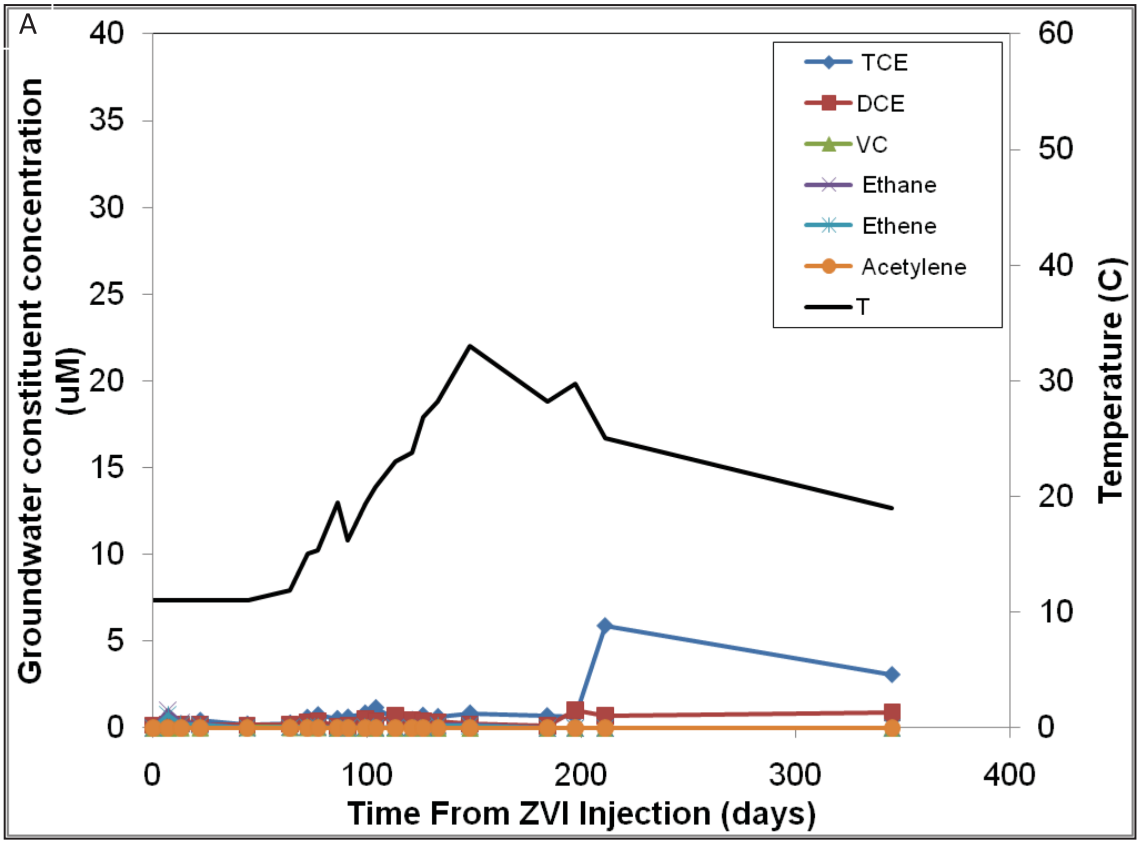


Figure 5-44. Groundwater concentrations at well MW7. (B) graph presents groundwater constituents at a refined scale to show details.



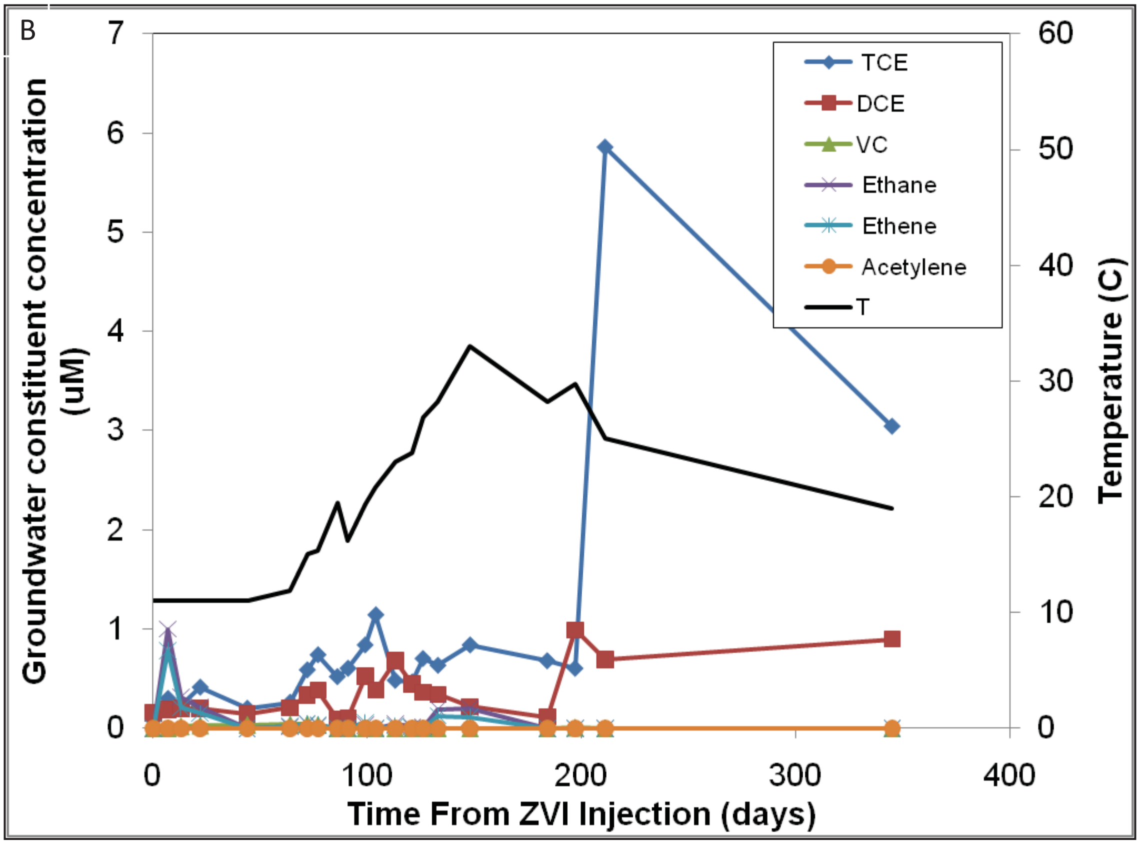


Figure 5-45. Groundwater concentrations at well MW8. (B) graph presents groundwater constituents at a refined scale to show details.

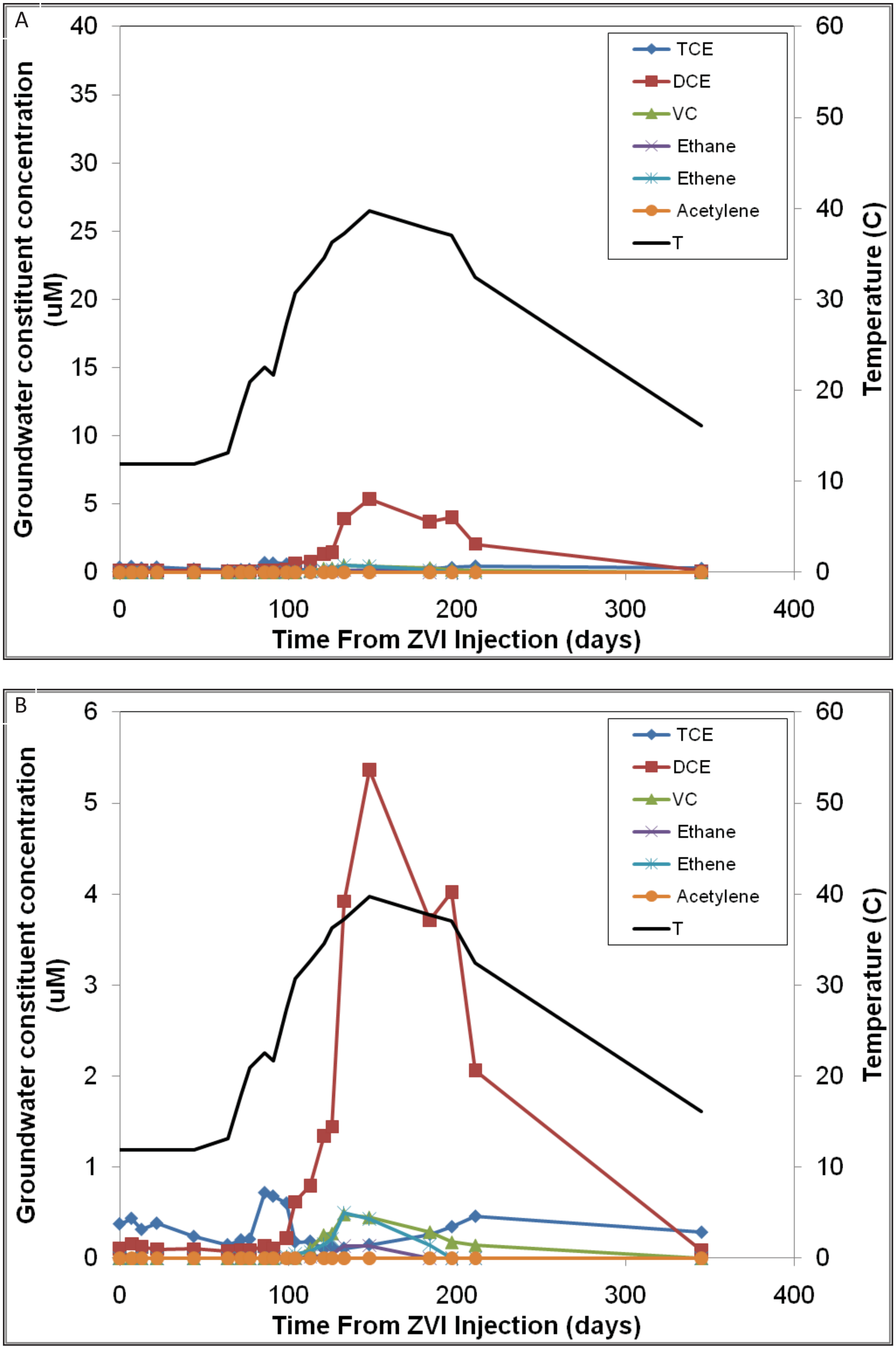


Figure 5-46. Groundwater concentrations at well MW9. (B) graph presents groundwater constituents at a refined scale to show details.

day 100 are not shown for ZVI-MW3 due to water level decreases significantly impacting the screen saturation level.

Additionally, at all of these wells except for the injection well, the total molar VOC concentration increased significantly within one week, including (with the exception of the injection well) an increase in TCE concentration. This apparent increase in molar concentrations suggests that a significant amount of mass transfer may have occurred from the NAPL and/or sorbed phases to the aqueous phase as a result of the ZVI solution injection. Radial displacement of the high pre-injection TCE concentrations near the injection well, TCE desorption, and reaction with ZVI are potential explanations for the increased total VOC concentration (Truex et al. 2010).

The total molar VOC concentration in the groundwater also increased significantly over the first 60 days of Phase 3 heating. Increases in dechlorination daughter products by a factor of about three without increases in TCE mass in the groundwater during initial heating suggest that heating enhanced dechlorination of sediment- or NAPL-associated TCE. The decline in daughter products after about 120 days and the subsequent rise in ORP by day 200 at most locations other than the injection well suggest that the reactivity of the injected ZVI had declined by this time or a decreased mass and therefore availability of TCE within the test cell (see also Truex et al. 2011). TCE groundwater rose at locations other than the injection well after about day 100, suggesting a decline in ZVI reactivity compared to the enhanced dissolution from the elevated temperature conditions.

A transient dechlorination response was observed at well ZVI-MW8, which only received a relatively small dose of ZVI. At ZVI-MW8, only limited dechlorination was observed and by day 44 the water chemistry had nearly returned to pre-injection conditions. The TCE concentration at ZVI-MW8 rose after day 184, but this effect may be related to water level variation during this time. TCE concentrations over time were not significantly impacted for well ZVI-MW9, which did not receive ZVI, until later in the test (after day 100) when the temperature at ZVI-MW9 increased to above 30^{o}C and data show evidence of reductive dechlorination processes occurring. Potentially, biological reactions coupled to organic matter in the sediment were the cause of this dechlorination.

General conclusions can be inferred from the groundwater data. For instance, increases in dechlorination products and decreases in TCE concentration with an overall increase in the total VOC concentration indicate that sediment- or NAPL-associated TCE was being treated and that the ZVI reaction transformed TCE at least as quickly as it was being released from the sediment, even under elevated temperature conditions. Because the groundwater TCE concentrations were maintained low during both Phase 2 and 3 treatment, the driving force for volatilization was low. The groundwater data also indicate that the ZVI induced both reductive dechlorination and beta elimination reactions. The relative rates for these reactions, including an analysis of how temperature impacted these rates is presented in Section 6. As an overall indication of treatment, **Table 5-25** shows the TCE and dechlorination concentrations in the groundwater before ZVI injection and at the end of the test. Treatment during the full Phase 2 and 3 duration of the ZVI test resulted in a decrease in groundwater TCE concentration. Except for DCE, final groundwater concentrations of organic dechlorination products were 1 to 2 orders of magnitude higher at the end of treatment. **Table 5-25** also shows that initial TCE concentrations were much higher inside compared to outside the test cell, indicating that the test was conducted in a contaminant source zone.

Table 5-25. Average groundwater concentration of TCE and dechlorination products.

	TCE (ug/L)	DCE (ug/L)	VC (ug/L)	Ethane (ug/L)	Ethane (ug/L)
Test cell (INJ, MW1, MW2, MW4, MW5, MW6, MW7)					
Start	3794	672	1	3	5
Finish	93	605	32	171	176
Outside (MW9)					
Start	49	17	0	0	0
Finish	37	64	0	0	0

Soil Vapor Monitoring

Concentrations of TCE, DCE, VC, ethene, ethane, and acetylene were measured in soil gas samples collected from the unsaturated filter pack sand above the well screen intervals in ZVI-MW2 through –MW7. However, as discussed in Truex et al. (2011), soil gas data were not used in the analysis because pre-test vapor-phase TCE and DCE concentrations were an average of 69 and 15 times higher, respectively, in these vapor samples than vapor concentrations calculated based on the measured groundwater concentration and equilibrium partitioning by Henry's Law. These data indicated the presence of significant vadose zone contamination above the test cell that would be an interference in directly measuring volatilization of contaminants from the groundwater. In addition to this initial interference for data interpretation, heating during Phase 3 was expected to impact this vadose zone source through enhanced volatilization, but quantification of this heating impact on soil gas concentrations is difficult and impose additional problems for use of the soil gas data to quantify volatilization from the groundwater. For these reasons, the soil gas data were not used in the mass-discharge analysis presented in Section 6. The soil gas data are presented in **Appendix E**, but not used further.

Soil Monitoring

Soil concentrations of TCE, DCE, and VC were measured before ZVI treatment, at the end of Phase 2 ambient treatment, and at the end of the test after Phase 3 heated treatment. **Figure 5-47** shows the TCE soil concentrations. DCE and VC soil concentrations were much lower than the TCE concentrations and are presented only in **Appendix E**. Soil TCE concentrations at the injection well averaged over 100 mg/kg compared to average concentrations of about 2.5 and 1.5 mg/kg at ZVI-MW1 and -MW2, respectively. Moderate decreases in average soil TCE concentrations were observed at ZVI-MW1 and ZVI-MW2 at the end of Phase 2, ambient

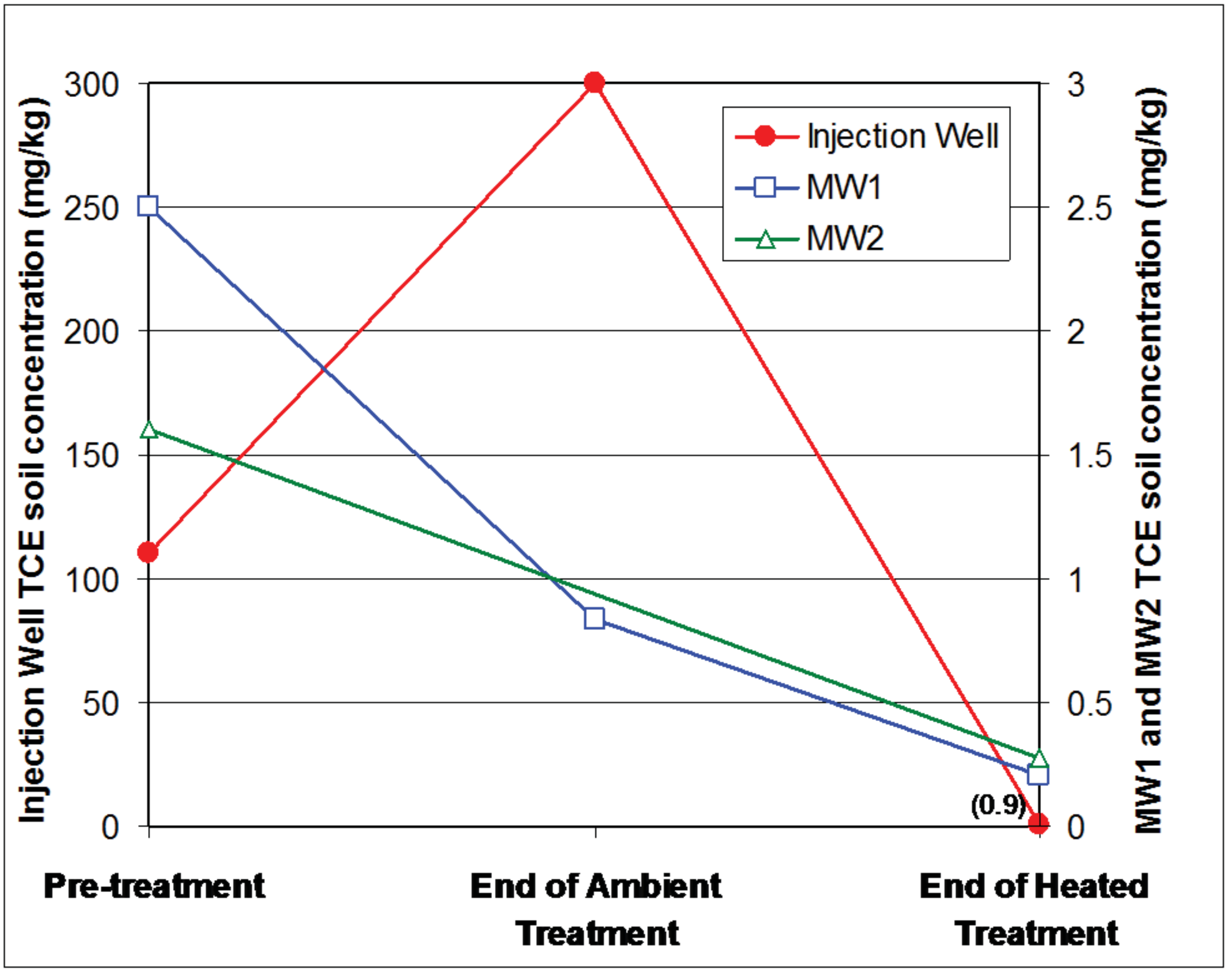


Figure 5-47. Soil concentrations of TCE, DCE, and VC measured before ZVI treatment and at the end of Phase 2, and Phase 3.

temperature treatment. Conversely, the average soil TCE concentration remained high with an average of about 300 mg/kg. By the end of the test, soil TCE concentrations were low at all locations dropping to below 1 mg/kg at the injection well. These data suggest that significant treatment of TCE contaminant mass occurred during the test. Other test data suggest that substantial TCE mass reduction occurred by day 120 of the treatment. The amount of mass reduction due to volatilization rather than reaction is difficult to quantify due to the lower data density after day 150. However, in all of these data, the TCE groundwater concentrations were lower than the concentrations of dechlorination products, suggesting that volatilization of TCE was low compared to dissolution and reaction.

Microbial Community

Molecular probe data were collected to evaluate the role of microbial reductive dechlorination during the test, in particular with respect to dechlorination DCE to ethane. These data are useful in helping evaluate whether the ethene and ethane observed can be attributed to beta elimination or to microbial reductive dechlorination. Microbial reductive dechlorination is a possible mechanism for production of ethane/ethane during the test, though unlikely due to low observed VC concentrations. Molecular DNA data targeting *Dehalococcoides*, the bacteria that converts DCE to ethene, remained at low levels during the test, generally below the threshold concentration of 10^6 gene copy L^{-1} to observe significant complete biotic dechlorination in JBLM groundwater (Macbeth and Sorenson 2011), confirming biotic DCE degradation was limited (**Figure 5-48**).

5.7.4 Phase 3: Low-Energy ERH

Power and Energy

During Phase-3 of operations energy input for the ZVI and ISB test cells were 60,038 kWh and 33,330kWh respectively; totaling 93,368 kWh for the entire project. Total energy input for the entire project was less than the design target of 113,00kWh due to lower than expected heat loss from each test cell. Initial power application to the ZVI test cell was started on June 17, 2009 with initial power application to the ISB test cell starting on September 26, 2009; power application was ceased to both treatment regions on March 22, 2010. **Figures 5-49** and **Figure 5-50** summarize the total cumulative energy input to both the ZVI and ISB test cells.

Unlike traditional ERH operations where power is consistently applied until the project objectives are met, low temperature heating requires an initial power application to bring the treatment volume to the desired temperature range and then power application is reduced either through cycling power application on and off or by reducing the direct power being applied from the PCU.

During initial heat up of the ZVI test cell daily power application rates averaged 30kW with weekly energy application peaking at 4,333kWh during week three of operations. After initial heat up, daily power application rates averaged 20-25kW to maintain temperatures within the ZVI test cell. Prior to complete removal of power application to both test cells at the end of Phase 3 operations, power was reapplied to the ZVI test cell at an increased rate the week of February 8, 2010 to bring the test cell back up to the desired temperature range. Although Phase3

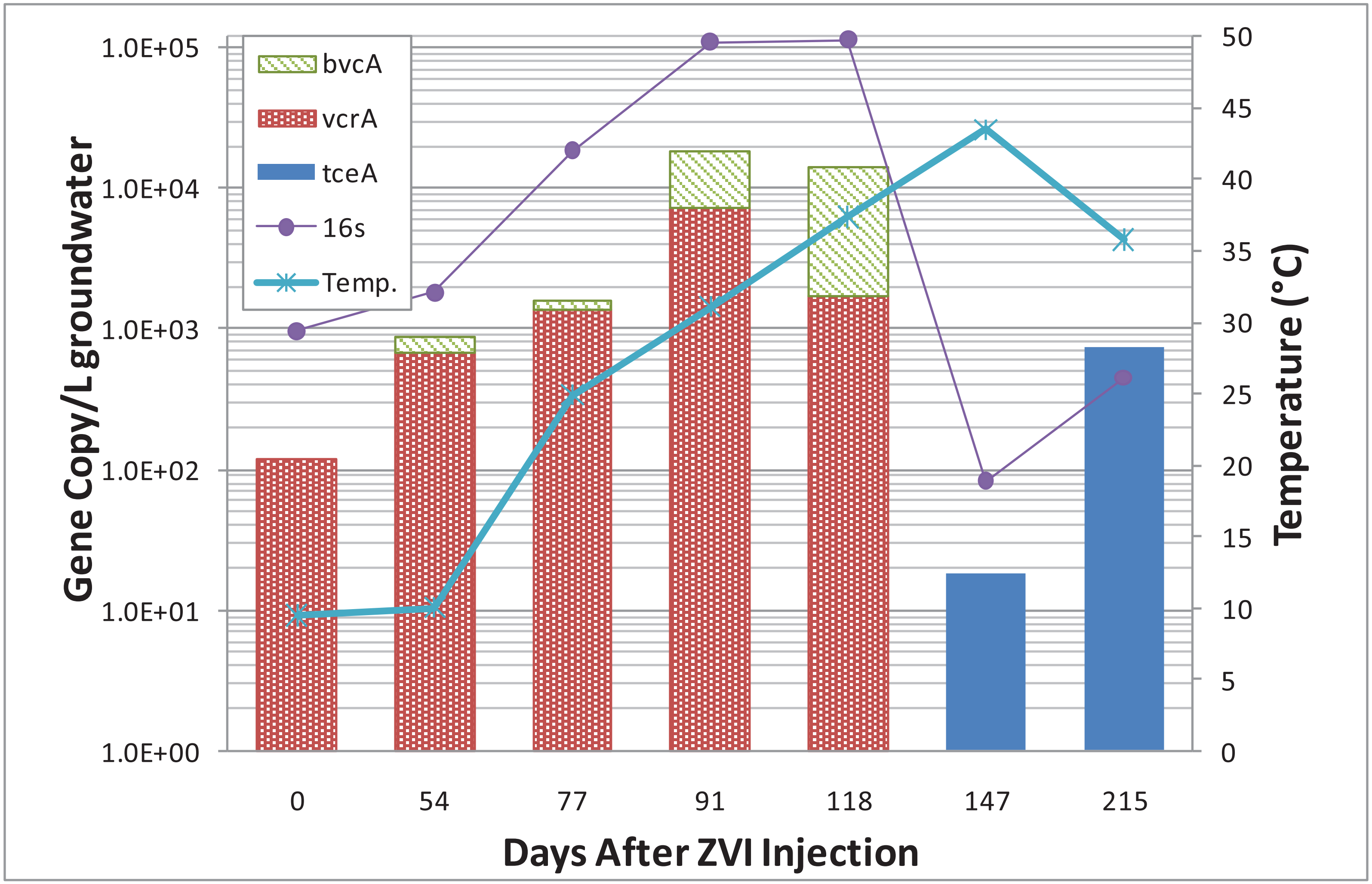


Figure 5-48. Microbial data during ZVI field test for functional genes (bvcA, vcrA, tceA), and 16S RNA gene copies (16s) as a function of temperature.

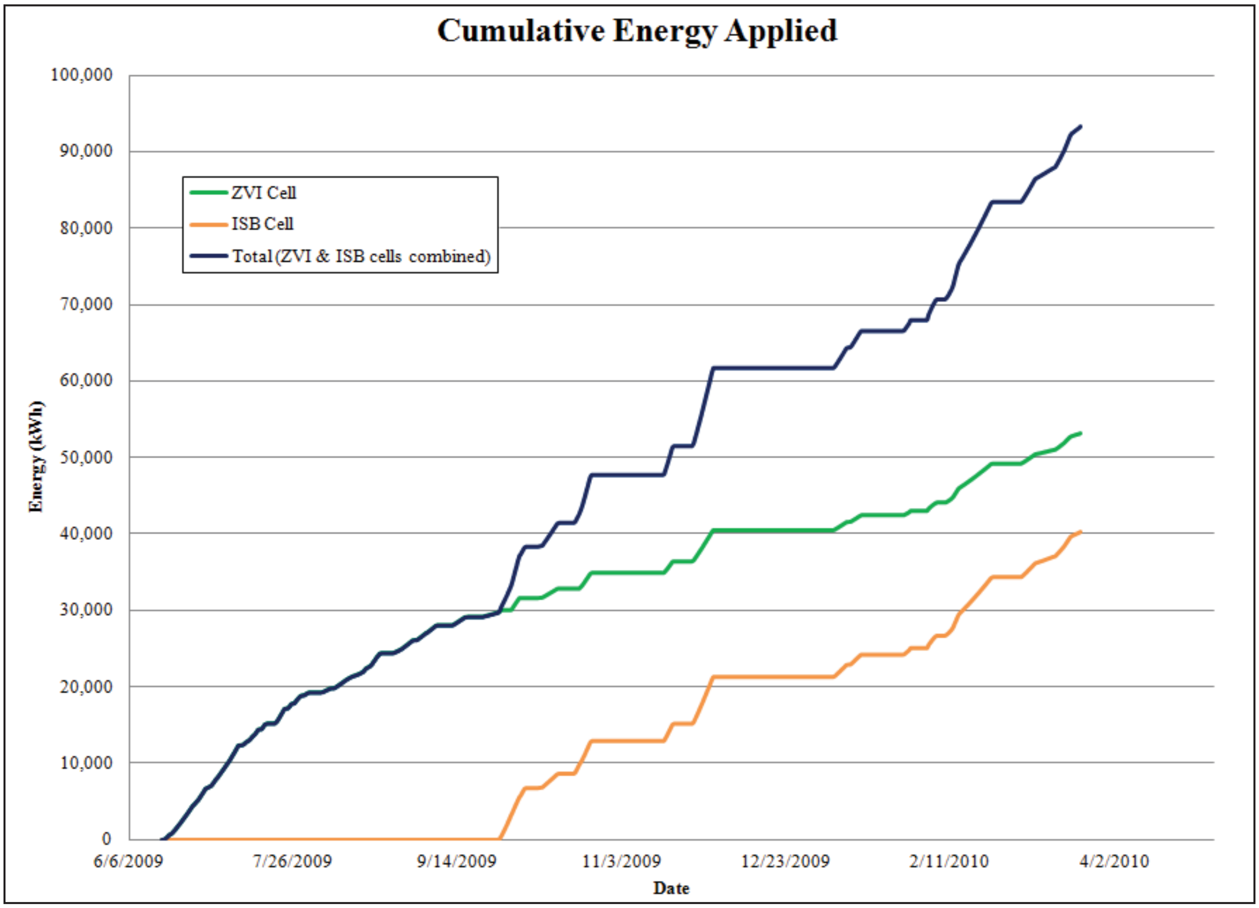


Figure 5-49. Cumulative Energy Applied to the ZVI and ISB Test Cells

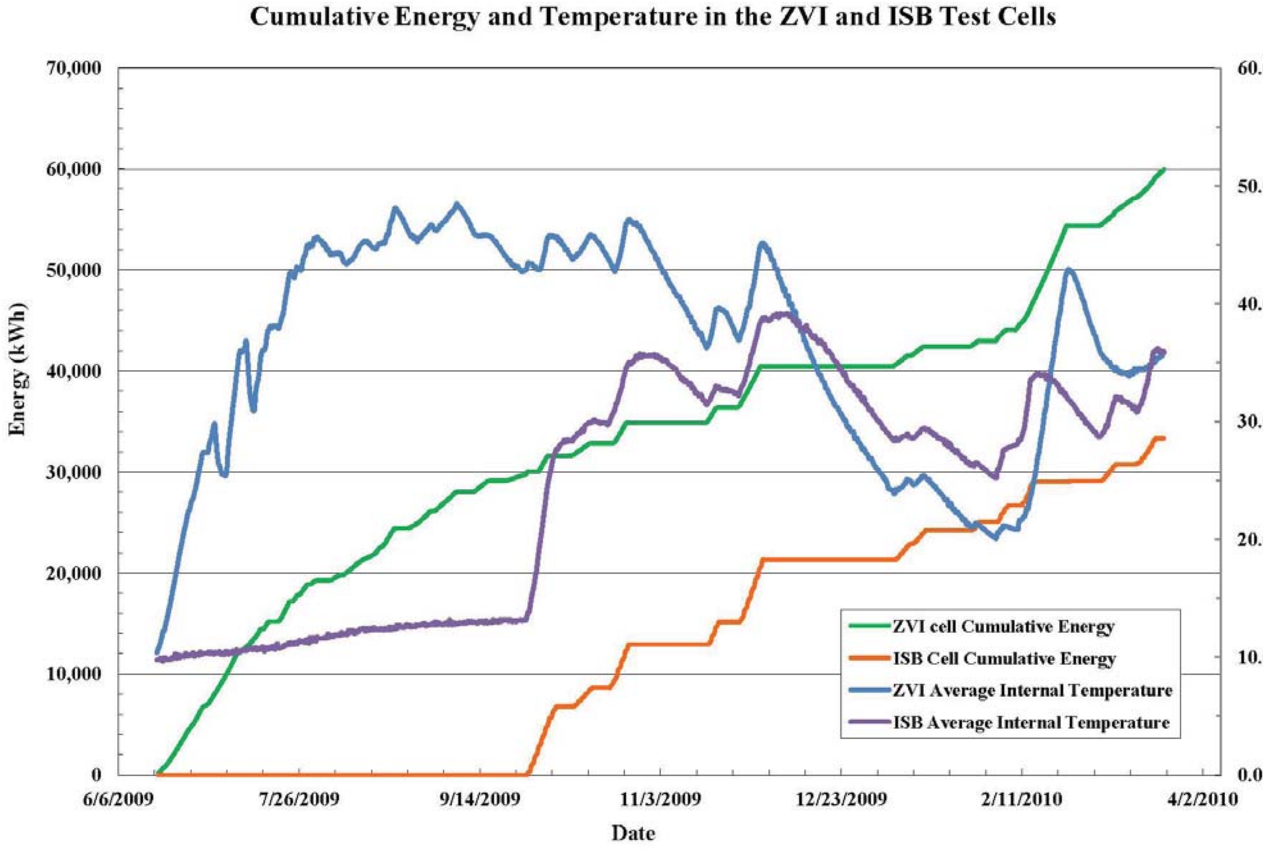


Figure 5-50. Cumulative Energy and Temperature in ZVI and ISB Test Cells.

operations were complete for the ZVI treatment region at that time, temperatures were increased to provide additional polishing within the test cell.

During initial heat up of the ISB test cell daily power application rates averaged 35-40kW with weekly energy application peaking at 3,775kWh during week two of operations. After initial heat up, daily power application rates averaged around 30kW to maintain temperatures within the ISB test cell. During week ten of ISB Phase 3 operations an increased rate of power was applied to the ISB treatment region to increase temperatures from the lower range of the desired temperature range back up to the top; power remained off for the following four weeks while temperatures drifted slowly down through the desired temperature range

Figure 5-51 and **Figure 5-52** summarize the weekly energy application rates for the individual ZVI and ISB test cells respectively.

Temperature

On June 16, 2009, at the start of Phase 3 heating, the average ambient subsurface temperature was 10°C in both the ZVI and ISB test cells.

Heating in the ZVI test cell was initiated at the beginning of Phase 3 and by July 21, 2009 the average temperatures in all treatment region TMPs had reached the lower limit of the desired temperature range (40-50°C) for the first time. During this period, the average subsurface temperature increased at a rate of 1°C per day. This average subsurface heat-up rate was increased at a rate to achieve project objectives in a timely manner but slow enough to avoid the creation of steam and volatilization of subsurface components with the treatment region.

The ZVI test cell average subsurface temperature remained in the desired temperature range for the next 110 days of operation until dipping slightly below the desired range for a period of 20 days, reaching a low of 36°C for a period of eight hours. Power was then increased to bring the average temperature back into the desired range for the final 10 days of the official end of Phase 3 operations within the ZVI test cell. Prior to disconnecting the electrodes and final demobilization of the ERH equipment from the ER-0719 site, power was reapplied to the ZVI test cell for additional polishing while the ISB test cell completed its Phase 3 operations.

Observed temperatures in the down-gradient external ZVI test cell TMP locations parallel trends normally observed at ERH sites where no hydraulic control exists. The upgradient TMP for the ZVI test cell, ZVI-MW9, displays slightly elevated temperatures associated with its close proximity to the treatment region and a treatment region electrode. Temperatures at ZVI-MW9 drop below observed downgradient TMP temperatures only after the official Phase-3 heating is completed in the ZVI test cell.

Average internal and external ZVI test cell temperatures are shown below in **Figure 5-53** and **Figure 5-54** respectively.

Heating of the ISB test cell was initiated on September 26, 2009. Over the first week of Phase 3 operations in the ISB test cell an unknown subsurface anomaly caused preferential heating near

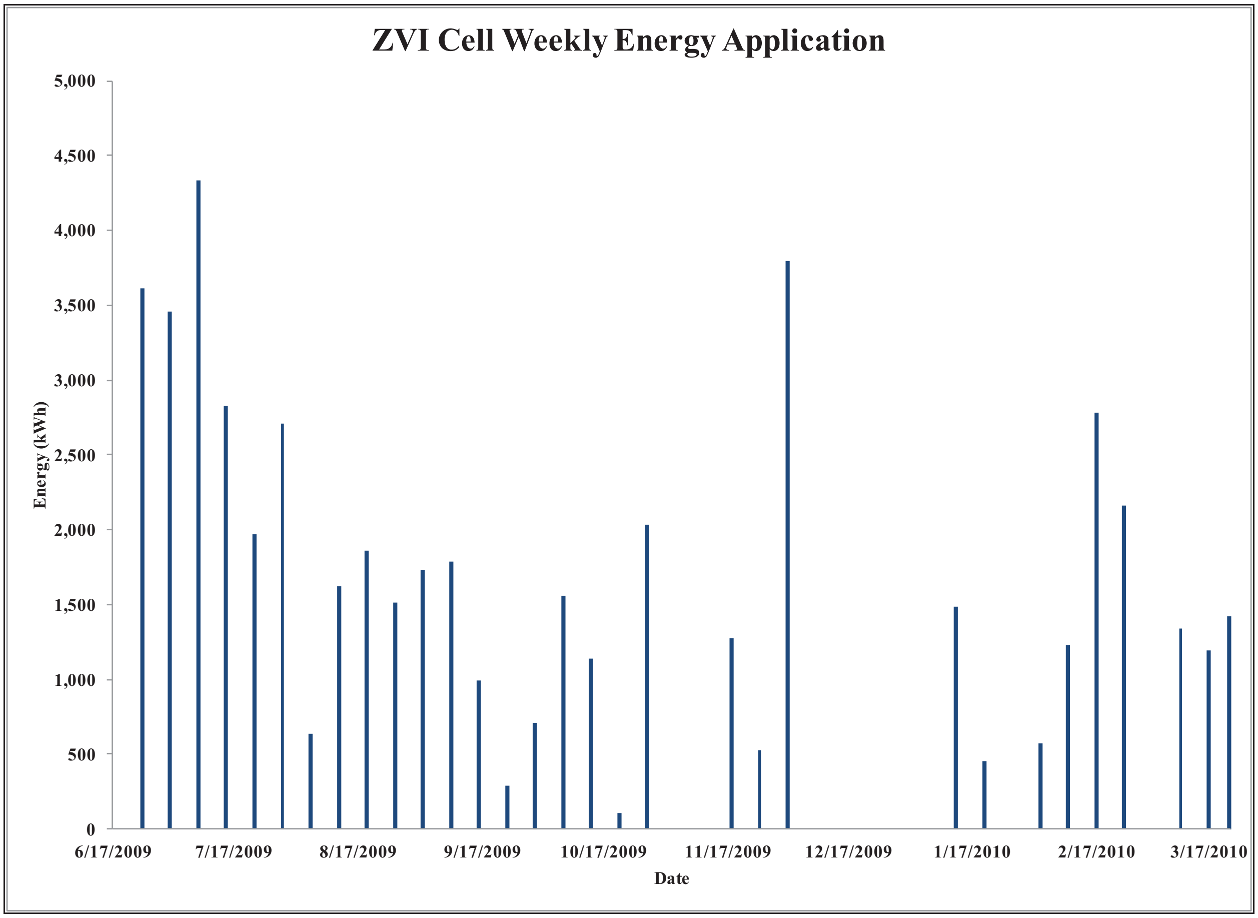


Figure 5-51. Weekly Energy Applied to the ZVI Test Cell.

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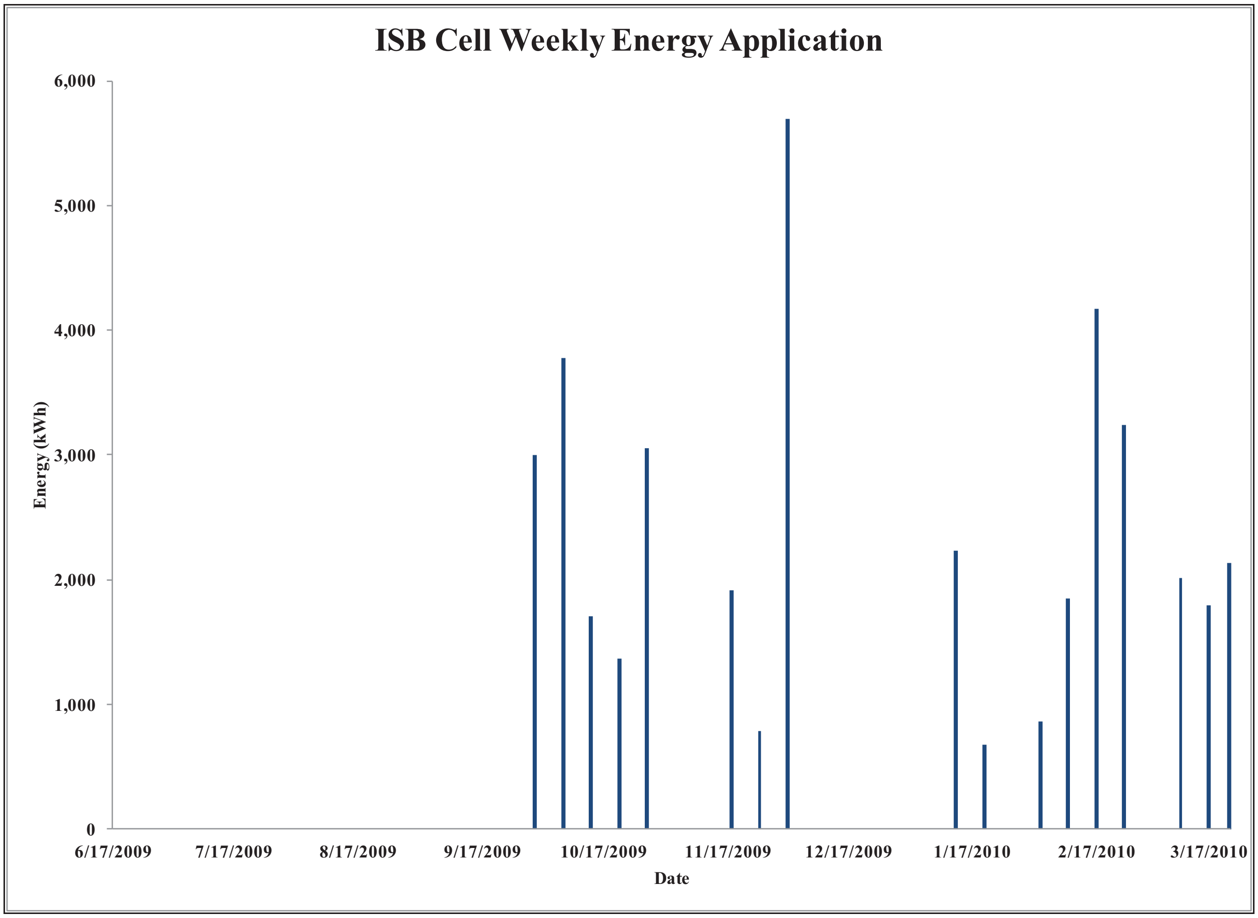


Figure 5-52. Weekly Energy Applied to the ISB Test Cell.

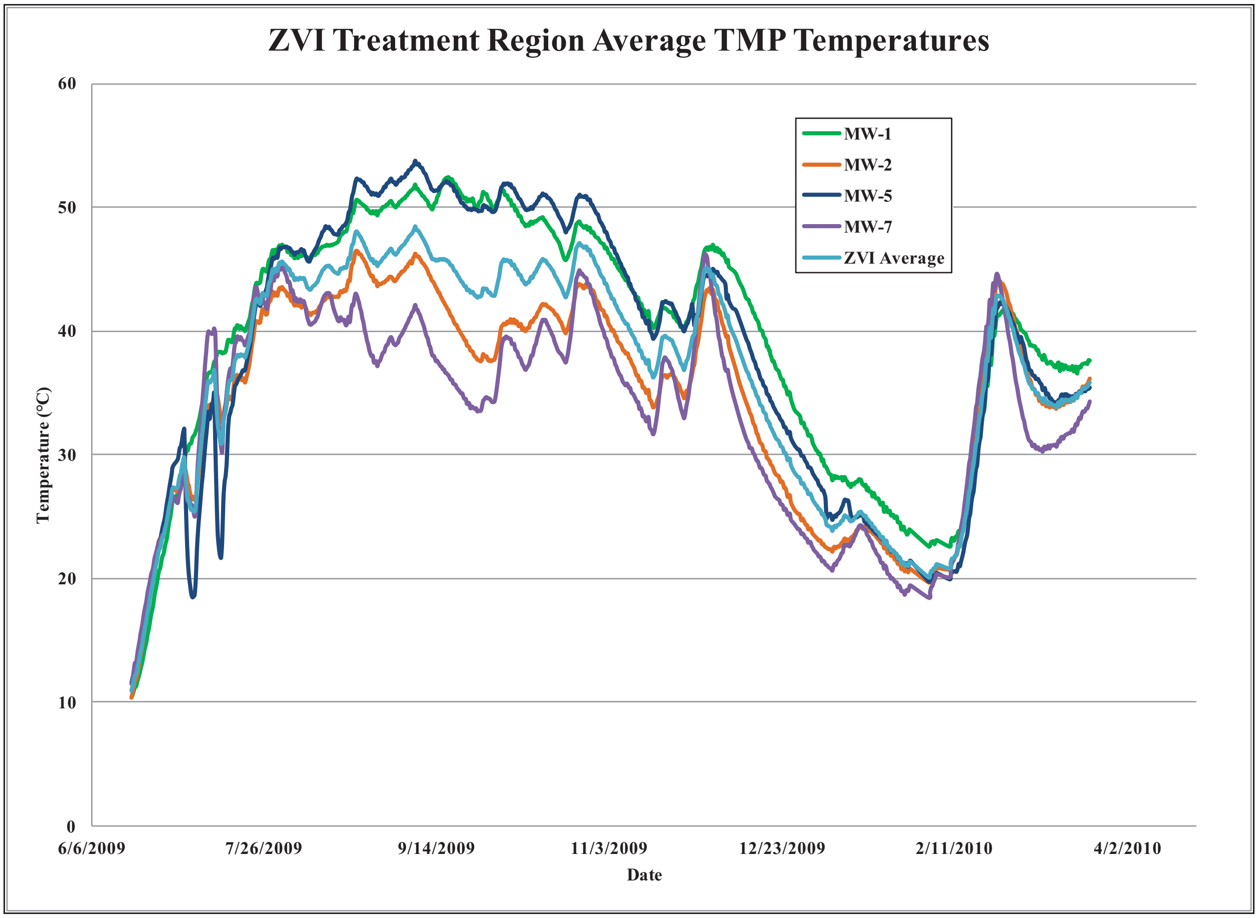


Figure 5-53. Average Internal ZVI Test Cell TMP Temperatures.

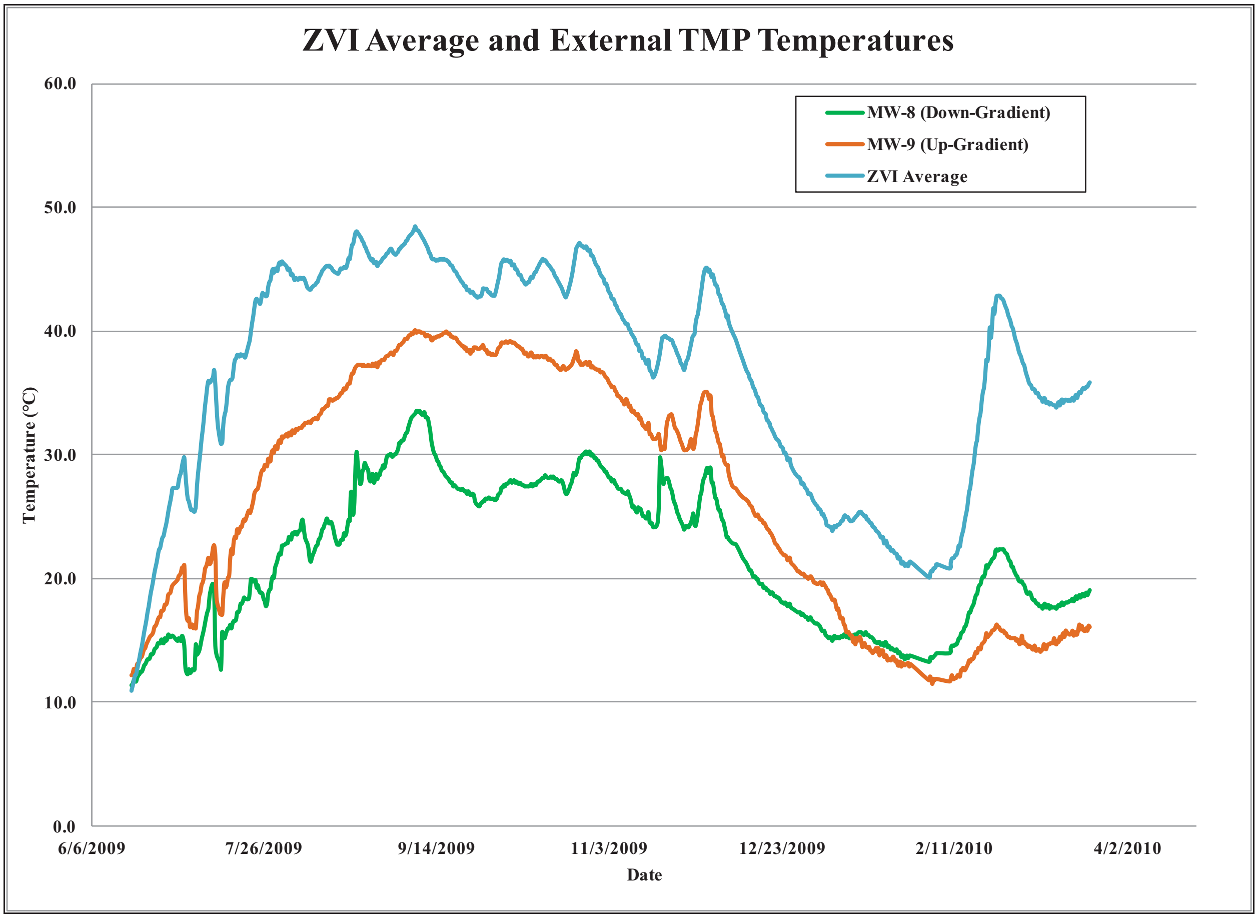


Figure 5-54. Average External ZVI Test Cell TMP Temperatures. 3

ISB-MW3 allowing it to reach 30°C within 5 days of operation. The PCU output configuration was changed immediately, with the electrode nearest the MW disconnected from the array, to address the preferential heating near ISB-MW3 and Phase 3 operations were continued in the ISB test cell.

By October 24, 2009, the average ISB test cell temperature had reached the lower limit of the desired temperature range (30-40°C) for the first time. During this period, the average subsurface temperature increased at a rate of 0.7°C per day. The ISB average subsurface heat-up rate was also increased at a rate to achieve project objectives in a timely manner but slow enough to avoid the volatilization of subsurface components with the treatment region.

The average subsurface temperatures in ISB-MW1 and ISB-MW2 remained in the desired temperature range for the next 154 days of operation until the end of Phase-3 operations on March 22, 2010.

Observed temperatures in the down-gradient external ISB TMP locations also parallel trends normally observed at ERH sites where no hydraulic control exists. The upgradient TMP for the ISB test cell, ISB-INJ, displays wide shifts of temperature that are associated with the injections performed within the ISB test cell at ISB-INJ. The temperature of the injected solution either increased the observed subsurface temperature during summer months or decreased the observed temperature during winter months due to storage in above grade ambient temperatures.

Internal and external ISB test cell average temperatures are shown in **Figure 5-55 and Figure 5-56** respectively.

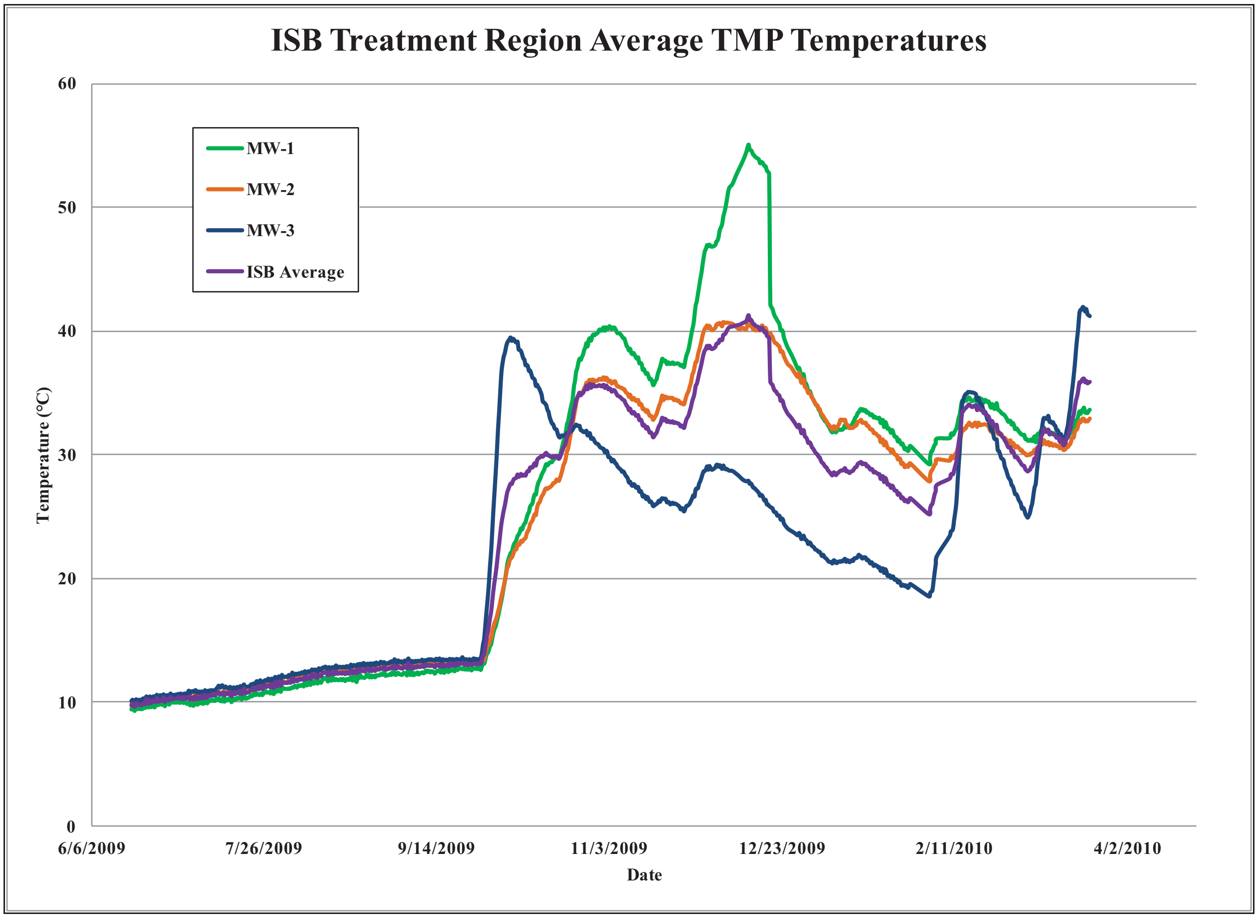


Figure 5-55. Average Internal ISB Test Cell TMP Temperatures. 4

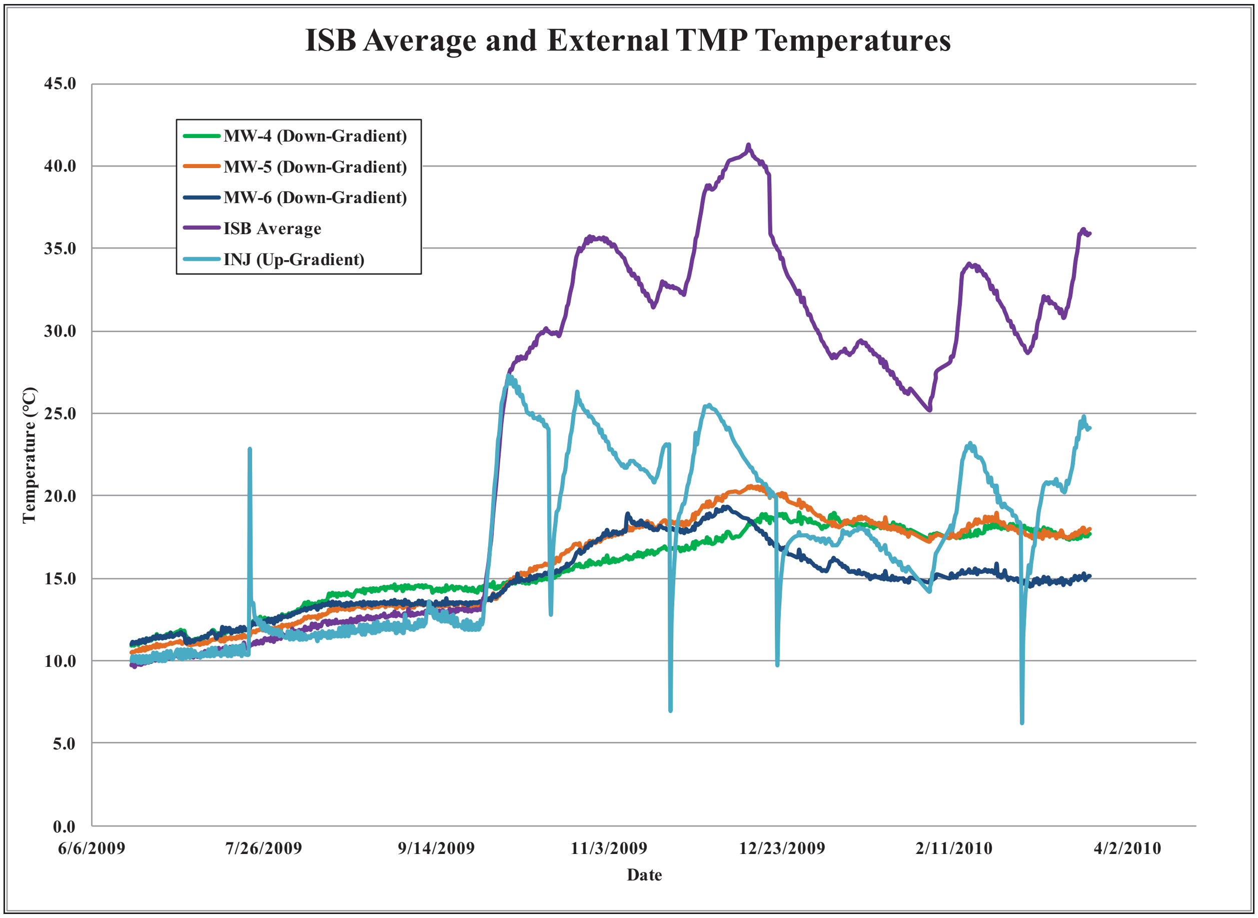


Figure 5-56. Average External ISB Test Cell TMP Temperatures. 5

SECTION 6
PERFORMANCE ASSESSMENT

Performance of the demonstration project was evaluated by conducted a mass balance assessment using a mass discharge approach in the test cells. However, how the approach applied varied due to the system configurations and results of each of the ISB and ZVI demonstrations. A mass discharge analysis was developed and applied to quantify the treatment zone processes using the data from MWs and considering the rate of groundwater flow through the treatment zone (e.g., **Figure 6-1**). The mass discharge analysis computes rates of the multiple processes in the treatment zone by comparing the inflow and outflow discharge rates for either the entire test cell (as for the ISB demonstration) or for a defined segments for the ZVI test cell. Because the treatment zone is a contaminant source area and upgradient water is relatively uncontaminated, dissolution from DNAPL or sediment-associated TCE is the main mechanism adding contamination to groundwater. Treatment performance in terms of reducing the contaminant source is a function of the relative rates of 1) contaminant dissolution to the groundwater, 2) migration out of the treatment zone due to advection or volatilization, and 3) contaminant degradation. In the field, constituent concentrations from MWs are the primary data available to quantify these processes.

The first step of the analysis was to compute the influent and effluent discharges from either the ISB test cell or the ZVI test cell segments. For the analysis, mass is represented as moles so that stoichiometric relations of different groundwater constituents can be considered. The influent mass discharge of constituents was estimated from Equation 1.

$$MD_{in}\left[mmol\cdot d^{-1}\right]=C_{upgradient}Q \qquad \text{(Equation 1)}$$

The effluent mass discharge in the water phase was estimated from Equation 2.

$$MD_{out-w}\left[mmol\cdot d^{-1}\right]=C_{w}Q \qquad \text{(Equation 2)}$$

The net contaminant dissolution rate Nd was estimated using Equation 3.

$$MD_{Dissolution}=\left(MD_{out-w}+MD_{out-v}\right)_{TCE+products}-MD_{in-TCE+products} \qquad \text{(Equation 3)}$$

The net TCE dissolution rate Nd was estimated using Equation 4.

$$Nd=\left(MD_{out-w}+MD_{out-v}\right)_{TCE}-MD_{in-TCE} \qquad \text{(Equation 4)}$$

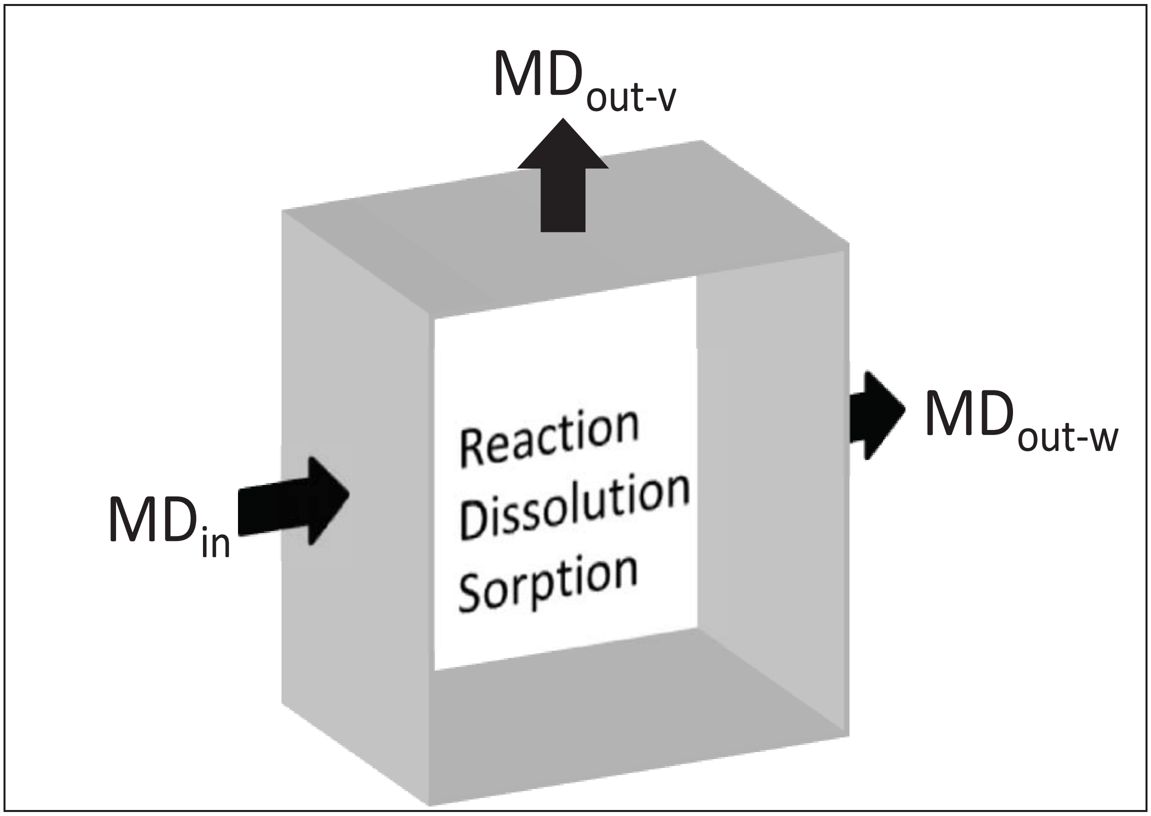


Figure 6-1. Mass-discharge analysis configuration where MDin is the influent mass discharge and MDout-w and MDout-v are the effluent mass discharge in the water and vapor phases, respectively (Truex et al. 2011).

Dechlorination reaction rates, R (mmol d-1), were estimated two methods, evaluating reductive daughter product concentrations using Equation 5 and evaluating chloride data using Equation 6.

$$R = \left(MD_{out-w} + MD_{out-v}\right)_{products} - MD_{in-products} \qquad \text{(Equation 5)}$$

$$R_{tc} = MD_{out-w-chloride} - MD_{in-chloride} \qquad \text{(Equation 6)}$$

With respect to the processes shown in **Figure 6-1**, sorption of dechlorination products to sediments is low at the site (Truex et al. 2006) and was not included in the analysis. Initial sediment concentrations of DCE were one to two orders of magnitude lower than TCE sediment concentrations and VC, ethene, and ethane were not detected. Thus, dissolution of TCE as a contamination source was the only dissolution process included in the analysis. The specifics of how these concepts were applied for each of the ISB and ZVI test cells is provided below.

6.1 Mass Balance Factors ISB

6.1.1 ISB Enhanced Mass Transfer

A mass balance evaluation of the ISB test cell was conducted quantify changes in 1) contaminant dissolution from the residual contaminant mass to groundwater, 2) migration out of the treatment zone due to advection or volatilization, and 3) contaminant degradation using the mass discharge approach. Comparisons were largely made from the ISB test cell as operations transitioned from Phase 2, ambient temperature ISB to Phase 3, moderate-heating ISB. For purposes of the mass balance evaluation, the last three timepoints during Phase 2 were used in the evaluation because reductive dechlorination had been established with conversion from TCE to DCE the predominant pathway. Conceptually, the approach was to quantify a mass balance as shown in **Figure 6-1** and Equations 1-4.

Contaminant concentrations outside the ISB heated zone were 2-4 orders of magnitude lower than within the test cell. Therefore, it was assumed that mass discharge into the test cell (MD_{in}) was negligible. In addition, the total mass discharge based on **Figure 6-1** and Equations 3 and 4 also account for mass leaving the test cell in soil gas. **Table 6-1** presents the total mass discharge in the groundwater (MD_{out-w}) across the ISB-MW2 and –MW1 transect and in soil gas across the entire heated zone area (MD_{out-v}) for two timepoints in Phase 2 and two in Phase 3. As shown, the contribution of MD_{out-v} represented by soil gas in both Phase 2 and Phase 3 ranged from 0.02-1.45% of the total. Therefore, the contaminant mass discharge modeled using MVS across transect ISB-MW1 and ISB-MW2 was used to evaluate enhanced dissolution ($MD_{dissolution}$) and reaction kinetics, and MD_{out} represented by soil gas was negligible and not included in the analysis.

Table 6-1. Comparison of mass discharge from the ISB test cell in groundwater and in soil gas.

			Vapor Discharge[a] (MD_{out-v})			Groundwater Discharge (MD_{out-w})			Total Discharge		
Date	**Days**	**Phase**	**TCE (g/d)**	**cDCE (g/d)**	**VC (g/d)**	**TCE**	**cDCE**	**VC**	**TCE**	**cDCE**	**VC**
July 2, 2009	147	2	0.03	0.06	0.00	29.72	297.91	1.32	29.75	297.97	1.32
August 26, 2009	193	2	0.04	0.06	0.00	11.99	102.48	0.80	12.04	102.54	0.80
November 18, 2009	286	3	1.25	0.49	0.13	86.54	271.37	21.03	87.79	271.86	21.17
December 18, 2009	314	3	2.58	0.52	0.09	252.13	398.53	31.71	254.71	399.06	31.79

[a] Average vapor flux calculated by averaging flux for MW1, MW2, MW3 and multiplying by test cell area.

To calculate mass flux and mass discharge, hydraulic conductivity data and groundwater elevation data were input into the 3D MVS software to establish a 3D groundwater flow field for three timepoints during Phase 2 (days 92, 147 and 193) and six timepoints during Phase 3 (days 251, 286, 314, 355, 384, 411). The average horizontal hydraulic conductivity measured at ISB-MW1 and ISB-MW2 for each of three depth intervals (approximately 12, 17 and 22 ft bgs) was used (**Table 5-7**). The vertical hydraulic conductivity was set at half the magnitude of the horizontal hydraulic conductivity. Groundwater elevation and contaminant concentrations measured at each timepoint were then input into the model and kriged in three dimensions. Groundwater contaminant mass flux was then calculated in three dimensions and a transect set through ISB-MW2 and -MW1 was used to evaluate mass discharge by integrating the mass flux values over the transect area (approximately 16 ft wide by 21 ft deep). This was used to develop the estimates for MD_{out} for total VOCs (TCE + products), reductive daughter products (DCE, VC, ethene) and chloride.

The total VOCs dissolution rate ($MD_{dissolution}$), reaction rate using daughter products (R) and reaction rates using chloride (R_{tc}) over the course of the demonstration, shown in **Figure 5-24** and **Table 5-20,** was plotted as a function of temperature (**Figure 6-2**). These data indicate a positive correlation for $MD_{dissolution}$ ($R^2 = 0.53$), R ($R^2=0.45$) and Rtc ($R^2=0.60$) as a function of temperature from the test cell.

The $MD_{dissolution}$ due to heating in Phase 3 was evaluated by comparing MD_{out} of total VOCs as a function of temperature. For this analysis, the influent MD_{in} and vapor $MD_{in\text{-}vapor}$ were assumed negligible. Based on the correlation in **Figure 6-2**, the total VOC dissolution increases by a factor of 4.6, or an increase from 177 g VOC as TCE/d to 812 g VOC as TCE/d when temperatures are increased from 10°C to 40°C. The increase is largely attributed to enhanced mass transfer due to the elevated temperature as opposed to reductive dechlorination reactions (i.e. enhancing the concentration gradient due to removal parent compounds and formation of daughter products) because the comparison was made between Phase 2, where dechlorination reactions had already been established at ambient temperatures and Phase 3.This is in good agreement with Imhoff et al 1997, which described the enhanced dissolution of TCE DNAPLs during hot water flushing. In this work the aqueous phase mass transfer coefficient, Ka, was developed experimentally and results applied to empirical model. Increasing temperatures from 10°C to 35°C increased in Ka by a factor of 2 and by 3 when temperatures increased to 55°C. These data suggest that significant enhanced dissolution occurs within areas containing DNAPLs at elevated temperatures.

6.1.2 ISB Impact of Elevated Temperature on Kinetics

To evaluate the impact of heating on treatment rates of TCE, the rate (R) was evaluated using Equations 4 and 5. First the reaction rate was estimated using reductive daughter products where MD_{out} of reductive daughter products was evaluated and used as the reaction rate, R (mmol/d). For this analysis, the influent MD_{in} and vapor $MD_{in\text{-}vapor}$ were assumed negligible. Based on the correlation developed in **Figure 6-2**, the R estimated increased by a factor of 3.6 when you

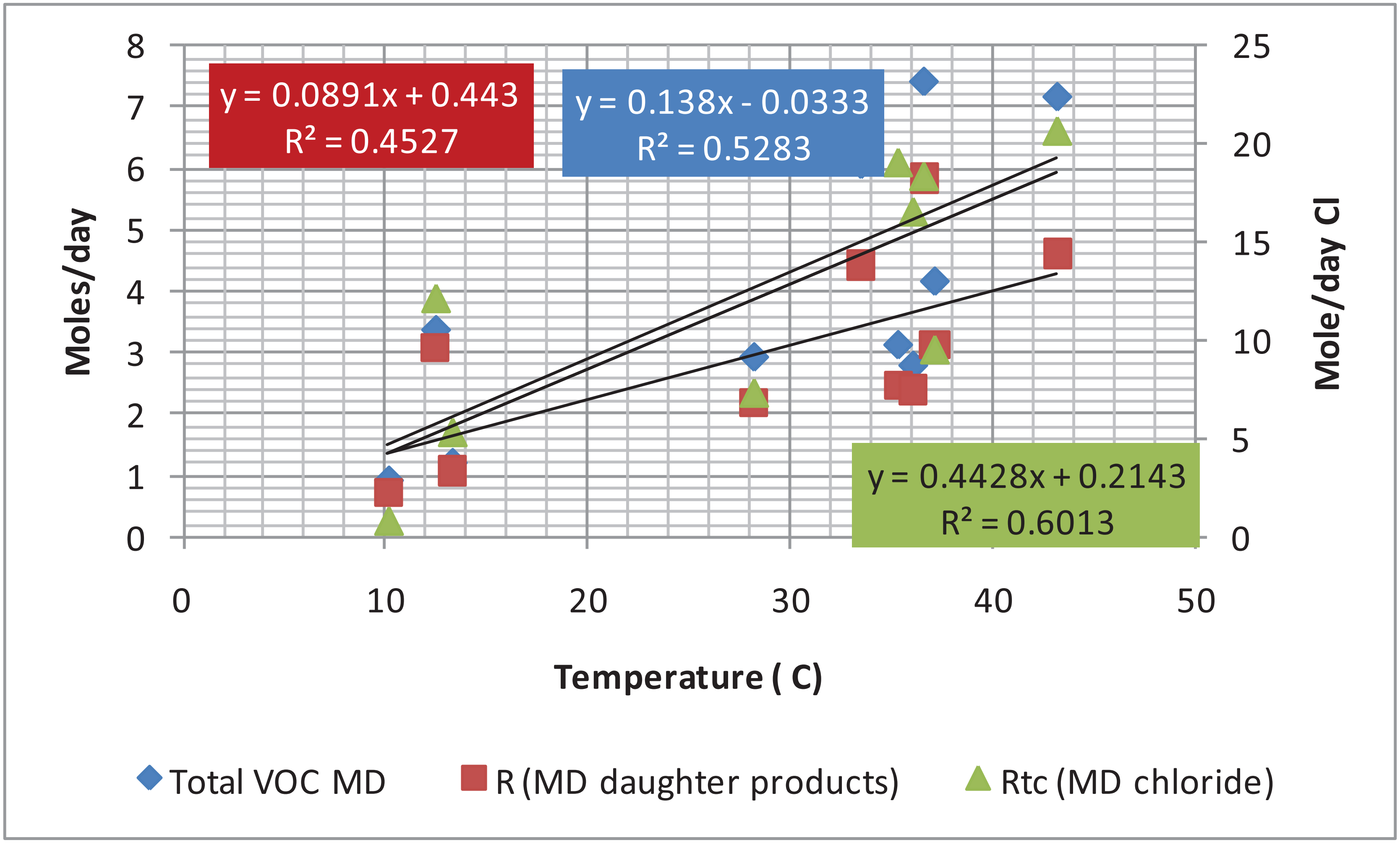


Figure 6-2. Linear correlation between $MD_{dissolution}$, R, and Rtc as a function of temperature.

increase temperatures from 10ºC to 40ºC or increase from 175g TCE treated/day to 585 g TCE treated/d.

Similarly, the rate of mass discharge of treated TCE can also be evaluated using chloride and Equation 5. The R_{tc} estimated using $(MD_{out})_{chloride}$ increased by a factor of 5.3 when you increase temperatures from 10ºC to 40ºC which corresponded to an increase from 337 to 1789 g TCE treated/d. The difference in these values is likely due to that fact that chloride is more conserved than the reductive daughter products especially compared to VC and ethene, which are lost to volatilization and biological oxidation. These are generally in good agreement with the Arrhenius equation, which suggests that the rate of reaction generally doubles for every 10ºC increase in temperature, this would correspond to a factor of 8 increase in rate of reaction at 40ºC compared to 10ºC. However, a direct assessment of kinetics cannot be established due to the increased flux of contaminants dissolved from the residual phase. The reaction rate R and R_{tc} is the total reaction rate resulting from both enhanced mass transfer and dechlorination reactions.

In order to assess the relative significance of enhanced mass transfer and dechlorination reactions an evaluation was conducted to quantify the relative mass discharge rates of TCE compared to total VOCs and reductive daughter products. An objective of the demonstration was to ensure that *in situ* dechlorination could treat TCE dissolved from the residual phase due to elevated temperatures and account for losses due to from volatilization or dissolution and advection. Therefore, mass discharge analysis included quantification the amount of TCE released from sediment- or NAPL-associated TCE (Nd from Equation 4) into the groundwater compared to the rate of the ISB reactions to transform the TCE. The proportion of Nd following Phase 2 activities that TCE represented was approximately 12 g TCE/d of the 625 g total VOC as TCE/d (accounting for approximately 2% of the total contaminant mass discharge). This suggests that the transformation rate was fast enough to dechlorinate TCE to reductive daughter products at the ISB-MW1 and MW-2 boundary.

During heating (Phase 3), the TCE mass discharge, Nd, increased reaching a maximum in December (day 314) with 252 g TCE /d of the total 943 g VOC as TCE/d (accounting for approximately 27% of the mass). This indicates that at the ISB-MW1 and-MW2 boundary that TCE was being discharged, although treatment rates were degrading nearly 75% of the mass. However, the ISB-MW1 and –MW2 boundary was within the DNAPL zone, especially at ISB-MW2. Therefore, the analysis was expanded to evaluate contaminant flux to areas downgradient of the test cell. The ISB treatment area was much larger than the heated treatment zone due to transport of carbon downgradient of the test cell. Transport of TCE and reductive daughter products was evaluated in three downgradient MWs ISB-MW4, -MW5 and -MW6. Of these, ISB-MW4 was the most impacted location due to its proximity downgradient of ISB-MW2. Following the onset of heating, an initial slug of DCE was observed at this location, with very low TCE concentrations (see **Figure 5-22B**). During the December, 2009 (day 314) and January, 2009 (day 355) sampling events, the TCE (93 and 20 ug/L), DCE (65 and 340 ug/L) were much lower than observed at ISB-MW2, suggesting attenuation was occurring along the flowpath. In addition, the proportion of VC also dramatically increased with time. These data suggest that although TCE was mobilized, that it could be mitigated, and treated, by creating a sufficiently large treatment area downgradient of the source zone to ensure treatment of mobilized TCE.

6.2 Mass Balance Factors ZVI

6.2.1 ZVI Mass Transfer

A mass balance/mass discharge analysis was applied to evaluate TCE dechlorination, dissolution, advection, and volatilization in the ZVI test cell. The analysis was designed to account for the ZVI distribution and hydraulic conditions in the test cell. Key considerations are described below.

ZVI mass in the test cell was highest surrounding the injection well (Truex et al. 2010). The ZVI test cell was centered on a high TCE contamination zone surrounded by groundwater at much lower TCE concentrations. Additionally, ZVI was distributed to the test cell using SlurryPro™, a shear-thinning fluid, which when static has a high viscosity (Truex et al. 2010). Data suggest that the groundwater flow rate through the ZVI test cell was much slower than the flow rate prior to injection of the ZVI and SlurryPro™, with a nominal post-injection value based on tracer elution of 0.38 m/d (Truex et al. 2010, 2011). While the flow rate could not be evaluated over the course of the test, test data do not suggest a large change in flow rate during the test. If a change were to occur, it would have increased the flow rate over time as the viscosity of the SlurryPro™ decreased due to dispersal or degradation. Thus, comparison of rates between initial Phase 2 ambient temperature operation and Phase 3 heated operations would tend to be conservative and underestimate rates in Phase 3 versus Phase 2 if the groundwater flow rate increased over time.

Based on the above considerations, the mass discharge (moles per time) was estimated for assigned test cell segments through well INJ as shown on **Figure 6-1**. The mass discharge analysis was applied to evaluate dechlorination in this segment along a flow path through the center of the test cell. This segments fall along the nominal flow path of groundwater through the test cell that intersects the zone of highest ZVI concentration (i.e., surrounding the injection well). The longitudinal dimension of the segment was based on the estimated distance to the edge of the ZVI/SlurryPro™ injection. The segment used a unit lateral dimension of 1 m and a thickness equal to the well screen interval (1.5 m).

The mass discharge analysis is presented in Truex et al. 2011 and repeated here. A mass-discharge analysis was developed and applied to quantify the treatment zone processes using the data from MWs and considering the rate of groundwater flow through the treatment zone segments ending at each MW (**Figure 6-3**). The mass-discharge analysis computes rates of the multiple processes in the treatment zone by comparing the inflow and outflow discharge rates for a defined segment as shown in **Figure 6-3**. Because the treatment zone is a contaminant source area and upgradient water is relatively uncontaminated, dissolution from DNAPL or sediment-associated TCE is the main mechanism adding contamination to groundwater. Treatment performance in terms of reducing the contaminant source is a function of the relative rates of 1) contaminant dissolution to the groundwater, 2) contaminant degradation, and 3) migration out of

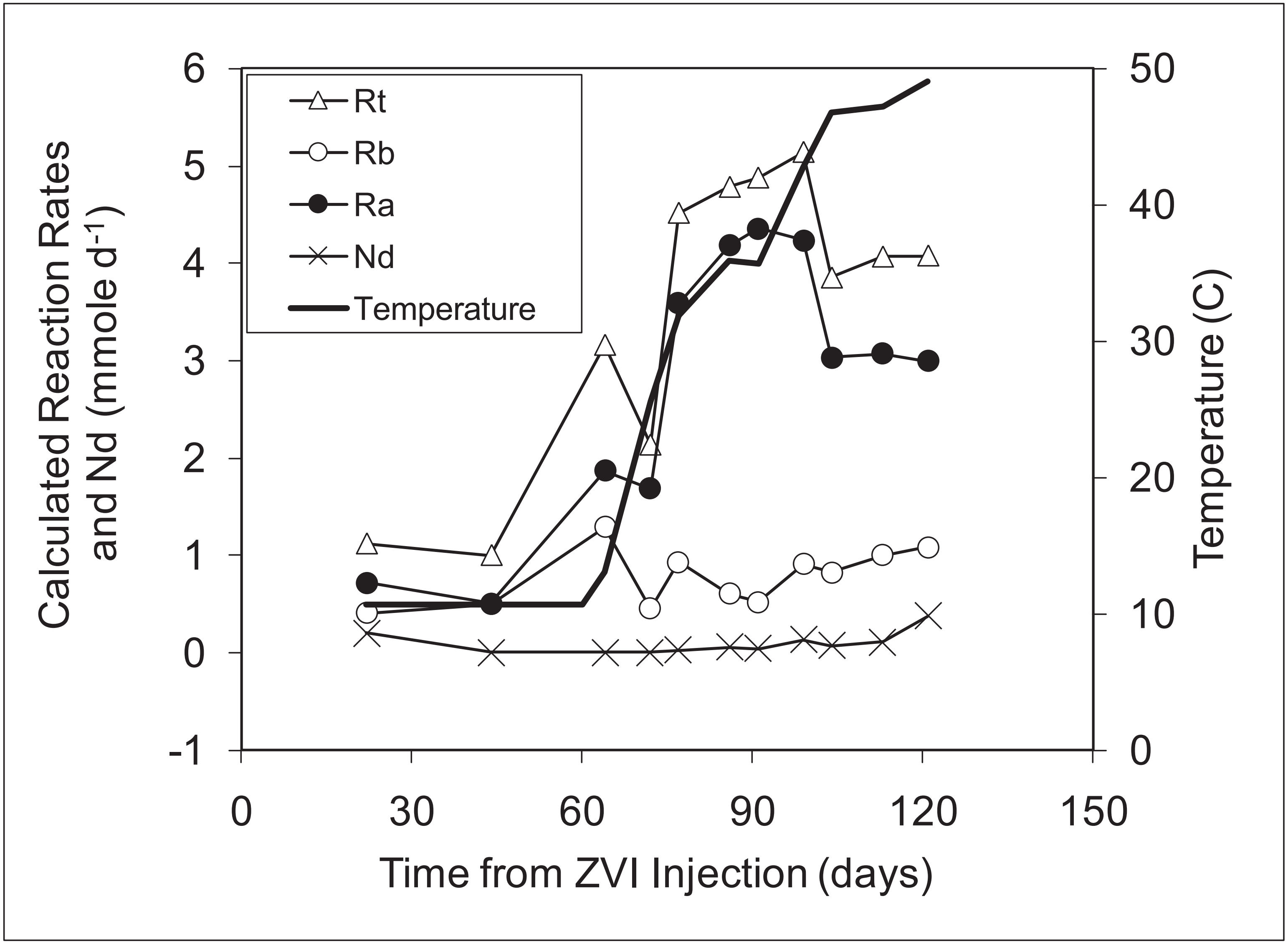


Figure 6-3. Calculated TCE reaction rates and Nd for the INJ segment (Truex etal. 2011).

the treatment zone due to advection or volatilization. In the field, constituent concentrations from MWs are the primary data available to quantify these processes. Additionally, a source area treatment analysis is unlike an analysis for a permeable reactive barrier where the primary goal is reduction of upgradient contaminants as they flow through the treatment zone.

The first step of the analysis was to compute the influent and effluent discharges of the segments. For the analysis, mass is represented as moles so that stoichiometric relations of different groundwater constituents can be considered. The influent mass discharge of constituents to each segment was estimated from Equation 1 where $C_{upgradient}$ [mmol L-1] is the concentration at well ZVI-MW9. Data for well ZVI-MW9 was assumed to represent conditions upgradient of the test cell because the ZVI injection did not reach this well (Truex et al. 2010). A groundwater flow rate, Q, of 103 L/d was calculated from the estimated linear velocity, porosity (0.18), and cross section area of the segments using Darcy's Law and assumed to remain constant. The effluent mass discharge in the water phase was estimated from Equation 2 where Cw [mmol/L] is the concentration at the MWs for the selected segments.

The effluent mass discharge in the vapor phase was estimated from Equation 6.

$$MD_{out-v}\left[mmol \cdot d^{-1}\right] = D_{as} A_v \left(\frac{C_w H}{L_v} \right) \qquad \text{(Equation 6)}$$

The diffusion coefficient for each compound in sediment, Das, was calculated from the individual gas diffusion coefficients (Yaws 2003) ($T=25^{o}C$) using the method of Millington and Quirk (1961), the measured porosity, and moisture content (14.5%[v/v]). The dimensionless Henry's Law coefficient, H, corrected for temperature was calculated for each compound from tabulated vapor pressure (Yaws 2009) and solubility data (Yaws 2009; Mackay et al. 2006) as a function of temperature. The distance from the water table to the ground surface, Lv, was estimated as the average vadose zone thickness of 2.13 m. The surface area for diffusive mass transfer, Av, was based on the distance from the upgradient edge of the treatment zone to the MW with a unit width of 1 m. Soil gas data were not used in the analysis because pre-test vapor-phase TCE and DCE concentrations were an average of 69 and 15 times higher, respectively, in samples from the unsaturated sand pack of wells ZVI-MW2 through -MW7 than vapor concentrations calculated based on the measured groundwater concentration and equilibrium partitioning by Henry's Law. These data indicated the presence of significant vadose zone contamination that would interfere with directly measuring volatilization of TCE and DCE from the groundwater.

The next phase of the analysis relates the segment inflow and outflow of groundwater constituents, computed using Equations 1-3, to the rates of reactions and processes occurring in these segments. This approach enables estimation of the overall TCE dissolution and degradation rates, the amount of TCE released from the source but untreated, and the reaction rates producing specific reaction products as a function of the conditions within the test cell (e.g., temperature). These segment reaction rates define the treatment performance and, along with the ZVI amendment information, can be used for process scale-up and performance estimation.

When all organic dechlorination products were considered, the estimated reaction rate from Equation 4 represents the overall rate of TCE transformation, Rt. An abiotic reaction rate, Ra (elimination reaction), was estimated using Equation 4 by only considering transformation to ethene, ethane, and acetylene products. A biotic reaction rate, Rb, was estimated using Equation 4 by only considering transformation to DCE as the product, representing the combined effect of both biotic and direct ZVI hydrogenolysis reactions. Because negligible VC was observed during the test (3 to 4 orders of magnitude lower concentrations than DCE), it was assumed that biological dechlorination converted TCE to DCE only. One could consider Ra as representing the sum of reactions that produce non-hazardous products and Rb as DCE-producing reactions. The actual reactions occurring in the treatment zone are likely a mix of biotic and abiotic reactions. For instance, ZVI degrades DCE and VC, though at lower rates than TCE. Additionally, some biotic dechlorination beyond DCE is possible, though unlikely due to low observed VC concentrations. Molecular DNA data targeting *Dehalococcoides*, the bacteria that converts cis-DCE to ethene, remained at low levels during the test, generally below the threshold concentration of 10^6 gene copy/ L to observe significant complete biotic dechlorination at JBLM groundwater (Macbeth and Sorenson, ESTCP ER-0318 Final Report), indicating biotic cis-DCE dechlorination was limited (Truex et al. 2011).

The overall rate of TCE dechlorination was also estimated using chloride data, Rtc (mmol d-1), using Equation 5. To convert chloride data to the equivalent moles of TCE, the chloride stoichiometry can be assigned based on the relative molar amounts of DCE, ethene, and ethane products observed at each time point.

6.2.2 ZVI Kinetic Changes

The impact of temperature on the *in situ* dechlorination reactions induced by injected ZVI are reported in Truex et al. (2011) and detailed here. A mass discharge analysis was used to evaluate the performance of the treatment with respect to dechlorination as a function of temperature. Due to seasonal variation, the water level declined such that a portion of the screen was unsaturated starting at about day 121 reaching a minimum of 70% saturated thickness by day 184. Because of this large change in hydrologic conditions, and the fact that the majority of TCE residual mass in the ZVI test cell was largely at the water table, the dechlorination rate analysis was constrained to data over the first 121 days of treatment.

Figure 6-3 shows the calculated TCE dechlorination rates and released but untreated TCE (Nd) over the first 121 days for the INJ segment. Flow paths through the test cell are uncertain. However, the INJ segment represents flow from upgradient through the zone of highest ZVI concentration.

Abiotic reactions predominate in the INJ segment. For the INJ segment, overall TCE transformation, Rt was 3.6-4.8 times higher at temperatures above 30°C compared to rates at the ambient temperature (~10°C). This result is consistent with laboratory tests where the TCE degradation rate at 40°C was 2.5 to 3 times greater than the rate at 20°C in batch microcosms with ZVI, JBLM sediment, and groundwater (Section 5.3). The Nd remained near zero in the INJ segment through 121 days, suggesting that the overall *in situ* transformation rate was comparable to the gross TCE dissolution rate.

Chloride concentrations (**Figure 6-4**) were also used in a mass discharge analysis to estimate the dechlorination rate as a function of temperature. The chloride data show an increase of about an order of magnitude in concentration coincident with the increase observed for organic dechlorination products during heating for wells ZVI-INJ, ZVI-MW4, and ZVI-MW5. A 2-3 times increase in chloride was observed for wells ZVI-MW1 and ZVI-MW6 where moderate amounts of ZVI where delivered during injection (Truex et al. 2010) and moderate dechlorination rates based on organic products were observed. Chloride concentrations were generally declining by 120 days after ZVI injection, although chloride concentrations remain highest at wells ZVI-INJ and ZVI-MW4. Wells ZVI-MW2 and ZVI-MW7 show only small changes in chloride concentration during the test corresponding to the relatively small amount of ZVI delivered to these portions of the test cell (Truex et al 2010) and low dechlorination rates based on organic products.

Average overall TCE transformation rates at the ambient temperature (~10°C) and for data at temperatures above 30°C through day 121 were calculated for the INJ segment using the organic dechlorination products (Rt) and chloride (Rtc) (**Table 6-2**). The two types of data show an increase in the reaction rate for temperatures above 30°C compared to the rate at the ambient temperature (~10°C). These and other field test data show that increasing temperature increases contaminant dissolution and degradation rates with minimal TCE volatilization and suggest that ZVI-based treatments can be enhanced with moderate heating. The mass discharge analysis provides a means to quantify the different processes occurring during treatment using MW data that is typically available for field applications.

Table 6-2. Average overall rate of TCE transformation based on organic dechlorination products (R_t) and chloride concentrations (R_{tc}) (Truex et al. 2011).

	R_t [mmol-TCE d^{-1}]	R_{tc} [mmol-TCE d^{-1}]
Injection Well Segment		
a) Ambient temperature	1.1	1.2
b) Temperature >30^{o}C	4.6	9.7
Ratio (b/a)	4.4	8.3

6.2.3 Biotic/Abiotic

Overall, abiotic reactions dominated in the upgradient half of the test cell (ZVI-MW1, ZVI-MW2, ZVI-MW7, and ZVI-INJ) with biotic (hydrogenolysis) reactions becoming more prevalent toward the downgradient portion (ZVI-MW4, ZVI-MW5, and ZVI-MW6) (TCE reaction rates and Nd are presented for all wells in Truex et al. 2011).

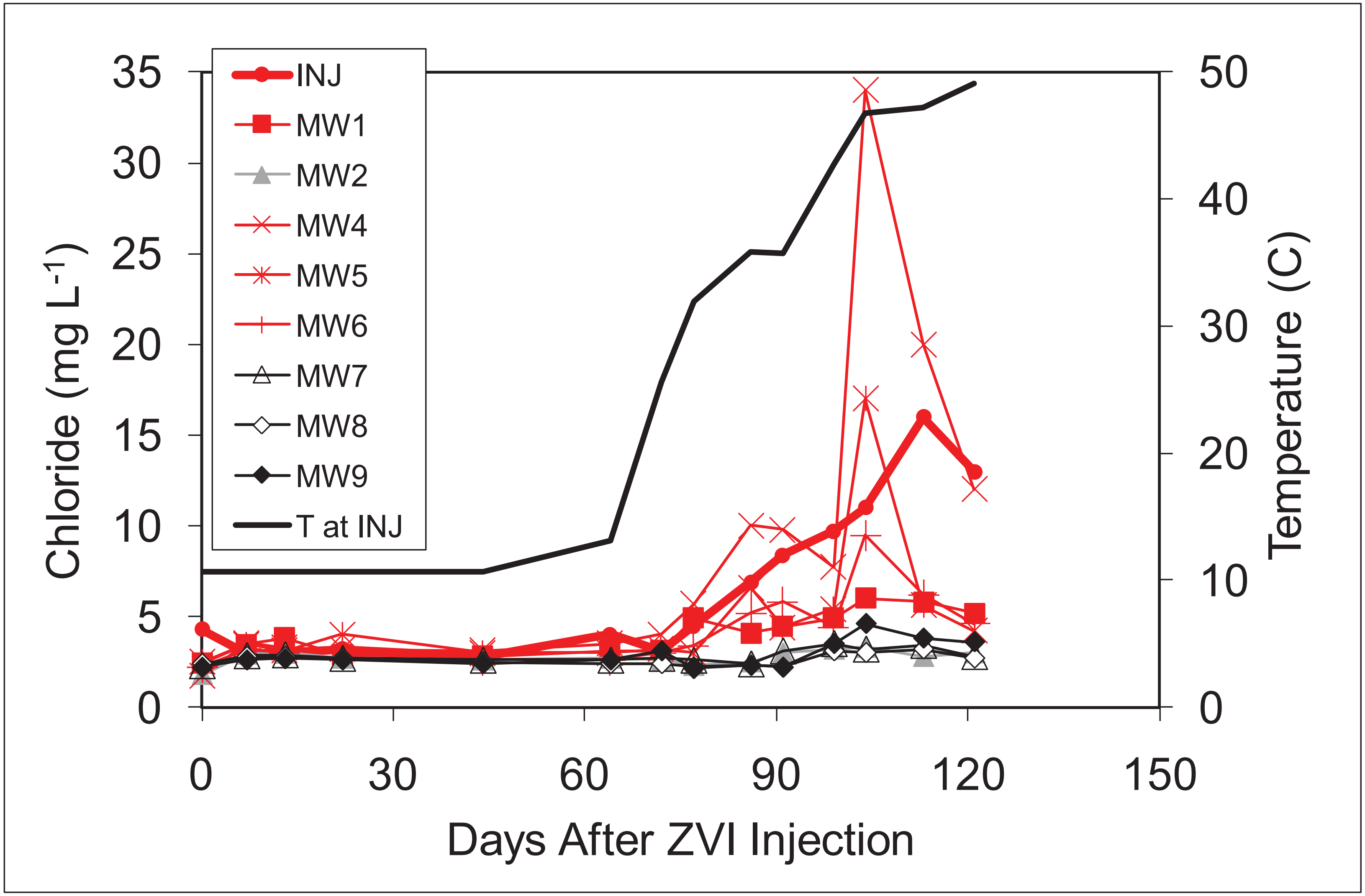


Figure 6-4. Chloride concentration over time in the ZVI test cell. Wells MW8 and MW9 are outside the injection zone, although a small amount of ZVI was distributed to MW8 during injection (Truex et al. 2011).

6.2.4 Impact of Temperature on Dissolution/Volatilization

Analysis for the impact f temperature on dissolution and volatilization are presented in Truex et al. (2011) and repeated here. An objective of the combined process was to promote *in situ* dechlorination and minimize volatilization of TCE. The maximum calculated volatilization rate of TCE (MD_{out-v}) at INJ (Equation 3) for the elevated temperature portion of the test (day 60 through 121) was about 1% of the Rt (Equation 4) due to the low aqueous TCE concentrations. By integrating the mass discharge from the INJ segment over the 121 day analysis period and assuming dechlorination was for sediment-associated TCE, the ZVI treatment reduced the average sediment concentration by 9 mg/kg in these segments with about 85% of this reduction occurring during the 60 days of heating.

The mass discharge analysis included quantification of the net TCE dissolution rate, Nd, as a means to evaluate the amount of TCE released from sediment- or NAPL-associated TCE into the groundwater in excess of the capacity of the ZVI reactions to transform the TCE (see Equation 5, Section 6.1.1). The Nd remained near zero in the INJ segments through 121 days, suggesting that the *in situ* degradation rate was comparable to the gross TCE dissolution rate over this time period (**Figure 6-3**) (Truex et al. 2011). The TCE concentration in the test cell began to increase after about day 100. Thus, past day 120, while not specifically quantified as described above, the net TCE dissolution increased. Note, however, that the TCE concentrations do not rebound significantly at the injection well where the initial TCE concentration was dramatically higher than elsewhere (e.g., indicative of the primary source zone). Higher ZVI mass in this area extended the ability to treat ZVI longer than in other areas. These overall dissolution data suggest that supplying sufficient ZVI mass to locations of high TCE source mass is critical, as expected. The extent of TCE rebound is an indication of how significantly the ZVI reduced the TCE mass before being expended. The ZVI treatment appears to have been sufficient to reduce most of the TCE mass during the treatment period because the TCE rebound is insignificant compared to the initial TCE concentrations. At other locations, some rebound was observed, but at generally low concentrations (Truex et al. 2011).

6.3 Summary of Performance related to Objectives

Table 6-3. Summary of Achievement of Demonstration Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?	
			ZVI	ISB
Qualitative	Induce dechlorination of chlorinated ethenes.	Dechlorination to desired endpoints will be achieved in each treatment cell.	Reductive dechlorination was achieved through abiotic reactions with the formation of ethene and ethane and biotic reactions with the formation of DCE.	Reductive dechlorination was achieved biotically converting TCE to DCE during Phase 2 and to DCE, VC and ethene during Phase 3.

Table 6-3. Summary of Achievement of Demonstration Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?	
	Reduction in parent compounds and accumulation of abiotic and/or biotic reductive daughter products.	Biotic contaminant removal will be the primary mechanism at ambient and elevated temperature in the ISB test cell. Abiotic and biotic contaminant removal will be significant in the ZVI test cell at ambient temperature; however, abiotic mechanisms will predominate at elevated temperature.	Abiotic and biotic dechlorination products observed for both ambient and elevated temperature.	Biotic contaminant removal was the primary mechanism at ambient and elevated temperature in the ISB test cell
Quantitative	Characterize nature of contamination with test cell.	Sufficient contaminant mass will be present in both test cells to meet demonstration objectives.	Initial TCE soil concentration averaged 115 mg/kg near INJ, estimated 1 kg total TCE in test cell (10 mg/kg average concentration)	Initial TCE soil concentration averaged 32 mg/kg with maximum concentrations of 130 mg/kg near ISB-MW2.
	Define rate of dechlorination as a function of temperature.	The rate of dechlorination will be enhanced at elevated temperature in both test cells relative to ambient temperature.	Rates at T>30C were higher than 10C by a factor of 4 based on dechlorination daughter products and a factor 8 using chloride.	Modeled rates based on empirical correlation at T=40C were higher than 10C by a factor of 3.6 based on dechlorination daughter products and a factor of 5.3 using chloride.

Table 6-3. Summary of Achievement of Demonstration Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?	
	Quantify test cell mass balance and loss mechanisms for chlorinated ethenes in the test cells as a function of temperature.	Contaminant mass removal will be enhanced at elevated temperature in both test cells relative to ambient temperature.	TCE mass loss = 9 mg/kg with 85% of loss at T>30C with volatilization accounting for less < 1% of losses based on modeling.	TCE treatment rate increased by a factor of 4.6 at T=40C compared to 10C based on empirical correlation. Most advective transport in groundwater with volatilization accounting for <1.45% of losses.
	Evaluate cost-effectiveness of heating.	The overall treatment efficiency at elevated temperature will be enhanced sufficiently to offset the cost of heating in both test cells.	ZVI cost = $626K ZVI+heat cost = $632K High Temp. Thermal=$692K	ISB cost = $599K ISB+heat cost =$567K High Temp. Thermal=$692K

SECTION 7
COST ASSESSMENT

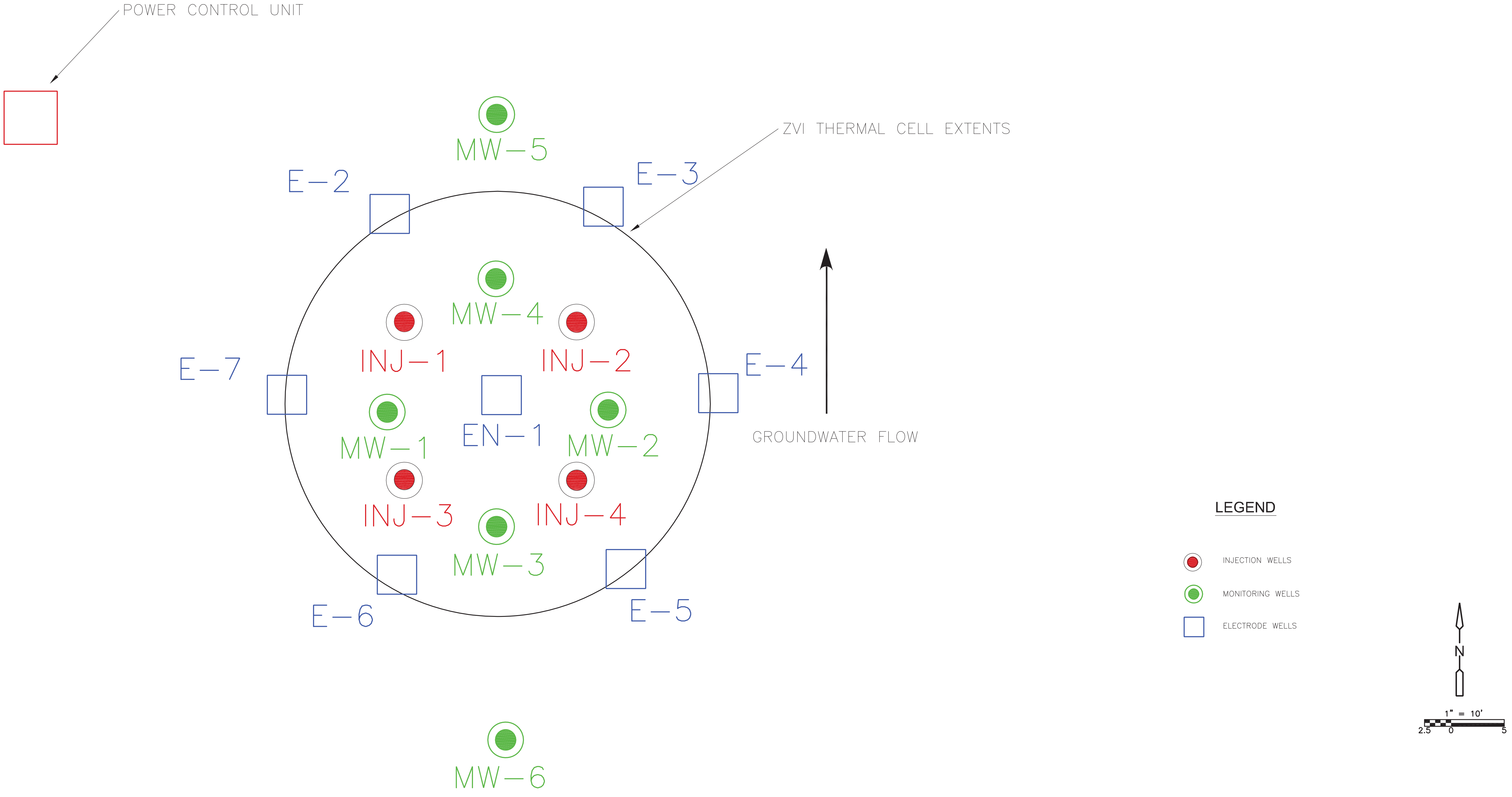
7.1 Cost Model

A simplified cost model for the project was developed in order to benefit professionals who may consider similar technology at other sites. The cost model incorporates all technology-specific cost elements required for implementation at a particular site. While costs may vary depending on site size, location, subsurface conditions, etc., the cost model details all the assumptions from which specific cost elements were based. Many of the assumptions pertain to labor expenditure rates and project scale. **Figure 7-1** illustrates the assumptions for the ZVI treatment area and system infrastructure used for the cost model. **Figure 7-2** illustrates the assumptions for the ISB treatment area and system infrastructure for the cost model. **Table 7-1** provides details of the cost model treatment volume. Therefore, professionals wishing to estimate potential costs at other sites may use the cost model developed for this project as a platform to revise with their own unique cost elements and assumptions. To compare the relative costs of the technologies, application of standard, high-temperature thermal treatment to compared to the low-temperature heating coupled to ISB and ZVI was evaluated. In addition, incremental costs for adding low-temperature ISB or ZVI was evaluated under the assumption that high-temperature thermal system was operated. There are several applications for how the technologies could be combined including:

Table 7-1. Cost Assumption Model.

Model Treatment Volume Dimensions		
Treatment Zone Dimensions and Volume		
n	0.25 --	total porosity estimated from previous data
ne	0.18 --	effective porosity from tracer test
l	12.2 m	treatment zone length
w	12.2 m	treatment zone width
h	9.1 m	length of filter pack
x sectional area	0 m^2	for total inflow/outflow
plan view area	148.7 m^2	for volatilization
Vt	1360 m^3	total volume

Treatment Zone Mass	
Bulk dens.	1900 kg/m^3
Total mass	40 kg
Ambient Rate	213 g/d
Heated Rate	470 g/d
Time to Treat	85 days



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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: T. MACBETH
DRAWN BY: K. HUFFSMITH
SHEET CHK'D BY:
CROSS CHK'D BY:
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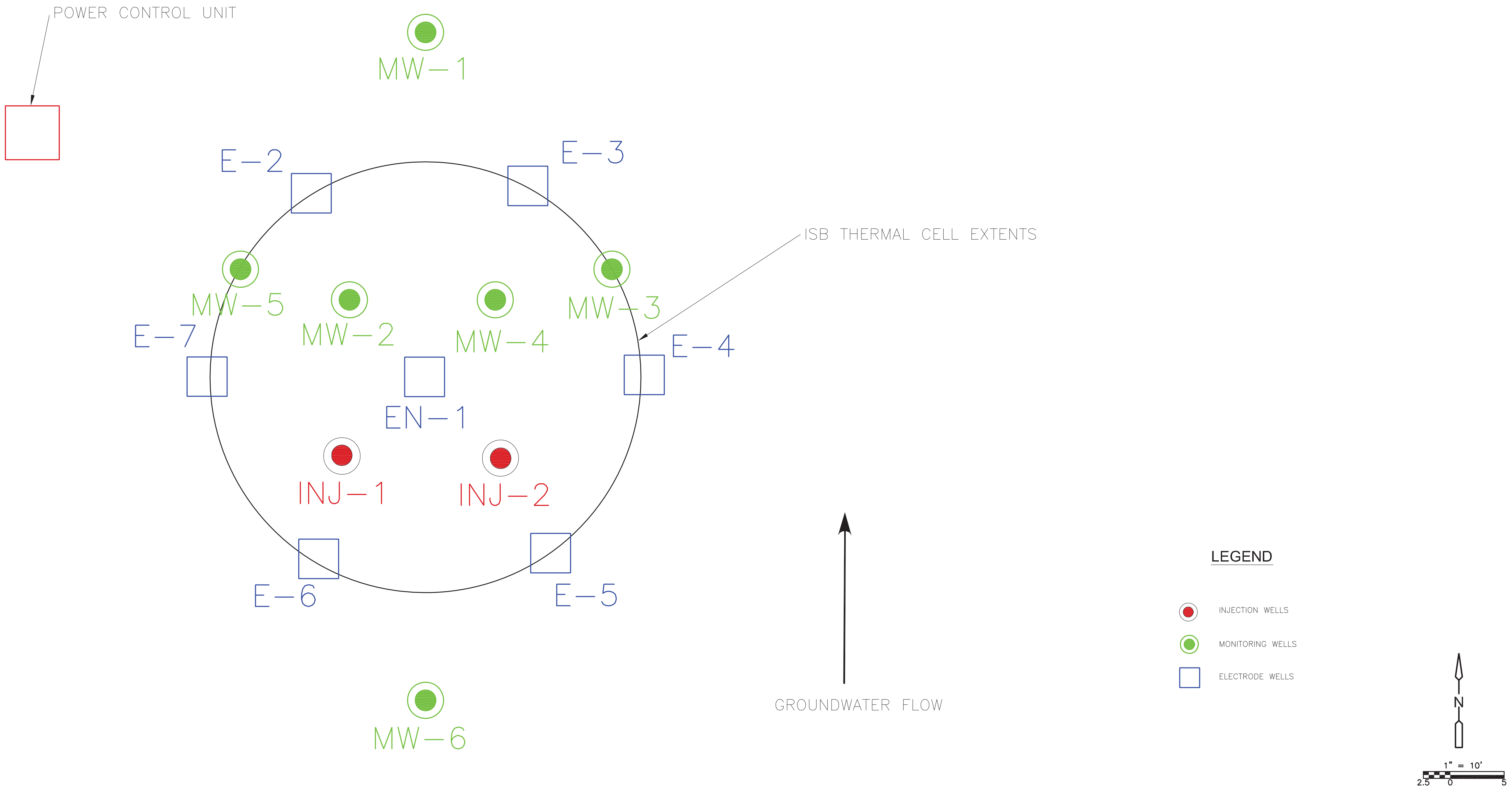
ZVI CONCEPTUAL
TREATMENT MODEL

ZVI COST MODEL TREATMENT AREA AND
SYSTEM INFRASTURCTURE

PROJECT NO. 72648.5219
FILE NAME: CSTSP001.DWG

FIGURE 7—1



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ISB ER0719 CONCEPTUAL
TREATMENT MODEL

ISB COST MODEL TREATMENT AREA AND
SYSTEM INFRASTRUCTURE

PROJECT NO. 72648.5219
FILE NAME: CSTSP001.DWG

FIGURE 7−2

- Implementation of low-temperature heating with ISB or ZVI as a stand-alone technology,
- Implementation of low-temperature heating with ISB or ZVI in conjunction with high-temperature thermal to address areas around the high-temperature thermal treatment zone where it is not cost-effective to treat with high temperature thermal,
- Implementation of low-temperature heating with ISB or ZVI in conjunction with high-temperature thermal as a polish following treatment.

To evaluate the technologies, a model system was developed. **Table 7-1** provides areal and depth of treatment dimensions of the model system, and a starting target-zone contaminant mass to evaluate treatment rates and durations in the model system. The model assumptions for in situ treatment based on the demonstration are as follows:

- Enhanced in situ treatment rates at elevated temperatures were primarily driven by enhanced dissolution due to increased temperatures relative to ambient treatment temperatures,
- The in situ treatment technologies can treat contaminants mobilized from the source at temperatures up to 50^{0}C effectively in the saturated zone,
- Contaminants transported to the vadose zone during low-temperature heating did not require additional treatment to address.

The model treatment zone dimensions are 40 feet (12.2 meters [m]) in length, 40 feet (12.2 m) in width, and 30 feet (9.1 m) in depth, for a total treatment volume of 1,778 cubic yards (1,360 m3). Additionally, an initial chloroethene contaminant mass of 40 kg is assumed. Therefore, one may wish to scale data accordingly if their site is considerably different in size or contains a considerable difference in contaminant mass. Treatment rates were based on modeling for the high temperature thermal and for dissolution of NAPL and with enhancement factors at elevated temperatures demonstrated in this project. The assumptions are as follows:

- A high temperature thermal treatment rate of 470 g/d are used to estimate a total treatment duration of 85 days.
- Energy consumptions was based on energy consumed during the demonstration for the ISB and ZVI, however, these are conservatively high as Ft. Lewis was a much higher groundwater velocities (and associated heat losses) compared to the model system.
- Treatment rates for both ISB and ZVI under ambient temperatures are assumed to be the same. Ambient contaminant discharge rates from the model treatment zone were assumed to be 6 grams of TCE per day (see below for description of assumptions). Therefore, the timeframe for dissolution of all 40 kg of the DNAPL is approximately 11 years assuming that the mass discharge rate is constant.

- For the low temperature ISB, the enhanced treatment rate factor was assumed to be 6 based on the assumption of a 40^{0}C operating temperature, and so 36 grams of TCE per day was assumed. Therefore treatment duration is approximately 1.8 years.
- For the low temperature ZVI, the enhanced treatment rate factor was assumed to be a factor of 8 greater than ambient temperatures based on the assumption of a 50^{0}C operating temperature, and so 48 grams of TCE per day was assumed. Therefore treatment duration is approximately 1.3 years.
- Ambient mass discharge rates out of the treatment zone are:

$$J=VaC$$

$$Md = \sum JA$$

Where J is the contaminant mass flux, Va is the Darcy velocity, C is the contaminant concentration, Md is the mass discharge and A is the treatment area transect. It is assumed that Va= 0.3 feet per day and average concentration across the treatment zone transect is 1,000 ug/L TCE giving an ambient temperature mass discharge rate of 10 grams TCE per day. **Figure 7-3** illustrates the treatment times for the four treatment scenarios using these assumptions.

For each cost element, cost data was tracked during the life cycle of the demonstration, and was captured in the model. Note that some cost elements which were not relevant components of this demonstration, but which may be components of other projects– for example, long-term monitoring – were not tracked in this cost model but which may be of interest for other projects. Within Section 7.1 of this report, for each cost element relevant to or unique to the technology, 1) the element is described with respect to the technology, and 2) the estimated cost associated with the element is provided.

The cost model is presented in Section 7.3. The cost model includes information pertinent to the remediation technologies of the demonstration. **Table 7-2** details a comparison between costs of ZVI combined with low temperature thermal. **Table 7-3** details a comparison between costs for ISB combined with low temperature thermal. The cost model has been broken out into elements specific to the in situ technology and the added costs for the heating elements so that an understanding of the relative cost increase by added the heating system could be gained. Costs have been divided into the common cost elements of 1) start-up, 2) capital, 3) operation and maintenance, 4) demobilization, and 4) waste disposal. These cost elements, as well as specific sub-categories of the elements, are described below.

7.1.1 "Summary Info ZVI-Thermal" Worksheet

This worksheet is a summary of annualized costs associated with the combined low-temperature thermal and ZVI treatment technologies. If one's own project is envisioned to take less than or greater than one year, their costs may be scaled accordingly.

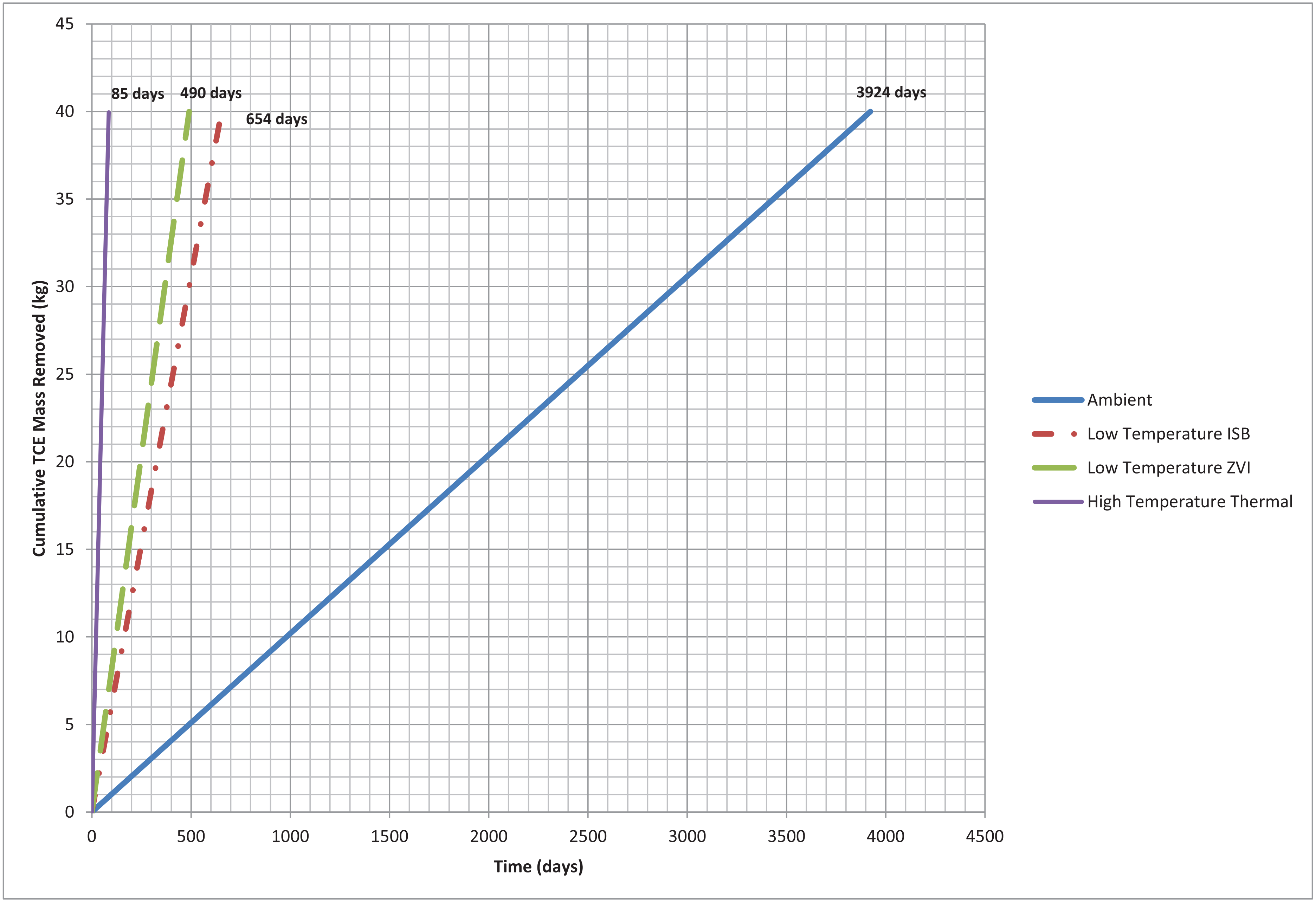

Figure 7-3. Treatment time comparison.

Start-Up Costs

Start-up costs include labor expenditures for initial and revised treatment system design by the project engineer, subsurface drilling and well and electrode installation oversight by a project geologist, and collection of samples and health and safety monitoring by a project field technician. Start-up costs also include contract costs associated with the drilling and well/electrode installation, and permitting. Additionally, preliminary site characterization cost in the form of a tracer injection test ($15,000) is shown as the final start-up cost. It is important to note that previous site characterization efforts were considered sufficient for the majority of treatment design, and that minimal additional characterization during treatment cell installation was used to finalize the design. The overall cost for this work element was $21,623. The most significant start-up costs for this demonstration were for design/permitting ($36,000), and drilling/ subsurface infrastructure installation ($38,448).

Capital Costs

Capital costs include expenditures directly applicable to the low-temperature thermal heating system installation. The specific capital costs for this demonstration were for electrode materials and shipping of materials to the site, engineering labor to install the electrodes, and electrical permitting and professional labor by an electrician to connect the electrodes to the on-site power control unit. It is assumed that a larger power control unit would be required during heating, but that a smaller unit could be used to maintain low temperatures. Total capital cost was $175,000.

Operation And Maintenance Costs

The work element of operation and maintenance includes the sub-category costs for energizing the thermal heating system, technical oversight costs while the treatment is underway, ZVI materials and injections, and sampling and analysis costs. All costs shown in the model are for one calendar year. Heating system O&M considers labor, travel, and other direct operational costs to increase and then maintain optimal temperature as well as electrical energy usage cost. Costs typically associated with higher-temperature thermal treatment such as that of vapor recovery and sampling are not required with the low-temperature thermal application. O&M technical oversight includes labor for a program manager and a project engineer. ZVI injections assume labor, materials, and injection system rental for 1.3 years. The labor for each injection assumes four individuals for four days each – two days set-up and two days injection. For the sampling and analysis sub-category, costs are further broken down as either laboratory analytical or labor costs. The labor costs assume time for a program manager, project engineer, and a field sampling technician performing four sampling events. Total operation and maintenance cost was $228,462, and the most significant individual costs were for the injectable ZVI material and shipment to the site ($124,592), and thermal remediation system operation ($76,560, including energy costs).

Demobilization Costs

Demobilization costs include only those costs incurred in the removal of the power control unit and other salvageable materials off site by the thermal contractor, decommissioning of the electrodes, and final reporting by the thermal contractor. The total cost of this work element was $21,000.

Waste Disposal Costs

This cost element included the labor, materials and disposal of drill cuttings and waste disposal which totaled $7,100.

Grand Total Combined ZVI-Thermal Costs for this Demonstration

The grand total cost for the combined low-temperature thermal and ZVI treatment cell demonstration for one calendar year was $632,705. The O&M cost element for the full demonstration period is detailed in the **Table 7-1**.

7.1.2 "Summary Info Bio-Thermal" Worksheet

This worksheet is a summary of annualized costs associated with the combined low-temperature thermal and in situ bioremediation treatment technologies.

Start-Up Costs

Start-up costs include labor expenditures for initial and revised treatment system design by the project engineer, subsurface drilling and well and electrode installation oversight by a project geologist, and collection of samples and health and safety monitoring by a project field technician. This cost element also includes contract costs associated with the drilling and well/electrode installation, and permitting. Additionally, preliminary site characterization cost in the form of a tracer injection test is shown as the final start-up cost. The same level of effort for this cost element is assumed for the combined in situ bioremediation – thermal demonstration as was for the combined ZVI – thermal demonstration. As before, previous site characterization efforts were considered sufficient for the majority of treatment design, and that minimal additional characterization during treatment cell installation was used to finalize the design. The overall cost for this work element was $121,623.

Capital Costs

Capital costs include expenditures directly applicable to the low-temperature thermal heating system installation. The specific capital costs for this demonstration were for electrode materials and shipping of materials to the site, engineering labor to install the electrodes, and electrical permitting and professional labor by an electrician to connect the electrodes to the on-site power control unit. Total capital cost was $175,000. The same level of effort and costs were assumed for the capital cost element for the combined ISB – thermal demonstration as in the combined ZVI – thermal demonstration.

Operation and Maintenance Costs

Operation and maintenance costs include sub-category elements of thermal heating system O&M, thermal system technical oversight and project management activities, bioremediation amendment injections, and sampling and analysis. All costs shown in the model are for one calendar year. Heating system O&M considers labor, travel, and other direct operational costs to increase and then maintain optimal temperature as well as electrical energy usage cost. Costs typically associated with higher-temperature thermal treatment such as that of vapor recovery and sampling are not required with the low-temperature thermal application. O&M technical oversight includes labor for a program manager and a project engineer. Bioremediation amendment injections assume labor, materials, and injection system rental for four events over 1.8 years. For the sampling and analysis sub-category, costs are further broken down as either laboratory analytical or labor costs. The labor costs assume time for a program manager, project engineer, and a field sampling technician performing four sampling events. Total operation and maintenance cost was $88,460 for O&M of the heating system and $150,853 for operations and performance monitoring of the in situ bioremediation system.

Demobilization Costs

Demobilization costs include only those costs incurred in the removal of the power control unit and other salvageable materials off site by the thermal contractor, decommissioning of the electrodes, and final reporting by the thermal contractor. The total cost of this work element was $21,000; the same as for the combined ZVI – thermal demonstration.

Waste Disposal Costs

This cost element included the labor, materials and disposal of drill cuttings and waste disposal which totaled $7,100. This cost was identical to that for the combined ZVI – thermal demonstration waste disposal cost element.

Grand Total Combined ISB-Thermal Costs For This Demonstration

The grand total cost for the combined low-temperature thermal and in situ bioremediation treatment cell demonstration for one calendar year was $566,996. The O&M cost element for the full demonstration period is detailed in the **Table 7-2**.

7.1.3 "Summary Info Thermal" Worksheet

Table 7-4 details all of the cost elements and sub-categories associated with high temperature ERH to compare to the low temperature applications. Cost elements include: start-up; capital costs; O&M, demobilization, waste disposal, and long-term monitoring. The worksheet is not annualized, thus the costs are for the entire duration of the project and are therefore higher than those in the combined technology summaries. Active energy application (O&M) occurred for an approximate nine month period, although combined costs from project start-up to the end of the project occurred over multiple years. The grand total cost associated with the thermal component of the demonstration project was $672,515.

7.2 Cost Drivers

7.2.1 ZVI

Emplacement is a cost element that needs to be considered for ZVI applications. ZVI has been used for a number of different applications and using several different methods for emplacing it in the targeted treatment zone. In this work, we demonstrated direct injection of ZVI into an aquifer using a shear-thinning fluid to facilitate ZVI distribution. Unlike surface-based emplacement such as trenching and soil mixing, cost for injection emplacement is not strongly dependent on the target depth. Up to a target injection thickness of approximately 20 ft, injection cost is likely not a strong function of thickness. However, cost for injection may increase in steps for thicker zones because multiple injection screens/wells may be needed to facilitate more uniform vertical distribution of the ZVI. Success in radial distribution of ZVI from an injection well will be a function of the site subsurface properties. The demonstration data suggest that distribution on the order of 2-4 m radially from the injection well is a likely range for sites with moderate to high permeability. The injection process, as with many other injection processes, would not be suitable for low permeability materials. Thus, for emplacement costs, the likely range for injection well spacing is on the order of 3 to 8 m.

Cost associated with the injection process are expected to be similar to injection of ISB amendments, but with somewhat different equipment. Unit operations for ZVI injection include mixing of the shear-thinning fluid and a solids feeder/entrainment system similar to what is used to feed whey into an injection stream. Unlike bioremediation, ZVI is more likely to require only one injection for the entire treatment period, thereby providing a savings in labor cost.

ZVI material cost is another factor for the technology. Because the ZVI is injected, a uniform small particle size ZVI material is necessary (Oostrom et al. 2007). The carbonyl ZVI micropowder used in this demonstration is the same as was used in previous laboratory studies (Oostrom et al. 2007) and was effectively distributed in the aquifer. However, its cost was about 3 times higher than ZVI materials more typically used for trenching or soil mixing applications. Potentially, less expensive ZVI material could be identified that is also suitable for injection, but this project did not evaluate other types of iron. It is also important that a sufficient dosing of ZVI is applied to reach the treatment goal. In this project, about 190 kg of ZVI was shown to effectively treat on the order of 1-2 kg of TCE. Optimization of dosing relative to mass of contaminant treated may be a worthwhile treatability effort for a specific site because of the high ZVI material cost. Because dosing will be higher for higher contaminant concentrations, for high concentration source areas, standard thermal treatment will likely become more cost effective. The thermally enhanced ZVI approach is likely more appropriate for source area with single to low 10s of mg/kg contaminant concentrations due to the cost implications of high dosing required for higher contaminant concentrations.

The thermally enhanced ZVI process proceeds rather rapidly, for instance, treating the case study site in the cost example in about 4 months. As such, compared to ambient temperature treatments that require much longer treatment periods, the monitoring requirements for thermally enhanced ZVI would be much lower. Additionally, the monitoring intensity for appropriate thermally enhanced ZVI applications would be lower than for standard thermal treatment of the same target because much less process control and associated monitoring is necessary.

The benefits of thermally enhanced ZVI include quicker and likely more thorough treatment than for ambient applications due to the enhanced reaction and contaminant dissolution rates observed during thermally enhanced treatment. To reap these benefits, heating infrastructure and power is necessary. Based on the demonstration results, heating to 40^{o}C is likely sufficient for TCE contamination. A standard electrical resistance heating approach was used to provide the heating for the demonstration. Optimization of this heating system may result in some cost savings compared to the heating cost basis used for the cost estimate herein.

7.2.2 ISB

As with most in situ remediation technologies, one of the key factors to achieving successful treatment using ISB in chlorinated solvent source areas is delivery and distribution of amendments. That is, amendment must be distributed throughout the target treatment zone to stimulate the desired degradation and enhanced mass transfer of residual DNAPL. Therefore, the major cost drivers are likely to be the hydraulic conductivity and the degree of vertical and lateral heterogeneity in both contaminant distribution and geology. The hydraulic conductivity of the treatment zone will determine the achievable radius of influence through a single injection well, which determines injection well spacing. In addition, heterogeneous distribution of contaminants, especially in residual source zones where a significant proportion of the contaminant mass could be in low conductivity zones, determines the vertical intervals that are targeted and the type of injection required to deliver amendments to the target vertical interval. Heterogeneity could also impact the treatment duration because a high degree of heterogeneity will increase the potential for preferential flow of amendments. A high degree of preferential flow will result in a cleanup timeframe that is dependent upon diffusion of contaminants from low conductivity zones to high conductivity zones more than advection, which will increase treatment duration, thereby increasing costs.

In addition, hydraulic conductivity and heterogeneity would determine the required spacing for the heating electrodes and also determine the power required to heat the treatment zone to the desired temperature. The higher the hydraulic conductivity or the presence of high groundwater flow vertical intervals could potentially result in a heat sink where water is transported out of the treatment zone faster than it can be heated. This would require hydraulic control to increase the residence time of water within the treatment zone and hydraulically isolate the area from upgradient groundwater flux. However, the need for hydraulic control would substantially increase installation and operating costs. However, given the Landfill 2 was a worst case scenario due to extremely high groundwater velocities, it is the opinion of the project team that hydraulic control would like not be required to implement this technology at most sites.

Similarly, the total mass of residual contamination can be a cost driver. As long as the source consists primarily of solvents at residual saturation or sorbed to the soil, mass removal can be fairly rapid subject to the potential constraints of hydraulic conductivity and heterogeneity discussed above. However, if DNAPL is present in pools, cleanup timeframe becomes limited by dissolution rates. While low temperature ISB can enhance the mass transfer by a factor of more 5 to even 10 or higher, large pools of DNAPL could still require decades to dissolve, driving costs up significantly. This is particularly important when considering thermally-enhanced ISB.

Another potential cost driver is hydraulic containment or development of a treatment zone large enough to allow for effective degradation of dissolved chlorinated solvents. If a sufficient downgradient buffer zone is not available at a site and extraction of groundwater is required to prevent the temporary increase in mass flux caused by thermal heating from impacting some nearby downgradient receptor, costs would increase. This is especially true if for some reason the extracted water cannot simply be reinjected in the source area to increase the hydraulic residence time.

A fourth potential cost driver is vapor intrusion. Although this demonstration indicted that volatilization was a small fraction of the total mass discharge from the treatment zone, if the treatment zone is under a building, significant VOC concentrations could accumulate. In addition, ISB of chlorinated solvents generates VC and methane. For shallow, unconfined groundwater sites, this creates the potential for these gases to reach fairly high concentrations in the unsaturated zone above the water table. If potential receptors were present above the treatment zone and soil vapor extraction was required, this would also increase technology costs.

7.2.3 Thermal

The cost drivers for the in situ heating system were the size of the treatment area, which dictated the thermal infrastructure needed. The power control unit and electrical system were significant cost drivers, less expensive systems could be developed for low-temperatures applications that were much less expensive than assumed here. In addition, availability of power is a significant cost driver for the thermal system, especially if a power drop would need to be installed over large distances.

7.3 Cost Analysis

A summary of cost factors for low-temperature ZVI and ISB is presented in **Tables 7-2** and **Table 7-3.** For comparison an estimate of high temperature heating was also provided in **Table 7-4**. These data suggest that low-temperature heating is less expensive than high temperature ERH, but only incrementally so, and due to the slower mass removal rates, likely makes sense only for sites that contain only low to moderate VOC concentrations as residual in soil where contaminant mass could be removed in less than 1-2 years. However, the benefit of heating to in situ reactions was clearly demonstrated both from an enhanced kinetics of degradation reactions and VOC mass removal rates. Therefore, combining in situ treatment with heating, especially for sites already considering high temperature heating, may provide added benefit. This is especially true for areas around and/or downgradient of the high concentration “core” of the source area outside high-temperature ERH treatment makes sense, but still contains high concentrations of VOCs in soil or groundwater. In addition, in situ technologies could be implemented after thermal shut down to treat any remaining contaminants in the treatment zone.

SECTION 8
IMPLEMENTATION

The controlling factors for implementation of thermally enhanced ISB or ZVI as demonstrated are 1) subsurface properties related to injection of the amendments, 2) contaminant type and associated reaction kinetics, 3) contaminant concentrations and the associated amendment dosing requirements, and 4) targeted treatment volume. These factors are discussed below based on the results of the field demonstration. As shown in the field demonstration, the thermally enhanced ZVI approach appears to be less impacted by groundwater flow velocity than other in situ technologies, including ISB using soluble amendments, due to the favorable fluid properties of the shear-thinning fluid and the static nature of the ZVI reaction catalyst.

Injected ZVI particles travel in the subsurface until they are filtered due to physical interaction with the sediment (e.g., contacting pores smaller than the particle size) or until the particles settle and are no longer suspended in the carrier fluid. ZVI injection with a shear-thinning fluid and surfactant components is designed to maximize ZVI particle transport by slowing the settling time of the particles (Oostrom et al. 2007). The viscosity of the fluid slows particle settling. Additionally, the surfactant helps prevent agglomeration of particles, which prevents enhanced settling. Filtration processes are minimized through use of a relatively small ZVI particle size (nominally 2 micron diameter particles).

As with other in situ treatment process that require fluid injection of amendments to the subsurface, the subsurface properties impact the injection process. Carrier fluid distribution and injection flow and pressure are impacted by sediment permeability and heterogeneity. Permeability constraints on fluid injection for ZVI are similar to those for other in situ technologies like bioremediation in that the injection fluid will tend to follow higher permeability pathways and injection into silt and finer materials will likely not be possible due to pressure constraints. For ZVI injection the particle size distribution and associated pore size distribution of the sediment will provide additional constraints due to filtration processes that are not present for solute injection. A reasonable portion of the porosity needs to be significantly greater than the 2-micron diameter of the ZVI particles. A similar type of constraint is typically considered for emulsified oil injection. For sites with small sediment pore sizes, injection of micron scale ZVI may be precluded. Use of nano-scale ZVI could be considered as an alternative to enable distribution of ZVI in these cases and has the potential to offer similar treatment benefits when coupled with heating. However, specific data for nano-scale iron was not collected in this demonstration and the beneficial aspects of nano-scale ZVI (high reactivity, enhanced particle delivery) along with the potential drawbacks (cost, retention in sediment, short-lived reactivity) would need to be considered for this alternative approach.

The reaction kinetics and daughter products of TCE dechlorination by ZVI and ISB were quantified in this project for the field test site. The kinetics and product distribution were shown to be enhanced by heating and favorable for relatively rapid treatment of moderate source contaminant concentrations as were present at the field test site and used for the cost evaluation. The specific contaminants, concentrations, and groundwater geochemistry at a specific site will impact the dechlorination reaction kinetics. Thus, either a review of literature (for resources, see Section 9 and Truex et al. 2010, 2011) to identify appropriate reaction kinetics or a focused laboratory treatability study as was conducted for this field demonstration would be needed to evaluate the effectiveness of thermally enhanced *in situ* treatment options for a specific site and as input to the treatment design.

The ZVI dosing (i.e., the mass of ZVI that needs to be delivered to the treatment zone) is a function of the total contaminant mass that needs to be treated (i.e., contaminant concentration in water and associated with NAPL or sediments multiplied by the treatment volume). Often, it is difficult to accurately estimate the contaminant mass within the treatment zone. Thus, an estimate from available data and use of a “safety factor” increase may be needed to calculate the ZVI dosing that will be sufficient. It may also be effective to make and initial ZVI dosing selection with the realization that a second injection can be used later if needed based on initial treatment results. There should be no major constraints to conducting multiple ZVI injections if needed unless the sediment conditions show that strong filtration of ZVI particles occurred near the injection well. As the contaminant mass increases, the ZVI dosing requirements increase. Two ultimate constraints related to contaminant mass may limit the applicability of the thermally enhanced ZVI. First, the concentration of ZVI in the injection stream is likely limited to a few weight percent ZVI in order for the fluid to carry the ZVI into the subsurface. The ZVI concentration in the injection fluid for the demonstration was about 1.4 wt %. As the ZVI concentration increases, problems with injection solution mixing and particle agglomeration may occur. The maximum ZVI concentration possible in the injection solution was not determined in this demonstration, but it is likely that concentrations significantly higher than 1.4 wt% will not work. Second, as the ZVI dosing requirement increase, the ZVI material costs increase. At some point, these material costs will render the thermally enhanced ZVI costs to be unfavorable relative to other technologies, in particular, at high contaminant concentrations, standard thermal treatment may become a preferred option.

For ISB, the key injection consideration was longevity and retention of the amendments within the target treatment zone. Increasing temperatures enhanced both the rate of amendment utilization and contaminant degradation. However, generally the biomass was more efficient at higher temperatures. In this demonstration, the dosing of whey was maintained constant during the ambient and heated phases, and the dechlorination was considerably enhanced, even with increased amendment utilization. Therefore, it is not the opinion of the project team that increased amendment dosing is required at elevated temperatures. However, retention of amendments was an issue at Landfill 2 due to extremely high groundwater velocities. While Landfill 2 represented a worst case scenario, both distribution and retention of amendments is a key design consideration. Of note, is that the requirement for carbon will likely be much smaller at most sites compared to Landfill 2. The majority of the amendment injected at Landfill 2 was lost due to advective transport out of the target treatment area. Therefore, the amount of amendment needed in the treatment zone would be a fraction (likely an order of magnitude less) at sites with slower groundwater velocities compared to the injection strategy implemented at Landfill 2.

Implementation of thermally enhanced ZVI and ISB treatment is impacted by the size of the targeted treatment volume. As with all treatment technologies, cost and implementation processes are a function of the treatment volume. In particular for the ZVI and ISB, the size will impact the design of the injection wells (screen length, spacing, total number) and layout of the heating infrastructure. The ZVI technology, while scalable, may not be as conducive to large volumes (i.e., more than 2 or 3 times the size used for the cost estimate case study) whereas technologies such as ISB that use solute amendments that are more readily distributed over large volumes.

8.1 Key Regulations

The project team did not have to prepare a State of Washington underground injection control (UIC) permit application to inject whey and/or ZVI and makeup water extracted from the area of contamination into the aquifer at the Fort Lewis Landfill 2 due to interpretation of the applicable sections of the Washington Administrative Code Chapter 173-218 Waster Acceptance Criteria (WAC) Underground Injection Control Program. Specific language in the WAC 173-218-040 UIC *well classification including allowed and prohibited wells*, allows for Class IV wells to reinject treated ground water “into the same formation from where it was drawn as part of a removal or remedial action if such injection is approved by EPA in accordance with the Resource Conservation and Recovery Act (RCRA), 40 CFR 144. Such wells must be registered and approved under RCRA and “Class IV wells that are not prohibited are rule authorized, after the UIC well is registered, for the life of the well if such subsurface emplacement of fluids is authorized under the Resource Conservation Recovery Act, 40 CFR 144.23(c).”

RCRA regulations [specifically 3020(b)] specifically allow for both injection of treatment agents, and reinjection of extracted water amended with treatment agents if certain conditions are met: “Specifically, the groundwater must be treated prior to reinjection; the treatment must be intended to substantially reduce hazardous constituents in the ground water – either before or after reinjection; the cleanup must be protective of human health and the environment; and the injection must be part of a response action under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Section 104 or 106, or a RCRA corrective action intended to clean up the contamination.” The demonstration met all these conditions and no other permitting requirements were required to implement the demonstration. No emissions were produced by demonstration of the in situ treatment technology.

The State of Washington classifies injection wells into classes based on construction and function. The state requires that all wells be registered and most wells must be rule authorized. The demonstration wells were registered with the Washington Department of Ecology (WDOE) and the injection well was rule authorized for the life of the well because it is authorized under the Resource Conservation Recovery Act, 40 CFR 144.23(c).

8.2 Other Regulatory Issues

RCRA provides opportunities for public involvement throughout the remedial action process to expand public access to information about the facility and its activities. Since the small scale demonstration was supplemental to the permitted remedial activities, the actions were not subject to formal public involvement. All activities were performed within the previously disturbed, contaminated area. Generally, in situ technologies used for the demonstration are regarded by the public as a safe, effective, low-risk technologies.

8.3 End-User Issues

End-users for this technology are contractors, potentially responsible parties, and state and federal agencies responsible for mitigating risks to human health and the environment posed by DNAPL in groundwater. This technology is readily scaled to any size site. This technology as implemented uses available amendments; all other process equipment is non-proprietary and readily commercially available. Deployment of this technology is tailored to the specific site. All or most of the previously identified design elements must be addressed during design and implementation, requiring the services of hydrogeologists and engineers.

8.4 Procurement

Equipment required for implementation is standard commercial off-the-shelf including equipment to inject amendments, amendment-types, and much of the thermal equipment. A specialty thermal contractor would be required to design and install either heating electrodes for ERH or heaters for thermal conduction heating.

SECTION 9
REFERENCES

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APPENDIX A
POINT OF CONTACT

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APPENDIX B
BORING LOGS

Hole No. ISB-MW1

DRILLING LOG	DIVISION	INSTALLATION FORT LEWIS, WA	SHEET 1 OF 2 SHEETS
1. PROJECT ESTCP ER-0719		10. SIZE AND TYPE OF BIT Nom. 5" core barrel / 6" casing	
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY		11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY BOART - LONGYEAR		12. MANUFACTURER'S DESIGNATION OF DRILL Track-mounted Rotosonic	
4. HOLE NO. (As shown on drawing title and file number)	ISB-MW1	13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED 3 | UNDISTURBED —
5. NAME OF DRILLER Jeremy Thompson		14. TOTAL NO. OF CORE BOXES —	15. ELEVATION OF GROUND WATER see remarks
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL		16. DATE HOLE	STARTED 8/22/08 | COMPLETED 8/22/08
7. THICKNESS OF OVERBURDEN		17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK N/A		18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE 30.0'		19. SIGNATURE OF INSPECTOR Jeff Powers	

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		black silty GRAVEL (GM) few 5" rnded cobbles		PID ppm MAX:	1003 start drill -relocate to 7'S and
	1.0		@1', 4' bgs	0-8'		3' W of ISB-MW2
	2.0		wire, roots/wood, brick (FILL)	8'RUN 4.4' REC	2.1 < ppm	
	3.0		moist, loose			chemical samples approx. 17.5' 19' 27.5'
	4.0					
	5.0				2.1	
	6.0					
	7.0		0.0-7.5'			
	8.0		gray cobble (cored through) >>5" diam dry 7.5-8.5'	8-10' 2'RUN		1018 hrs @ 8'
	9.0		brn silty GRAVEL (GM) moist to wet, cohesive "sticky consistency"	2.8' REC-OVERY	21 ppm ▽	1023 hrs @ 10' difficult drilling
	10.0		till-like			10-16' groundwater, enct'd ~10' bgs
	11.0		few cobbles	10-20'	7.7	9.5' slight sheen
	12.0			10'RUN 10'REC-OVERY		11.0' No sheen
	13.0		sandy GRAVEL lens 13.0-13.5, wet			
	14.0				12.2	
	15.0					

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PROJECT ESTCP ER-0719

HOLE NO. ISB-MW1

DRILLING LOG (Cont Sheet)

ELEVATION TOP OF HOLE

Hole No. ISB-MW1

1. PROJECT ESTCP ER-0719	2. INSTALLATION Ft Lewis, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		brn silty GRAV (GM) CONT'D ...	10-20'	12.2 ppm	
	16.0		8.5-16.5'	10'RUN		16.5' slight sheen
			brn sandy GRAVEL (GP), wet, loose, predom 1/2 to 3/4" rnd grav, coarse sand water-bearing	10'REC	509	
	17.0				715	17.5' slight sheen 17.5' dye test-Negative
	18.0				91	Solvent-like ador 16.5-20'
	19.0				98	
	20.0		below 20': 70% ~1/2" diam rounded gravel 30% coarse sand			1047 hrs @ 20'
	21.0				19.8	
	22.0					22.0' NO sheen
	23.0					
	24.0		16.5-24.5'		26.6	
	25.0		brn Sandy GRAVEL w/ cobbles (GP) coarser gravel: 1-2" diam coarse sand wet, loose, WATER-BEARING			25.0' No sheen
	26.0				44.2	
	27.0		24.5-28.0'			27.5' No sheen 27.5' dye-test-negative
	28.0		brn gravelly SAND (SP), wet, loose, coarse-grained 28.0-29.0'			
	29.0		cobbles & coarse gravel 2-3½" diam. 29.0-30.0		10 PPM	29.0' No sheen
	30.0		B.O.H. = 30.0'			

ENG FORM JUN 67 **1836-A** *(ER 1110-1-1801)*

PROJECT	HOLE NO.
ESTCP ER-0719	ISB-MW1

Hole No. ISB-MW2

DRILLING LOG	DIVISION	INSTALLATION Ft Lewis, WA	SHEET 1 OF 2 SHEETS
1. PROJECT ESTCP ER-0719		10. SIZE AND TYPE OF BIT Nom 5" core barrel / 6" casing	
2. LOCATION (Coordinates or Station) FORT LEWIS EDGY		11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY BOART-LONGYEAR		12. MANUFACTURER'S DESIGNATION OF DRILL Track-mounted Rotosonic	
4. HOLE NO. (As shown on drawing title and file number)	ISB-MW2	13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED 3 / UNDISTURBED —
5. NAME OF DRILLER Jeremy Thompson		14. TOTAL NO. OF CORE BOXES	15. ELEVATION OF GROUND WATER see remarks
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED	DEG. FROM VERTICAL	16. DATE HOLE	STARTED 8/20/08 / COMPLETED 8/20/08
7. THICKNESS OF OVERBURDEN		17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK N/A		18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE 30.0'		19. SIGNATURE OF INSPECTOR Jeff Powers	

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dark brown silty GRAVEL (GM), few 3.5" cobbles, dry to sl. moist		MAX PID ppm:	0929 hrs start drill
	1.0		gravel up to 3" and rounded old roots, wood, pc. sheet metal	0-5' 5'RUN		chemical samples approx:
	2.0		(FILL)	2'* Recovery (~80%)	9.3 ppm	9' 14' 19'
	3.0					
	4.0					4.0' No sheen
	5.0		color change to black below 5.0'			* 0-5' sample placed in too large a sample sleeve; condensing more sample into smaller length-interval
	6.0		wood pcs, "oily look & feel" (FILL)	5-10'	3.0	0934 hrs @ 5.0' bgs
	7.0		0.0-7.0' Lt. brown gravelly SAND (SP)	5'RUN		
	8.0		med to coarse sand, minor silt, gravel 1/2 to 2½" rnded, moist to wet, loose 4" rnd. cobble @ 8'	5'RECOVERY		1015 hrs @ 10.0' bgs
	9.0		wet below 9.7'		63	9.0' slight sheen 9.0' dye test - SL. positive
	10.0		7.0-10.0' brn sandy GRAVEL (GW), w/ minor silt, well-graded gravel			▽ groundwater enct'd 9.7' bgs
	11.0		few 5" cobbles wet, loose	10-20'		No visible NAPL observed.
	12.0			10'RUN	1555 ppm	strong solvent-like odor below 10'
	13.0			7'RECOVERY		
	14.0		10.0-14.5'			14.0' heavy sheen 14.0' dye test - slight positive
	15.0		(ML) See next sheet			

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PROJECT ESTCP ER-0719

HOLE NO. ISB-MW2

DRILLING LOG (Cont Sheet)

ELEVATION TOP OF HOLE

Hole No. ISB-MW2

1. PROJECT ESTCP ER-0719

2. INSTALLATION Ft Lewis, WA

SHEET 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		brown gravelly SILT (ML), few 4" cobbles ~55% silt, 40% grav. wet, cohesive		PID: 4000 ppm	Strong solvent-like odor to 19' bgs
	16.0					
	17.0		14.5-17.0' brn sandy GRAVEL (GW), trc. silt, well-graded, 1/4 to 1 1/2" rnd gravel, predom sand is coarse-grained, wet, loose 5" cobble stuck in core barrel shoe @ 19.5'			
	18.0				9300	18.5' moderate sheen 18.5' dye test-negative
	19.0					
	20.0					1101 hrs @ 20' bgs
	21.0		17.0-21.5'		81	
	22.0		brn sandy GRAVEL (GP), poorly graded 1/2 to 1" diam rnded gravel, coarse sand, wet, loose water-bearing	20-30' 10' run 9' RECOVERY		22.0' No sheen
	23.0				0.4	
	24.0					
	25.0		25-26.5 gravel zone w/ very little sand			
	26.0				0.9	
	27.0		21.5-27.5'			27.0' No sheen
	28.0		brn gravelly SAND (SP), coarse sand, 1/2 to 1" rnd gravel wet, loose water bearing			
	29.0		more gravel 29.5-30'		2.1 ppm	
	30.0		27.5-30.0' B.O.H. = 30.0'			1155 hrs @ 30' bgs

ENG FORM JUN 67 1836-A (ER 1110-1-1801)

PROJECT ESTCP ER-0719

HOLE NO. ISB-MW2

Hole No. ISB-MW3.

DRILLING LOG	DIVISION	INSTALLATION FORT LEWIS, WA	SHEET 1 OF 2 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART-LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) ISB-MW3
5. NAME OF DRILLER Jeremy Thompson
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK N/A
9. TOTAL DEPTH OF HOLE 30.0'
10. SIZE AND TYPE OF BIT Nom 5" corebarrel / 6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL Track-Mounted Rotosonic
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED UNDISTURBED —
14. TOTAL NO. OF CORE BOXES —
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 8/21/08 COMPLETED 8/21/08
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING
19. SIGNATURE OF INSPECTOR Jeff Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		black gravelly SILT (ML), (OR SILTY GRAV GM?) moist		MAX PID ppm:	1105 start drilling
	1.0		wood, roots, nail, sm. pc. concrete, tarpapn (FILL) glass, steel		3.3 ppm	relocate to approx Location of RS0060 due to no evidence of contamination 0-20' @ original location
	2.0			0-10'		
	3.0			10' RUN	78	chemical samples @ approx:
	4.0		0.0-4.0' black silty GRAVEL (GM), rounded 1/4 to 1.5" diam, moist, loose (LIKELY FILL) 4.0-5.0'	7.3' Recovery		9' 16' 14.5'
	5.0		dark brown gravelly SAND (SP), coarse-grained sand, 1" rounded grav. moist, loose			
	6.0		1 4" cobble @ 8.5'		29.2	
	7.0					
	8.0					9.0' no sheen 9.0' dye test-negative
	9.0				197	▽ Groundwater enctd 9.5'
	10.0		wet below 9.5'			1120 hrs @ 10.0' bgs
	11.0		5.0-10.0 brown silty GRAVEL (GM), well-graded gravel, rounded, wet, loose/soft		7.1	
	12.0					
	13.0				7.2	
	14.0					14.5' dye test-negative
	15.0				142 ppm	

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PROJECT ESTCP ER-0719

HOLE NO. ISB-MW3

DRILLING LOG (Cont Sheet)

ELEVATION TOP OF HOLE

Hole No. ISB-MW3

1. PROJECT ESTCP ER-0719

2. INSTALLATION Ft Lewis, WA

SHEET 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		brn siltyGRAV(GM), CONTD, 10.0-16.0'	10-20'	PID: 2662 ppm	15.0' no sheen
	16.0		brn sandy GRAVEL (GW), well-graded, wet, loose	10' RUN		16.0' no sheen 16.0' dye test-negative
	17.0		Sand predominantly coarse trc. silt	8' RECOVERY		solvent-like odor 15-20' bgs
	18.0				11	
	19.0					19.0' no sheen 19.0' dye test-negative
	20.0		some cobbles below 20'			1140 hrs @ 20.0' bgs
	21.0		WATER-BEARING		3.4	
	22.0					
	23.0			20-30' 10' RUN		No odor, NO sheen below 20'
	24.0			7.8' recovery	0.6	
	25.0					
	26.0					
	27.0				3.9	
	28.0		16.0-28.5'			
	29.0		brn SAND (SP), poorly-graded, coarse, wet, loose, wtr-bearing 28.5-29.0' brn sandy GRAVEL (GW), wet, loose 29.0-30.0'		0.9 ppm	
	30.0'		B.O.H. = 30.0'			

ENG FORM JUN 67 **1836-A** *(ER 1110-1-1801)*

PROJECT ESTCP ER-0719

HOLE NO. ISB-MW3

Hole No. ABANDONED ISB-MW1

DRILLING LOG	DIVISION	INSTALLATION FORT LEWIS, WA	SHEET 1 OF 2 SHEETS
1. PROJECT ESTCP ER-0719		10. SIZE AND TYPE OF BIT Nominal 5" core barrel/6" casing	
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY		11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY BOART LONGYEAR		12. MANUFACTURER'S DESIGNATION OF DRILL Track-mounted Rotosonic	
4. HOLE NO. (As shown on drawing title and file number) ABANDONED ISB-MW1		13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED 0 / UNDISTURBED —
5. NAME OF DRILLER Jeremy Thompson		14. TOTAL NO. OF CORE BOXES —	15. ELEVATION OF GROUND WATER see remarks
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL		16. DATE HOLE	STARTED 8/21/08 / COMPLETED 8/22/08
7. THICKNESS OF OVERBURDEN —		17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK —		18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE 20.0'		19. SIGNATURE OF INSPECTOR Jeff Powers	

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		black gravelly SILT (ML), moist, loose,		MAX PID (ppm):	1626 hrs start drill (8/21)
	1.0		wood, root, brick pcs (FILL)	0-5'		
	2.0		gravel is well-graded 1/4" to 3", rounded	5' RUN 1.6' Rec-overy	6.7 ppm	poor sample recovery 0-5' (1.6/5' = 32%)
	3.0					partially recovered lost interval in Next soil core run of 5-6' bgs
	4.0				11 ppm	4.0' slight sheen
	5.0			5-6' 1' RUN 2.2' REC	3.6 ppm	1630 hrs @ 5.0' 1646 hrs @ 6.0'
	6.0		0.0-6.0' Lt gray COBBLE, crushed, DRY 6.0-6.4' brn sandy GRAVEL (GW), dry to MOIST, loose 6.4-7.0'		1.9	very difficult drilling ~6' bgs
	7.0		brown gravelly SAND (SP), moist to wet, predom. medium- to coarse-grained sand gravel 1/2 to 3" diam.	6-10' 4' RUN	7.7	9.0' No sheen 9.0' dye test - Negative No odor
	8.0			4.2' REC-OVERY		
	9.0		7.0-10.0'		3.8	depth at which groundwater encountered was Not recorded; likely was ~9-10' based on logged moisture descriptions.
	10.0		brown GRAVEL (GW), w/ occ. cobbles, tr sand and silt, wet, loose			1649 hrs @ 10'
	11.0		well-graded gravel some coarse		1.0	
	12.0		water-bearing	10-20' 10' RUN		No chemical samples taken
	13.0		less sand & fines below 13'	7.8' REC-OVERY		
	14.0				1.3 ppm	boring decommissioned w/ 3/4" bentonite chips to ground surface due to apparent lack of contamination
	15.0		10.0-15.0'			

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	ABANDONED **Hole No.** 1SB-MW1
1. PROJECT ESTCP ER-0719	2. INSTALLATION FT Lewis, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		brown gravel & cobbles, wet, loose (GP)		max PID (ppm):	13.0' No sheen
	16.0				1.3 ppm	17.0' No sheen 17.0' dye test-Negative
	17.0					No odoR
	18.0				1.3 ppm	
	19.0		15.0 - 20.0'			20.0' No sheen
	20.0		B.O.H. = 20.0'			1701 hrs (8/21) @ 20' decision to abandon boring on 8/22

ENG FORM JUN 67 1836-A *(ER 1110-1-1801)*

PROJECT ESTCP ER-0719

HOLE NO. ABANDONED 1SB-MW1

Hole No. ABANDONED 1SB-MW3

DRILLING LOG	DIVISION	INSTALLATION FORT LEWIS, WA	SHEET 1 OF 2 SHEETS
1. PROJECT	ESTCP ER-0719	10. SIZE AND TYPE OF BIT	Nominal 5" core barrel / 6" casing
2. LOCATION (Coordinates or Station)	FORT LEWIS EGDY	11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY	BOART LONGYEAR	12. MANUFACTURER'S DESIGNATION OF DRILL	Track-mounted ROTOSONIC
4. HOLE NO. (As shown on drawing title and file number)	ABANDONED 1SB-MW3	13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED 0 UNDISTURBED —
5. NAME OF DRILLER	JEREMY THOMPSON	14. TOTAL NO. OF CORE BOXES	—
		15. ELEVATION OF GROUND WATER	see remarks
6. DIRECTION OF HOLE	☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL	16. DATE HOLE	STARTED 8/21/08 COMPLETED 8/21/08
7. THICKNESS OF OVERBURDEN	—	17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK	—	18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE	20.0'	19. SIGNATURE OF INSPECTOR	Jeff Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		black silty GRAVEL (GM), w/ roots, moist, loose		MAX PID (ppm):	0939 hrs start drill
	1.0		rounded gravel up to 2" diam.	0-5' 5' RUN	0.4 ppm	No chemical samples taken
	2.0			3.3' REC-OVERY		boring decommissioned w/ 3/4" bentonite chips
	3.0		small wood fragments @ 3' (FILL)		0.5 ppm	to ground surface due to apparent lack of contamination
	4.0		4" rnd. cobble @ 4'			
	5.0					0941 hrs @ 5.0'
	6.0		0.0 - 6.5'	5-10' 5' RUN	3.6 ppm	
			brown gravelly SAND (SP), moist to wet, loose, two 5" diam. rnd cobbles			
	7.0		medim-to coarse-grained sand	4' REC-OVERY		
	8.0				5.2 ppm	No odor 9.0' No sheen
	9.0					▽ Groundwater encountered 9.5'
	10.0		6.5-10.0'			0950 hrs @ 10'
			brown sandy GRAVEL (GW), w/ occasional cobbles, wet, loose			
	11.0				6.2 ppm	
	12.0			10-20' 10' RUN		
	13.0			8.5' Recovery	11.4 ppm	No odor
	14.0		water-bearing zone w/ less sand below 14'			14.0 No sheen
	15.0					

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PROJECT ESTCP ER-0719

HOLE NO. ABANDONED 1SB-MW3

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	**Hole No.** ABANDONED ISB-MW3
1. PROJECT ESTCP ER-0719	2. INSTALLATION Ft Lewis, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. max f PID: (ppm)	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		brn sandy GRAV (GW)			
			wet, loose		6.4 ppm	
	16.0		cont'd	10-20'		
				10' RUN		
	17.0			8.5' REC-OVERY		
	18.0				11.7 ppm	
	19.0					
			10.0-20.0'			1015 hrs @ 20'
	20.0		B.O.H. = 20.0'			

ENG FORM JUN 67 **1836-A** *(ER 1110-1-1801)*

PROJECT ESTCP ER-0719

HOLE NO. ABANDONED ISB-MW3

Hole No. ZVI-INJ1

DRILLING LOG

DIVISION	INSTALLATION Ft Lewis, WA	SHEET 1	OF 2 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART-LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) ZVI-INJ1
5. NAME OF DRILLER Jeremy Thompson
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK N/A
9. TOTAL DEPTH OF HOLE 25.0'
10. SIZE AND TYPE OF BIT NOM. 6.5" CORE BARREL/8" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL TRACK-MOUNTED ROTOSONIC
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED 3 UNDISTURBED —
14. TOTAL NO. OF CORE BOXES —
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 8/19/08 COMPLETED 8/19/08
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING
19. SIGNATURE OF INSPECTOR Jeff Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0 1.0		dark brown gravelly SILT (ML), moist, loose FILL 5" pc. red brick 0.5' 0.0–1.5'	0-5' 5' RUN 4' RECOVERY	PID (ppm) 18.1 ppm	0850 Start drill
	2.0 3.0 4.0 5.0		dark brown sandy GRAVEL (GW) well-graded rounded gravel, few 4" rnd. cobbles, medium grained sand, moist, roots, sm. brick frags. FILL 1.5–5.0'		76	chemical samples @ approx. 8' 13' 16'
	6.0 7.0 8.0		dk brn to black silty GRAVEL (GM), moist to wet, abundant metal debris (can lids), glass 4" rnd. cobble @ 8', FILL 5.0–8.5'	5-10' 5' RUN 5' RECOVERY	99 112	hydrocarbon odor 6.0' slight sheen odor 8.0' heavy sheen 8.0' dyetest - negative
	9.0 10.0		red-brn sandy GRAVEL (GP), med. sand, rounded grav to 1.5", moist, loose 8.5–10.5'		17	9.5' No sheen 0915 hrs.
	11.0 12.0 13.0		gray-brn silty GRAVEL (GM) moist to wet, soft, sl. cohesive, rnd'd gravel; poorly graded to 3", 5" cobbles @ 11.5, 13 10.5-13.0'	10-15' 5' RUN 5' RECOVERY	40 100	odor 10.5-13' ▽ Groundwater enct'd 13'
	14.0 15.0		brn gravelly SAND (SP), wet, loose coarse sand, fine to med rnd. gravel WATER-bearing 13.0-15.0'		45 ppm	13.0' moderate sheen 13.0 NAPL on bag 13.0 dye test - positive 0937 hrs

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PROJECT ESTCP ER-0719 HOLE NO. ZVI-INJ1

DRILLING LOG (Cont Sheet)

ELEVATION TOP OF HOLE

Hole No. ZVI-INJ1

1. PROJECT ESTCP ER-0719

2. INSTALLATION Ft Lewis, WA

SHEET 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		brown gravel (GP), poorly-graded wet, loose	15-20'	PID: 10 ppm	NAPL on sample sleeve 15-20'
	16.0		water-bearing	5' RUN	2.1	16.0' heavy sheen 16.0' dye test-negative
	17.0		15.0-17.5'	5' RECOVERY		17.0' slight sheen 17.0' NAPL on bag
	18.0		gray brn sandy GRAVEL (GP) med. to coarse sand, grav 1-2" rounded, few 3" cobbles wet, loose		2.0	17.0' dye test-positive
	19.0					
	20.0		water-bearing			0949 hrs
	21.0			20-25'	3.5	
	22.0			5' RUN 5' RECOVERY		
	23.0				2.2 ppm	
	24.0					
	25.0		17.5-25.0'			1100 hrs 8/19
			B.O.H. = 25.0'			

ENG FORM JUN 67 1836-A (ER 1110-1-1801)

PROJECT ESTCP ER-0719

HOLE NO. ZVI-INJ1

Hole No. ZVI-MW1

DRILLING LOG	DIVISION	INSTALLATION Ft Lewis, WA	SHEET 1 OF 2 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART-LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) ZVI-MW1
5. NAME OF DRILLER Jeremy Thompson
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK N/A
9. TOTAL DEPTH OF HOLE 20.0'
10. SIZE AND TYPE OF BIT Nom. 5" corebarrel / 6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL TRACK-mounted Rotosonic
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED 3 UNDISTURBED —
14. TOTAL NO. OF CORE BOXES —
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 8/18/08 COMPLETED 8/18/08
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING
19. SIGNATURE OF INSPECTOR Jeff Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		black silty GRAVEL (GM), moist w/ brick, nail (FILL)		PID (ppm):	1150 hrs start drill
	1.0		rounded gravel			
	2.0				25 ppm	chemical samples: approx
	3.0			0-10' 10' RUN		6.5' 14' 18'
	4.0		color change to dark brown @ 4.0'	5' RECOVERY (50%)		
	5.0		few cobbles glass, ceramic pcs.		48	
	6.0		0.0-7.0'			6.5' moderate sheen 6.5' dye test – negative
	7.0		red-brn sandy GRAVEL (GP) medium sand, rounded gravel to 2" moist			
	8.0				13	
	9.0					1200 hrs @ 10' bgs
	10.0				14.1	core barrel stuck inside casing while clean-out run occurs to 10' — Add water to borehole
	11.0			10-15' 5' RUN		
	12.0		gray 12.5-13.0'	5' RECOVERY	17.3	12.0' NO sheen
	13.0		4" rounded cobble @ 13.3'			12-hr static water level 13.6' bgs ▽
	14.0				31.9 ppm	hydrocarbon odor 14.0' heavy sheen 14.0' NAPL blobs on bag 14.0' dye test – POSITIVE
	15.0					

ENG FORM MAR 71 1836 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. ZVI-MW1

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	**Hole No.** ZVI-MW1
1. PROJECT ESTCP ER-0719	2. INSTALLATION Ft Lewis, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		Same GP finer gravel to 3/4" coarse sand	15-20' 5' RUN	PID (ppm): 78 ppm	1410 hrs @ 15.0'
	16.0		wet, loose	5' RECOVERY		hydrocarbon odor
	17.0		water-bearing 7.0-18.0'			18.0' NAPL blobs on bag 18.0 dye, test-positive 18.0' heavy sheen
	18.0		gray sandy GRAVEL (GW) few rnd'd 4" cobbles			solvent-like odor 19.0' moderate sheen
	19.0		wet, loose water-bearing		11 ppm	
	20.0		B.O.H. = 20.0'			1455 hrs 8/18

ENG FORM JUN 67 1836-A (ER 1110-1-1801)	PROJECT ESTCP ER-0719	HOLE NO. ZVI-MW1

Hole No. ZVI-MW2

DRILLING LOG	DIVISION	INSTALLATION Ft Lewis, WA	SHEET 1 OF 2 SHEETS
1. PROJECT ESTCP ER-0719		10. SIZE AND TYPE OF BIT Nom. 5" core barrel / 6" casing	
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY		11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY BOART-LONGYEAR		12. MANUFACTURER'S DESIGNATION OF DRILL Track-mounted Rotosonic	
4. HOLE NO. (As shown on drawing title and file number)	ZVI-MW2	13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED 3 / UNDISTURBED
5. NAME OF DRILLER Jeremy Thompson		14. TOTAL NO. OF CORE BOXES –	15. ELEVATION OF GROUND WATER see remarks
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL		16. DATE HOLE	STARTED 8/19/08 COMPLETED 8/19/08
7. THICKNESS OF OVERBURDEN		17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK	N/A	18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE	20.0'	19. SIGNATURE OF INSPECTOR Jeff Powers	

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dark brown silty GRAVEL (GM), trc. sand, dry to slightly moist, loose	0-5'	PID ppm:	1425 hrs start drill
	1.0		Lg. pc metal @ 0.5' 5" concrete @ 1.0'	5' RUN 3.8' REC-OVERY	5.4 ppm	chemical samples @ approx:
	2.0		4" brick, ceramic @ 5' (FILL)			7.5' 13' 17'
	3.0				9.4	
	4.0					
	5.0		more abundant & larger gravel below 5' (up to 3" diam)			1430 hrs @ 5'
	6.0		brick @ 6.5'	5-10'	12.6	
	7.0		wood pcs @ 7.0' 0.0-7.5'	5' RUN 5' REC-OVERY	42.5	7.5' slight sheen 7.5' slight hydrocarbon odor 7.5' dye test-negative
	8.0		brn sandy GRAVEL (GW), well-graded rnded fine to 3" grav, medium sand, moist, loose			
	9.0				(NOT Recorded)	
	10.0		trace silt below 10'			1434 hrs @ 10'
	11.0		5" cobble @ 11.5' 7.5-11.5'	10-16'	21.9	11.0' moderate sheen
	12.0		clayey GRAVEL (GC), dry to SL. moist 11.5-12.5'	6' RUN 6' REC-OVERY	37	Groundwater enct'd 13'
	13.0		gray GRAVEL (GP), minor sand poorly-graded grav 0.5-0.75" coarse sand, wet 12.5-14.0'		103 ▽	13.0' heavy sheen 13.0' dye
	14.0		gray-brn sandy GRAVEL w/ trc silt (GP) wet, loose		9.2 ppm	
	15.0					

PROJECT ESTCP ER-0719

HOLE NO. ZVI-MW2

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE		**Hole No.** ZVI-MW2
1. PROJECT ESTCP ER-0719	2. INSTALLATION Ft Lewis, WA		**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		gray-brn sandy GRAVEL (GP) w/ trc silt wet, loose 14.0-16.0			
	16.0		gray silty GRAVEL (GM) wet, loose to sl. cohesive	16-20' 4' RUN 4.5' Recovery	6.4 ppm	
	17.0					17.0' slight sheen 17.0' dye test-Negative
			16.0-18.0'			
	18.0		brn sandy GRAVEL (GP) w/ few 3" cobbles, coarse sand wet, loose			
	19.0		water-bearing 18.0-20.0		1 ppm	
	20.0		B.O.H. = 20.0			1550 hrs

ENG FORM JUN 67 **1836-A** *(ER 1110-1-1801)*

PROJECT	HOLE NO.
ESTCP ER-0719	ZVI-MW2

Hole No. (New) ZVI-INJ1

DRILLING LOG

DIVISION

INSTALLATION FORT LEWIS, WA

SHEET 1 OF 2 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) (New) ZVI-INJ1
5. NAME OF DRILLER Jeremy Thompson
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK N/A
9. TOTAL DEPTH OF HOLE 25.0'
10. SIZE AND TYPE OF BIT Nom 6.5" core barrel/8" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL Track-mounted Rotosonic
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED 3 UNDISTURBED —
14. TOTAL NO. OF CORE BOXES
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 11/17/08 COMPLETED 11/17/08
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING
19. SIGNATURE OF INSPECTOR J Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brown to black gravelly SILT (ML)		PID ppm MAX.	1030 hrs begin drilling
	1.0		FILL	0-5' 5'RUN	2.1	Located 7' From I-15/mw-2 in a 53°
	2.0		moist, loose misc. metal debris, nails, etc	4.7' Recovery	8.9	heading from North
	3.0					
	4.0				30.5	Soil analytical samples 8.8 15.3 10.5' bgs
	5.0					Note: 10.5' bgs collected LAte since waited
	6.0				84	for higher PID readings at depth tha never materialized
	7.0		0.0-7.0' brn silty GRAVEL (GM)	5-15'		
	8.0		moist, loose	10'RUN	484	
	9.0			10.5' REC	629	∇ Groundwater enct'd 9.5'
	10.0		7.0-10.0' brn gravel & cobbles water-bearing, wet, loose, trc silt 10.0-11.0			
	11.0		brn gravelly SAND (SP) wet, loose, water-bearing trc silt, fine grav/coarse sand		15	Sheen testing results: 4' No sheen (NS)
	12.0		11.0-13.0'			7' NS 8.8' NS 10.5' NS
	13.0		brn sandy GRAVEL (GP)			15.3' NS 20 NS 24 NS
	14.0		wet, loose, water bearing		5	
	15.0					

ENG FORM MAR 71 1836

PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. (NEW) ZVI-INJ1

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	**Hole No.** (NEW) ZVI-INJ1
1. PROJECT ESTCP ER-0719	2. INSTALLATION Ft Lewis, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0				PID:	
			brn Sandy GRAVEL			dye test results:
	16.0				4	5' Negative
			wet, loose		ppm	10' Neg.
	17.0			15-25'		15' Neg
			water-bearing	10' RUN		20' Neg.
	18.0				2.4	
				recovery Not recorded		
	19.0					
	20.0				3.3	
	21.0					
					0.3	
	22.0					
	23.0					
					1.4	
	24.0					
			13.0-25.0'			
	25.0		B.O.H. = 25.0'			

ENG FORM JUN 67 **1836-A** *(ER 1110-1-1801)*

PROJECT	HOLE NO.
ESTCP ER-0719	(New) ZVI-INJ1

Hole No. (NEW) ZVI-MW1

DRILLING LOG

DIVISION

INSTALLATION FORT LEWIS, WA

SHEET 1 OF 2 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) (NEW) ZVI-MW1
5. NAME OF DRILLER JEREMY THOMPSON
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK N/A
9. TOTAL DEPTH OF HOLE 25.0'
10. SIZE AND TYPE OF BIT Nom. 5" core barrel / 6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL Track-mounted Rotosonic
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED 3 UNDISTURBED –
14. TOTAL NO. OF CORE BOXES
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 11/17/08 COMPLETED 11/17/08
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING
19. SIGNATURE OF INSPECTOR J Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brn to black gravelly SILT (ML) (FILL) 0-1'		PID ppm MAX:	1447 hrs Start drilling
	1.0				1.6 ppm	Located 11' From mw2 and 4' From INJ1 in 53° from north heading
	2.0		suspected FILL	0-10' 10' RUN		
	3.0			3' Recovery ☆		Soil analytical samples: 11, 16, 20.5' bgs
	4.0					
	5.0				NA (LOSS)	☆ complete core loss in interval approx 1-8' bgs
	6.0					
	7.0					
	8.0		Same FILL (?) or from higher up? 8-9'			
	9.0		brn gravelly SAND (SP) moist, loose, medium-grained Sand wet below 10' trc. silt 9.0-11.0'		17.9	
	10.0				10.6	▽ Groundwater enc't'd 10' bgs
	11.0		gravel & cobbles to 5", rounded wet, loose, water-bearing 11.0-12.0'			sheen test results:
	12.0		brn gravelly SAND (SP), wet, loose water-bearing		14.4	9.5' No Sheen (NS) 11' NS 12.5' NS
	13.0					15' NS
	14.0				1.9	16' Slight sheen (SS) 19' NS 20.5' SS
	15.0					23' NS

ENG FORM MAR 71 1836 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. (New) ZVI-MW1

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	**Hole No.** (New) ZVI-MW1
1. PROJECT ESTCP ER-0719	2. INSTALLATION FT. LEWIS, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		brn grav. SAND (SP) cont'd.		PID:	
	16.0				0.7 ppm	dye test results: 10' Negative 15' Neg. 20' Neg.
			12.0-17.0			
	17.0		brn Sandy GRAVEL, (GP)			
	18.0		wet, loose			
	19.0		water-bearing		0.4	
	20.0					
	21.0			20-25'		
	22.0			5' RUN	0.7	
	23.0			2.6' REC		
	24.0					
			17.0-25.0'			
	25.0		BOH=25.0'			

ENG FORM JUN 67 1836-A (ER 1110-1-1801)

PROJECT ESTCP. ER-0719	HOLE NO. (New) ZVI-MW1

Hole No. (New) ZVI-MW2

DRILLING LOG

DIVISION		INSTALLATION FORT LEWIS, WA	SHEET 1 OF 2 SHEETS
1. PROJECT ESTCP ER-0719		10. SIZE AND TYPE OF BIT Nom. 5" core barrel/6" casing	
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY		11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY BOART LONGYEAR		12. MANUFACTURER'S DESIGNATION OF DRILL Track-mounted Rotosonic	
4. HOLE NO. (As shown on drawing title and file number)	(New) ZVI-MW2	13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED 3 UNDISTURBED —
5. NAME OF DRILLER Jeremy Thompson		14. TOTAL NO. OF CORE BOXES	15. ELEVATION OF GROUND WATER see remarks
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED	DEG. FROM VERTICAL	16. DATE HOLE	STARTED 11/17/08 COMPLETED 11/17/08
7. THICKNESS OF OVERBURDEN		17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK N/A		18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE 25.0'		19. SIGNATURE OF INSPECTOR J Powers	

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brn to black gravelly SILT, (ML)		PID ppm max:	1330 begin drilling
	1.0		FILL few rounded cobbles			Located At I-15 Soil gas Location
	2.0		small non-native roots	0-10'	14 ppm	
	3.0			10' RUN 7.5'		Soil analytical samples:
	4.0		0-4.5'	RECOVERY	42	12' bgs 16.5' 20'
	5.0		brn silty sandy GRAVEL (GP-GM)			
	6.0		moist, loose			
	7.0		~50% gravel up to 2" diam 30% sand			
	8.0		20% silt			
	9.0		wet below 9.5'		16.7	▽ Groundwater enc'd 9.5'
	10.0		4.5-10.0'			Sheen test results:
	11.0		brn sandy GRAVEL (GP) wet, loose water-bearing		14.8	3' bgs slight sheen 9.5' No sheen (NS)
	12.0		coarse sand, predom grav. to 1" rounded, few to 2"	10-20' 10' RUN		14' NS 20' NS
	13.0			9.8'	32.9	
	14.0			REC		
	15.0					

ENG FORM MAR 71 1836 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. (New) ZVI-MW2

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	**Hole No.** (New) ZVI-MW2
1. PROJECT ESTCP ER-0719	2. INSTALLATION FT. LEWIS, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15.0		brn sandy GRAVEL (GP) wet, loose, water-bearing		PID:	
	16.0				1.4 ppm	dye test results: 5' Negative 10' Neg. 15' Neg. 20' Neg.
	17.0					
	18.0				9.8	
	19.0					
	20.0					
	21.0		4" rounded cobble @ 21.5'	20-25' 5' RUN 2.8' REC.		
	22.0				0.7	
	23.0					
	24.0		10.0-25.0'			
	25.0		BOH = 25.0'			

ENG FORM JUN 67 **1836-A** *(ER 1110-1-1801)*

PROJECT ESTCP ER-0719

HOLE NO. (New) ZVI-MW2

Hole No. ZVI-MW7

DRILLING LOG

DIVISION

INSTALLATION FORT LEWIS, WA

SHEET 1 OF 1 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) ZVI-MW7
5. NAME OF DRILLER Ken Phillips
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK —
9. TOTAL DEPTH OF HOLE 15.0'
10. SIZE AND TYPE OF BIT 6.5" core barrel/6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL Truck-mounted sonic
13. TOTAL NO. OF OVERBURDEN SAMPLES DISTURBED — UNDISTURBED —
14. TOTAL NO. OF CORE BOXES
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 12/8/08 COMPLETED 12/8/08
17. ELEVATION TOP OF HOLE —
18. TOTAL CORE RECOVERY FOR BORING —
19. SIGNATURE OF INSPECTOR J Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brown to black silty GRAVEL (GM), FILL moist, loose		MAX PID in ppm	Boring completed as ZVI MW
	1.0			0-5' 5' RUN 3.7' Recovery	0.9	0905 begin drilling
	2.0					
	3.0				9.8	No analytical soil samples collected
	4.0					
	5.0		0.0-5.5'			
	6.0		brn silty sandy GRAVEL (GW-GM) moist, loose		5.6	
	7.0					
	8.0			5-15' 10' RUN	13.4	
	9.0		5.5-9.0' brn sandy GRAVEL (GP), moist (wet below 10'), loose, trc. silt will bear water			
	10.0			10' REC		▽ groundwater encountered 10'
	11.0				5.2	
	12.0		9.0-12.5'			No visible or olfactory evidence of contamination
	13.0		brn gravelly SAND (SP), wet, loose, water-bearing			
	14.0				1.8	
	15.0		12.5-15.0' BOH = 15.0'			

ENG FORM MAR 71 1836 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. ZVI-MW7

Hole No. ZVI-MW9

DRILLING LOG	DIVISION	INSTALLATION FORT LEWIS, WA	SHEET 1 OF 1 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) ZVI-MW9
5. NAME OF DRILLER Ken Phillips
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN —
8. DEPTH DRILLED INTO ROCK —
9. TOTAL DEPTH OF HOLE 15.0'
10. SIZE AND TYPE OF BIT 6.5" core barrel / 6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL truck-mounted sonic
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED — UNDISTURBED —
14. TOTAL NO. OF CORE BOXES
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 12/8/08 COMPLETED 12/8/08
17. ELEVATION TOP OF HOLE —
18. TOTAL CORE RECOVERY FOR BORING —
19. SIGNATURE OF INSPECTOR J Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brn to black silty GRAVEL (GM) moist, loose		MAX PID in ppm	Boring completed as ZVI MW
	1.0		FILL (wire pcs., nails, 2 4" metal rings Springs)	0-5' 5' RUN	0.2 ppm	1033 began drilling
	2.0					
	3.0			4' Recovery		no analytical soil samples collected
	4.0				0.7	
	5.0					
	6.0				0.3	
	7.0					
	8.0				4.0	
	9.0		0.0-9.0' Large cobble 9-10'			▽ Groundwater encountered ~9'
	10.0		mixture of crushed rock flour/powder and water native mat'l believed to be missing poor recovery		Not meas-ured.	cobble @ 9-10' driven downward by core barrel created "soupy" sample/poor recovery below 10'
	11.0					
	12.0					
	13.0				0.0	No visible or olfactory evidence of contamination.
	14.0		← more pc. of cobble @15'			
	15.0		BOH = 15.0'			

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. ZVI-MW9

Hole No. ISB-MW4

DRILLING LOG

DIVISION		INSTALLATION FORT LEWIS, WA	SHEET 1 OF 2 SHEETS
1. PROJECT ESTCP ER-0719		10. SIZE AND TYPE OF BIT Nom. 5" core barrel/6" casing	
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY		11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY BOART LONGYEAR		12. MANUFACTURER'S DESIGNATION OF DRILL track-mounted sonic	
4. HOLE NO. (As shown on drawing title and file number)	ISB-MW4	13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED — / UNDISTURBED
5. NAME OF DRILLER Jeremy Thompson		14. TOTAL NO. OF CORE BOXES	15. ELEVATION OF GROUND WATER see remarks
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED	DEG. FROM VERTICAL	16. DATE HOLE	STARTED 11/20/08 / COMPLETED 11/20/08
7. THICKNESS OF OVERBURDEN —		17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK —		18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE 25.0'		19. SIGNATURE OF INSPECTOR J Powers	

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dark brn to BLACK gravelly SILT (ML), moist to wet, loose			Boring completed as ISB downgradient well
	1.0		FILL			
	2.0					1313 hrs. began drilling
	3.0			0-10'		No analytical soil samples collected
	4.0			10' RUN		
	5.0			5.9' RECOVERY		NO PID measuements or sheen or dye test conducted.
	6.0		0.0-6.0'			
			brn sandy GRAVEL (GW), moist, loose, medium-sand well-graded gravel			
	7.0					
	8.0					
	9.0					
	10.0		6.0-10.0'			▽
			brn sandy GRAVEL (GP), wet, loose, tr. silt water-bearing			groundwater encountered 10'
	11.0		gravel predom 3/4"; up to 3"			
	12.0					
	13.0			10-20'		
				10' RUN		
	14.0			8.6' REC.		
	15.0					

ENG FORM MAR 71 1836 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. ISB-MW4

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	**Hole No.** ISB-MW4
1. PROJECT ESTCP ER-0719	2. INSTALLATION Ft Lewis, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15		brn sandy GRAVEL (GP) CONT'D			
	16.0			10-20' 10' RUN		
	17.0			8.6' REC		
	18.0					
	19.0					No visible or olfactory evidence of contamination.
	20.0					
	21.0			20-25'		
	22.0		10.0-23.0'	5' RUN		
	23.0		brn gravelly SAND (SP), wet, loose, medium to coarse sand water-bearing, 23.0-25.0'	4.8' REC		
	24.0					
	25.0		BOH = 25.0'			

ENG FORM JUN 67 1836-A (ER 1110-1-1801)

PROJECT ESTCP ER-0719

HOLE NO. ISB-MW4

Hole No. ISB-MW5

DRILLING LOG

DIVISION		INSTALLATION FORT LEWIS, WA	SHEET 1 OF 2 SHEETS
1. PROJECT ESTCP ER-0719		10. SIZE AND TYPE OF BIT Nom. 5" core barrel/6" casing	
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY		11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY BOART LONGYEAR		12. MANUFACTURER'S DESIGNATION OF DRILL track-mounted sonic	
4. HOLE NO. (As shown on drawing title and file number)	ISB-MW5	13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED — UNDISTURBED —
5. NAME OF DRILLER Jeremy Thompson		14. TOTAL NO. OF CORE BOXES	15. ELEVATION OF GROUND WATER see remarks
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED	DEG. FROM VERTICAL	16. DATE HOLE	STARTED 11/20/08 COMPLETED 11/20/08
7. THICKNESS OF OVERBURDEN —		17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK —		18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE 25.0'		19. SIGNATURE OF INSPECTOR J Powers	

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brn to blk. gravelly SILT (ML),			Boring completed as ISB down-gradient well
	1.0		Lg. pc metal 0.5' cobble 0.3'			
	2.0		moist, loose	0-10'		1037 hrs began drilling
	3.0		FILL	10' RUN		
	4.0		0.0-5.0'	6.7'		No analytical soil samples collected
	5.0		brn sandy GRAVEL (GW), moist to wet, loose, trc SILT	RECOVERY		NO PID, sheen, dye testing conducted.
	6.0					
	7.0					
	8.0		5.0-8.5'			
			Cobble (cored through) 8.5-9.0'			
	9.0		brn sandy GRAVEL (GP), wet, loose			▽ groundwater encountered ~9'
	10.0					
	11.0		9.0-11.5'			
	12.0		Silty GRAVEL (GM), some sand, wet, loose	10-20'		
	13.0		11.5-13.5'	10' RUN		
	14.0		brn sandy GRAVEL (GP), trc silt, wet, loose	9.4' REC		
	15.0					

ENG FORM MAR 71 1836 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. ISB-MW5

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	**Hole No.** ISB-MW5
1. PROJECT ESTCP ER-0719	2. INSTALLATION Ft lewis, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15		brn Sandy GRAVEL (GP) CONT'D			
	16.0		16.5' Large 6" cobble			
	17.0			10-20' 10' RUN		
	18.0			9.4' REC		
	19.0					
	20.0					no visible or olfactory evidence of contamination
	21.0			20-25'		
	22.0			5' RUN		
	23.0		13.5-24.0'	4' REC		
	24.0		brn gravelly SAND (SP), wet, loose, med. to coarse sand 24.0-25.0'			
	25.0		BOH=25.0'			

ENG FORM JUN 67 **1836-A** *(ER 1110-1-1801)*

PROJECT ESTCP ER-0719

HOLE NO. ISB-MW5

Hole No. ISB-MW6

DRILLING LOG	DIVISION	INSTALLATION FORT LEWIS, WA
		SHEET 1 OF 2 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) ISB-MW6
5. NAME OF DRILLER Jeremy Thompson
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN —
8. DEPTH DRILLED INTO ROCK —
9. TOTAL DEPTH OF HOLE 25.0'
10. SIZE AND TYPE OF BIT Nom. 5" corebarrel / 6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL track-mounted sonic
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED — UNDISTURBED —
14. TOTAL NO. OF CORE BOXES
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 11/19/08 COMPLETED 11/20/08
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING
19. SIGNATURE OF INSPECTOR J Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brn to black gravelly SILT (GM), moist, loose FILL (nails, wire) 0.0-5.5'			Boring completed as ISB downgradient well
	1.0					
	2.0			0-7' 7' RUN		1600 hrs begin drilling (11/19 2008)
	3.0			5.3' REC-OVERY		
	4.0					no analytical soil samples collected
	5.0					No PID, sheen, or dye testing conducted
	6.0		brn sandy GRAVEL (GW), moist, loose 2 3" cobbles 5.5-7.0'			
	7.0		Cobble, crushed 7.0-7.5'			
	8.0		brn sandy GRAVEL (GW), moist, (wet below ~8.5') well-graded gravel fine to 3", rounded 7.5-10.0'	7-10' 3' RUN 4' REC.		
	9.0					begin drillings 0829 @ 10' on 11/20/08
	10.0		brn silty sandy GRAVEL (GW-GM) wet, loose 10.0-11.0'			▽ Groundwater encountered ~10'
	11.0		brn sandy GRAVEL (GW), w/ minor silt, well-graded, wet, loose			
	12.0			10-20' 10' RUN		
	13.0			7.5' REC.		
	14.0					
	15.0					

ENG FORM MAR 71 1836 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. ISB-MW6

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	**Hole No.** ISB-MW6
1. PROJECT ESTCP ER-0719	2. INSTALLATION Ft Lewis, WA	**SHEET** 2 **OF** 2 **SHEETS**

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	15		brn sandy GRAVEL (GW) CONT'D			
	16.0					
	17.0			10-20' 10' RUN 7.5' REC		
	18.0					
	19.0					
	20.0		less silt below 20' (trc to none)			
	21.0		water-bearing			
	22.0			20-25' 5' RUN 3.7' REC.		No visible or olfactory evidence of contamination
	23.0					
	24.0					
	25.0		11.0-25.0' B.O.H. = 25.0'			

ENG FORM JUN 67 **1836-A** *(ER 1110-1-1801)*

PROJECT ESTCP ER-0719	HOLE NO. ISB-MW6

Hole No. ZVI-MW3

DRILLING LOG

DIVISION	
INSTALLATION	Fort Lewis, WA
SHEET	1
OF	1 SHEETS
1. PROJECT	ESTCP ER-0719
2. LOCATION (Coordinates or Station)	FORT LEWIS EGDY
3. DRILLING AGENCY	BOART LONGYEAR
4. HOLE NO. (As shown on drawing title and file number)	ZVI-MW3
5. NAME OF DRILLER	Ken Phillips
6. DIRECTION OF HOLE	☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN	—
8. DEPTH DRILLED INTO ROCK	—
9. TOTAL DEPTH OF HOLE	11.0'
10. SIZE AND TYPE OF BIT	6.5" core barrel / 6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
12. MANUFACTURER'S DESIGNATION OF DRILL	Truck-mounted Sonic
13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED — UNDISTURBED —
14. TOTAL NO. OF CORE BOXES	
15. ELEVATION OF GROUND WATER	see remarks
16. DATE HOLE	STARTED 12/5/08 COMPLETED 12/5/08
17. ELEVATION TOP OF HOLE	
18. TOTAL CORE RECOVERY FOR BORING	
19. SIGNATURE OF INSPECTOR	J Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dark-brown to black silty GRAVEL (GM) moist, loose		MAX PID in ppm	Boring completed as ZVI MW
	1.0		FILL sm roots	0-8'	14.2	
	2.0		oily appearance 0-5.5'	8' RUN		No analytical soil samples collected
	3.0			8' RECOVERY		
	4.0		0.0-5.0'		106	
	5.0		brn silty sandy GRAVEL (GW-GM), moist, loose			Sheen test: 5' slight sheen 9' No sheen
	6.0				7.0	
	7.0					
	8.0			8-11'		encountered groundwater depth not recorded.
	9.0			3' RUN	20.3	
	10.0		5.0-11.0'	2' REC		
	11.0		BOH = 11.0'			
	12.0					
	13.0					
	14.0					
	15.0					

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PROJECT ESTCP ER-0719

HOLE NO. ZVI-MW3

Hole No. ZVI-mw4

DRILLING LOG	DIVISION	INSTALLATION FORT LEWIS, WA
SHEET 1 OF 1 SHEETS		
1. PROJECT ESTCP ER-0719	10. SIZE AND TYPE OF BIT 6.5" core barrel / 6" casing	
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY	11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY BOART LONGYEAR	12. MANUFACTURER'S DESIGNATION OF DRILL Truck-mounted RotoSonic	
4. HOLE NO. (As shown on drawing title and file number) ZVI-mw4	13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED UNDISTURBED —
5. NAME OF DRILLER Ken Phillips	14. TOTAL NO. OF CORE BOXES	15. ELEVATION OF GROUND WATER see remarks
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL	16. DATE HOLE	STARTED 12/5/08 COMPLETED 12/5/08
7. THICKNESS OF OVERBURDEN —	17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK —	18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE 15.0'	19. SIGNATURE OF INSPECTOR J Powers	

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brown to black silty GRAVEL w/ cobbles (GM) FILL moist, loose roots, brick frags slick, oily appearance		MAX PID in ppm	Boring completed as ZVI MW
	1.0					
	2.0				18.6	no analytical soil samples collected
	3.0			0-10' 10' RUN 8.5' RECOVERY	23.0	
	4.0					
	5.0					
	6.0				32.7	sheen test: 4' No sheen (NS) 9' NS 14' NS
	7.0		0.0-7.5'			
	8.0		brn silty sandy GRAVEL (GW-GM), moist, loose		66	slight odor ~8'
	9.0					
	10.0		wet below 10.5'			
	11.0			10-15' 5' RUN 5' REC	11.4	▽ Groundwater enct'd ~10.5'
	12.0		7.5-12.5'			
	13.0		brn gravelly SAND (SP) wet, loose, water-bearing			
	14.0		12.5-14.0' brn sandy GRAVEL (GP) wet, loose, water-bearing 14.0-15.0'		4.4	
	15.0		BOH=15.0'			

ENG FORM MAR 71 1836 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT ESTCP ER-0719

HOLE NO. ZVI-MW4

Hole No. ZVI-MW5

DRILLING LOG

DIVISION

INSTALLATION Fort Lewis, WA

SHEET 1 OF 1 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) ZVI-MW5
5. NAME OF DRILLER Ken Phillips
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN —
8. DEPTH DRILLED INTO ROCK —
9. TOTAL DEPTH OF HOLE 15.0'
10. SIZE AND TYPE OF BIT 6.5" core barrel / 6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL Truck-mounted Rotosonic
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED — UNDISTURBED
14. TOTAL NO. OF CORE BOXES
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 12/5/08 COMPLETED 12/5/08
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING
19. SIGNATURE OF INSPECTOR J Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brown to black silty GRAVEL (GM), moist, loose FILL (wood, wire)		MAX PID in ppm:	BORING COMPLETED as ZVI MW
	1.0			0-4' 4'RUN	2.1	1535 hrs start drilling
	2.0			4' Recovery		No analytical soil samples collected
	3.0		0.0-3.0'		10.4	
			brn sandy GRAVEL, moist, loose			
	4.0		3.0-4.0'			
			dk brn to black gravel FILL, possible slough?			
	5.0			4-8' 4'RUN	12.9	difficult drilling ~4-8'
	6.0					
	7.0			4.4' REC	14.2	"No sheen" tests @ 5,7,10.5'
	8.0		4.0-8.0'			
			brn silty sandy GRAVEL (GW-GM), moist to wet, loose			
	9.0			8-15'	5.9	
	10.0			7'RUN		▽ groundwater encountered 10.0'
	11.0		8.0-11.5'	6.6' REC.	3.0	
			brn gravelly SAND (SP), wet, loose, water-bearing			
	12.0					No visible or olfactory evidence of contamination.
	13.0				2.8	
	14.0		11.5-14'			
			brn sandy GRAV (GP), wet, loose water-bearing 2-4" cobbles @ 14' 14.0-15.0			
	15.0		BOH = 15.0'			

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PROJECT ESTCP ER-0719

HOLE NO. ZVI-MW5

Hole No. ZVI-MW6

DRILLING LOG

DIVISION

INSTALLATION FORT LEWIS, WA

SHEET 1 OF 1 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) ZVI-MW6
5. NAME OF DRILLER Ken Phillips
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN —
8. DEPTH DRILLED INTO ROCK —
9. TOTAL DEPTH OF HOLE 15.0'
10. SIZE AND TYPE OF BIT 6.5" core barrel / 6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL Truck-mounted Rotosonic
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED — UNDISTURBED
14. TOTAL NO. OF CORE BOXES
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 12/6/08 COMPLETED 12/6/08
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING
19. SIGNATURE OF INSPECTOR J Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dk brown to black silty sandy GRAVEL (Gm) FILL moist, loose (metal, wood pcs)		MAX PID in ppm:	Boring completed as ZVI MW
	1.0					0818 hrs start drilling
	2.0			0-5'	0.9	NO analytical soil samples collected
	3.0			5' RUN		
	4.0			4.7' recovery	2.4	
	5.0					
	6.0			5-10'	2.7	
	7.0			5' RUN 3.3' REC		
	8.0		0.0-9.0'			
	9.0		brown sandy GRAVEL (GW) trc silt, wet, loose		10.9	▽ Groundwater encountered 9.0'
	10.0					10.0' No sheen
	11.0		10.0-12.0'	10-15' 5' RUN	1.3	No visible or olfactory evidence of contamination
	12.0		brown sandy GRAVEL (GP), wet, loose, poorly-sorted water-bearing	5' REC		
	13.0				1.5	
	14.0		12.0-15.0'			
	15.0		BOH = 15.0'			

Hole No. ZVI-MW8

DRILLING LOG

DIVISION	INSTALLATION FORT LEWIS, WA
SHEET 1 OF 1 SHEETS	
1. PROJECT ESTCP ER-0719	10. SIZE AND TYPE OF BIT 6" CORE BARREL / 6" CASING
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY	11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
3. DRILLING AGENCY BOART LONGYEAR	12. MANUFACTURER'S DESIGNATION OF DRILL TRUCK-MOUNTED ROTOSONIC
4. HOLE NO. (As shown on drawing title and file number) ZVI-MW8	13. TOTAL NO. OF OVER-BURDEN SAMPLES: DISTURBED — UNDISTURBED —
5. NAME OF DRILLER KEN PHILLIPS	14. TOTAL NO. OF CORE BOXES
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL	15. ELEVATION OF GROUND WATER see remarks
7. THICKNESS OF OVERBURDEN	16. DATE HOLE: STARTED 12/4/08 COMPLETED 12/4/08
8. DEPTH DRILLED INTO ROCK	17. ELEVATION TOP OF HOLE
9. TOTAL DEPTH OF HOLE 15.0'	18. TOTAL CORE RECOVERY FOR BORING
	19. SIGNATURE OF INSPECTOR J Powers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		dark brown to black silty GRAVEL (GW), moist, loose		PID MAX in ppm:	Boring completed as downgradient ZVI MW
	1.0		FILL 0.0-2.0'		4.7	1443 hrs began drilling
	2.0		brown sandy GRAVEL (GW) moist, loose well-graded.			
	3.0					No analytical soil samples collected.
	4.0			0-10' 10' RUN	1.0	
	5.0			8.5' RECOVERY		
	6.0				1.7	
	7.0					
	8.0					
	9.0		wet below 9.0'		5.6 ∇	Groundwater enct'd 9' bgs
	10.0		2.0-10.0' brown SAND (SP), wet, loose med-coarse			9.0' no sheen
	11.0		10.0-11.5'		3.0	11.0' No sheen
	12.0		brown sandy GRAVEL (GP) wet, loose coarse gravel	10-15' 5' RUN		No visible or olfactory evidence of contamination
	13.0		water-bearing	3.7' REC		
	14.0		11.5-15.0'		1.0	
	15.0		BOH=15.0'			

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PROJECT ESTCP-ER0719

HOLE NO. ZVI-MW8

Hole No. ZVI-SB1

DRILLING LOG	DIVISION	INSTALLATION FORT LEWIS, WA	SHEET 1 OF 1 SHEETS
1. PROJECT ESTCP ER-0719		10. SIZE AND TYPE OF BIT Nom. 4" core barrel / uncased.	
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY		11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY BOART LONGYEAR		12. MANUFACTURER'S DESIGNATION OF DRILL TRAIK-MOUNTED ROTOSONIC	
4. HOLE NO. (As shown on drawing title and file number)	ZVI-SB-1	13. TOTAL NO. OF OVER-BURDEN SAMPLES	DISTURBED / UNDISTURBED
5. NAME OF DRILLER Jeremy Thompson		14. TOTAL NO. OF CORE BOXES —	15. ELEVATION OF GROUND WATER see remarks
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL		16. DATE HOLE	STARTED 6/5/09 COMPLETED 6/5/09
7. THICKNESS OF OVERBURDEN		17. ELEVATION TOP OF HOLE	
8. DEPTH DRILLED INTO ROCK N/A		18. TOTAL CORE RECOVERY FOR BORING	
9. TOTAL DEPTH OF HOLE 15.0'		19. SIGNATURE OF INSPECTOR J Powers	

ELEVATION a	DEPTH (FEET) b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		brown topsoil, roots, gravel 0.0-0.5 dry, loose		PID	1130 hrs begin drilling
	1.0		dark brown to black sandy GRAVEL (GW-GM), FILL moist, slightly cohesive		(ppm)	Soil analytical samples collected @ 8, 10, 13 Ft bgs
	2.0			0-10'		
	3.0		50% gravel, rounded, up to 2" diam.	10' RUN		Soil moisture composite sample collected in vados zone
	4.0			7.4' REC-OVERY	<2.7	ZVI iron distribution samples collected.
	5.0					
	6.0		pieces wood @ 6-6.5'			Sheen testing: 5' No sheen (NS) 9.5' NS 14' NS
	7.0		nail @ 7' 0.5-7.5'			
	8.0		brown gravelly SAND (SP), few 3" cobbles, rounded, coarse sand wet, loose		2.7 ppm	▽ groundwater encountered Approx 8'
	9.0		7.5-10.0'		4.4 ppm	dtw @ well ZVI-MW1 2.4' southwest of boring: 7.14' bgs
	10.0		brown GRAVEL (GP), poorly-graded, 3/4" to 1" diam, wet, loose, water-bearing 10.0-11.0'			
	11.0		brown gravelly SAND (SP), wet, loose	10-15'		
	12.0		11.0-12.5	5' RUN		Immediately backfilled boring upon completion w/
	13.0		light brown sandy GRAVEL w/minor silt (GW-GM), wet, loose	5.0' REC.	7.2 ppm	1.5 bags 3/8" diam Holeplug bentonite chips
	14.0					
	15.0		12.5-15.0' BOH = 15.0'			

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PROJECT ESTCP ER-0719

HOLE NO. ZVI-SB1

Hole No. ZVI-SB2

DRILLING LOG	DIVISION	INSTALLATION FORT LEWIS, WA	SHEET 1 OF 1 SHEETS

1. PROJECT ESTCP ER-0719
2. LOCATION (Coordinates or Station) FORT LEWIS EGDY
3. DRILLING AGENCY BOART LONGYEAR
4. HOLE NO. (As shown on drawing title and file number) ZVI-SB2
5. NAME OF DRILLER Jeremy Thompson
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED DEG. FROM VERTICAL
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK N/A
9. TOTAL DEPTH OF HOLE 15.0'
10. SIZE AND TYPE OF BIT Nom. 5" core barrel/6" casing
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL TRACK-MOUNTED ROTOSONIC
13. TOTAL NO. OF OVER-BURDEN SAMPLES DISTURBED UNDISTURBED
14. TOTAL NO. OF CORE BOXES —
15. ELEVATION OF GROUND WATER see remarks
16. DATE HOLE STARTED 6/5/09 COMPLETED 6/5/09
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING
19. SIGNATURE OF INSPECTOR JPowers

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOV-ERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		brown topsoil, w/roots, dry 0-0.5'		PID (ppm)	1209 hrs began drilling
	1.0		dark brown to black Silty GRAVEL (GM), organics/ wood pieces, small pcs. metal & nails			Soil analytical samples collected @ 8,10,12.5-13 ft bgs
	2.0		2" white ceramic frag @ 2'	0-10'		
	3.0		few cobbles moist, loose	10' RUN		Soil moisture composite sample collected in vadose zone
	4.0			6.2' RECOVERY	<10	ZVI iron distribution samples collected.
	5.0					
	6.0					Sheen testing: 3.5' No sheen (NS) 10' NS
	7.0		0.5-7.0' yellow-brown sandy GRAVEL (GP), wet, loose			12.5' slight sheen & solvent odor ▽
	8.0				14.4 ppm	groundwater encountered approx. 7.5' bgs
	9.0		same except color change to brown @ 9'			
	10.0		7.0-10.0' dark-gray GRAVEL w/ some sand (GP), rounded, wet, loose		19.9 ppm	dtw @ well ZVI-INJ1 1.8' to North-northwest of boring: 7.27' bgs
	11.0		Water-bearing	10-15'		
	12.0		4" cobble @ 14'	5' RUN 5' REC.	96 ppm	Immediately backfilled boring upon completion w/ 1.5 bags 3/8" diam Holeplug bentonite chips
	13.0		10.0-13.5' brown sandy GRAVEL (GP) wet, loose, ~55% grav 45% sand			
	14.0					
	15.0		13.5-15.0' BOH = 15.0'			

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PROJECT ESTCP ER-0719

HOLE NO. ZVI-SB2

APPENDIX C
LABORATORY TEST REPORT

Bench-Scale Treatability Test Results: Reactivity of Zero-Valent Iron Emplaced by Polymer Solutions

Prepared for:
Environmental Security Technology Certification Program

Prepared by:
North Wind, Inc.

Pacific Northwest National Laboratory

October 2008

NWI-1504-002

Bench-Scale Treatability Test Results: Reactivity to Zero-Valent Iron Emplaced by Polymer Solutions

October 2008

Prepared for:
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Contract No. ER-0719/PNNL 52036

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ACRONYMS

EGDY	East Gate Disposal Yard
ESTCP	Environmental Security Technology Certification Program
FID/ECD	flame ionization detector/electrochemical detector
GC	gas chromatograph
NAPL	nonaqueous phase liquid
TCE	trichloroethene
ZVI	zero-valent iron

Bench-Scale Treatability Test Results: Reactivity of Zero-Valent Iron Emplaced by Polymer Solutions

1. BACKGROUND

Zero-valent iron (ZVI) has been developed and applied for in situ remediation of inorganic compounds and chlorinated solvents through engineered permeable reactive barriers. Use of injectable ZVI particles for in situ remediation is also being developed and tested, including Environmental Security Technology Certification Program (ESTCP) project ER-0719 efforts (Lynch et al. 2007) and previous (Quinn et al. 2005) applications for treatment of chlorinated solvent source zones. Reaction mechanisms for ZVI and chlorinated solvents, including the proposed target compound trichloroethene (TCE), have been described by Roberts et al. (1996) and are illustrated along with potential microbially-mediated reactions in Figure 1. The reductive elimination reaction that occurs with ZVI and TCE is favorable for in situ remediation because no persistent hazardous reaction products result from the reaction, in contrast to microbially catalyzed reductive dechlorination of TCE. Initial kinetics of TCE dechlorination by ZVI are relatively fast and have been studied as a function of TCE concentration (Orth and Gillham 1996; Grant and Kueper 2004), type of iron (Miehr et al. 2004; Lin and Lo 2005; Ebert et al. 2006), and presence of multiple chlorinated solvents and other organic and inorganic species (Dries et al. 2004; Dries et al. 2005 D'Andrea et al. 2005). While initial kinetics of ZVI reactions are relatively fast, reaction kinetics can diminish over time due to corrosion and mineral precipitation, and the rate and extent of decrease in reaction rates are a function of groundwater chemistry (Farrell et al. 2000; D'Andrea et al. 2005; Kohn and Roberts 2006).

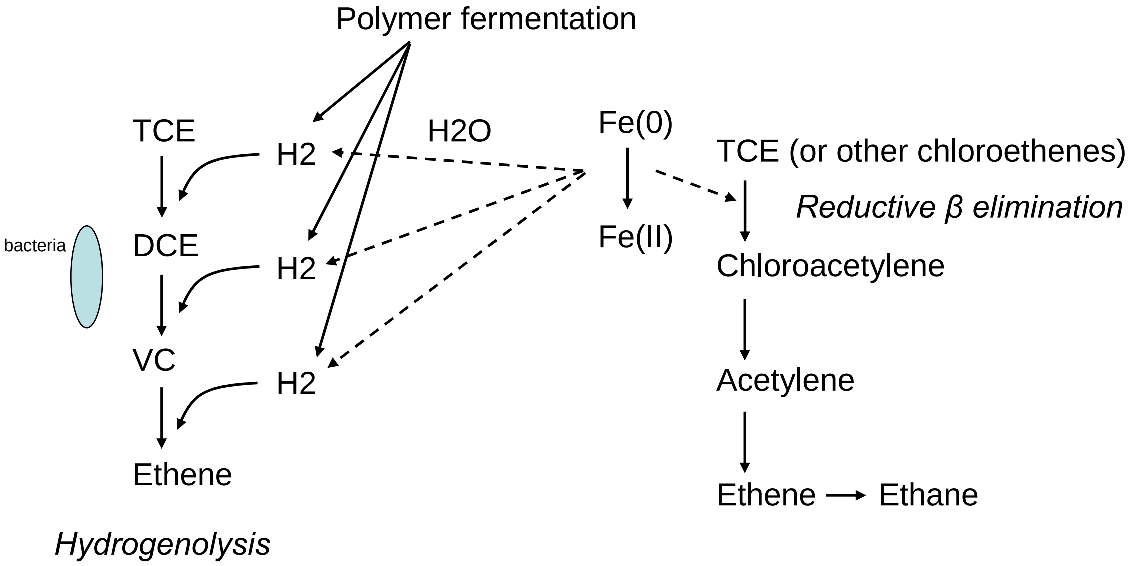

Figure 1. Potential TCE transformation reactions with ZVI. The ER-0719 project work is focusing on the reductive elimination pathway.

A key aspect of ZVI application is successful distribution of the ZVI particles in the subsurface and contact and reaction with the contaminant of concern. Installation via trenching has been implemented but is not relevant for some situations. ZVI can be injected as either nano-scale or micron-scale particles. The focus of this proposed work is use of micron-scale particles to establish a discrete zone of iron-amended aquifer at a target treatment location within a chlorinated solvent source area.

Micron-scale ZVI, and not nano-scale ZVI, was selected for the ESTCP field demonstration for the following reasons:

1. Nano-scale ZVI could potentially be extracted through the sampling system and be lost downgradient rather than remain as a reactive zone in the aquifer.

2. Micron-scale ZVI particles have a longer reactive lifetime.

While micron-scale particles are preferred, injection of micron-scale particles is problematic due to the high density of the iron particles, which limits the distance particles can be injected from a well. Research on improved injection strategies for iron particles has been conducted using emulsified oil (Quinn et al. 2005), hydrofracturing of the aquifer (www.GeoSierra.com), use of carrier particles (Schrick et al. 2004), and co-injection of iron with polymers (Cantrell et al. 1997a, b; DOE 2004; Oostrom et al. 2005, 2007). Results from a field test of emulsified ZVI revealed problems with the uniformity of the injection. In addition, it promoted microbial reductive dechlorination as a major reaction process stimulated by the emulsified oil rather than exclusively the reductive elimination reaction from the injected iron (Quinn et al. 2005). At the elevated temperatures required for the field pilot demonstration, significant biological reductive dechlorination is not favored and therefore, emulsified ZVI is not desirable because the effectiveness of the product relies on biological reduction.

Emplacement of ZVI via hydrofracturing has been applied for multiple purposes in the subsurface (www.GeoSierra.com; EPA 1993) but is not suitable for many sites due to the site geology and does not result in a uniform distribution of injected materials around the injection point. Carrier particles (i.e., hydrophilic carbon and poly acrylic acid) have been tested to promote better transport of iron through porous media. However, these tests (Schrick et al. 2004), conducted in small downward-flow columns, have not addressed particle density issues and injection uniformity from an injection well and therefore, are not poised for field testing.

For the thermally-enhanced ZVI field demonstration, the use of shear-thinning polymers to distribute micron-scale ZVI has significant promise in meeting project objectives. These polymers have been shown to promote uniform distribution of ZVI particles in columns and large-scale wedge-shaped flow cells (Cantrell et al. 1997a, b; DOE 2004; Oostrom et al. 2005, 2007). In contrast to the other mechanisms for ZVI injection that rely on encapsulating or carrying the iron particles, the relatively low concentrations of polymer required (fraction of a percent) minimize the amount of organic carbon added to the aquifer. For the ESTCP demonstration, limiting the amended carbon is desired to minimize the biotic reactions in the ZVI test cell making the data interpretation of relative abiotic degradation rates under ambient and heated conditions more straightforward.

The cost benefit of thermally-enhanced processes relies on offsetting the cost of heating by more efficient in situ treatment. Under this condition, it is important to effectively deliver a sufficient amount of reactive ZVI to take advantage of the increased reaction rates at higher temperatures and complete treatment within a short period of time. The delivery method must be suitable for emplacing the ZVI and enabling the abiotic degradation mechanisms to proceed unhindered (i.e., without interference from encapsulation materials). For these reasons, polymer assisted ZVI injection was selected as the most promising injection method for the ESTCP field test. Existing laboratory data provide a good basis for designing an effective injection strategy for the field test. However, the impact of the polymer on the ZVI reactivity needs to be determined to confirm that the polymer does not negatively impact the ability of the emplaced ZVI to degrade contaminants. A key performance metric of the field test will be examining the effectiveness of the treatment in terms of relative degradation rates under ambient and heated condition. Thus, the potential impacts of the polymer on ZVI reactivity needs to be understood in order to more effectively interpret data collected during the field demonstration.

2. OBJECTIVES

Distribution of ZVI particles for the ESTCP field test using polymer solutions was selected as the most promising technique to meet the needs of the field test (as discussed above). The characteristics of the polymer delivery will enhance the ability to distribute ZVI more uniformly in the target treatment zone compared to other potential delivery methods for micron-scale ZVI. The injection will emplace both ZVI and polymer within the test zone. While the reactivity of ZVI is relatively well known in aqueous media, the impact of the polymer on reactivity has not been measured. The reactivity of ZVI in the polymer was determined to 1) finalize selection of the polymer as the delivery mechanism for the ZVI, 2) determine injection parameters such as the quantity of ZVI/polymer addition, and 3) provide baseline reaction kinetics to assist in field data interpretation.

3. METHODS

Two different experimental methods were employed in evaluating the dechlorination reactivity of ZVI under conditions relevant to the design of the field test. One set of experiments was conducted in serum bottles with Fort Lewis sediment, water or water and SlurryPro, ZVI, and TCE. These experiments included two different initial TCE concentrations and incubation at 20 and 40^{o}C. This experimental method provides for testing of ZVI reactivity under conditions approximating the field site conditions. The maximum laboratory incubation of 40^{o}C is lower than the targeted temperature for the field test (50 to 55^{o}C). However, preliminary laboratory tests at higher incubation temperatures were problematic and consistent results could only be obtained at 40^{o}C or lower. Additionally, while 55^{o}C is the final target temperature for the field test, the likely heating rate of about 1 to 2^{o}C/day will result in a relatively long period of the test when the temperatures are between 12^{o}C (ambient) and 55^{o}C. Site sediments were glacial outwash material obtained from a borehole within the TCE plume about 100 yards downgradient of the East Gate Disposal Yard (EGDY). The other set of experiments was conducted in serum bottles with water or water and SlurryPro, ZVI, and TCE. These experiments included two different initial TCE concentrations, two different ZVI concentrations, and incubation at 20 and 40^{o}C. Chloride concentrations were used as the primary measure of dechlorination. A stoichiometry of 3 moles of chloride per mole of TCE dechlorinated was used to convert chloride concentrations to equivalent TCE concentrations. All treatments were conducted in duplicate and experimental methods included control treatments to monitor for TCE loss and to set baseline chloride levels for comparison to active treatments. The headspace for all treatments was nitrogen gas. The experimental matrix is summarized in Table 1.

Experiments were conducted in a 250-mL serum bottle sealed with VICI Mininert™ valves, a nitrogen headspace, and the specific treatment components defined in Table 1. TCE concentrations were analyzed from headspace samples injected directly to a gas chromatography using Static Headspace Sampling and injected on a Agilent Technologies 6890N gas chromatograph (GC) with a DB-624 column and flame ionization detector/electrochemical detector (FID/ECD) detection. Aqueous chloride samples were analyzed by ion chromatography using a Dionex system with a AS11HC anion exchange column and suppressed conductivity detection.

Table 1. Treatment matrix.

Type	Water (mL)	Sediment (g)	ZVI (g)	SlurryPro (%)	TCE (g)	Temperature (^oC)
High ZVI Loading	150	50	30	--	0.16	20
	150	50	30	0.02	0.16	20
	150	50	30	--	0.016	20
	150	50	30	0.02	0.016	20
	150	50	--	--	0.16	20
	150	--	30	--	0.16	20
	150	--	--	--	0.16	20
	150	50	30	--	0.16	40
	150	50	30	0.02	0.16	40
	150	50	30	--	0.016	40
	150	50	30	0.02	0.016	40
	150	50	--	--	0.16	40
	150	--	30	--	0.16	40
	150	--	--	--	0.16	40
Low ZVI Loading	190	--	1.9	--	0.22	20
	190	--	1.9	0.02	0.22	20
	190	--	1.9	--	0.02	20
	190	--	1.9	0.02	0.02	20
	190	--	1.9	--	0.22	40
	190	--	1.9	0.02	0.22	40
	190	--	1.9	--	0.02	40
	190	--	1.9	0.02	0.02	40

4. RESULTS

The results of the bench-scale treatability testing are presented in terms of reaction stoichiometry and dechlorination rate for the high and low ZVI loading rate experiments. The high ZVI loading experiments provided excess ZVI with a focus on quantifying the dechlorination rate under the different experimental conditions. The low loading experiments were designed to provide information about the stoichiometry of the dechlorination reaction and supplemental rate information.

4.1 Stoichiometry

4.1.1 High ZVI Loading

The high ZVI loading experiments were conducted with ZVI added such that full dechlorination represents a reaction stoichiometry of 0.005gTCE/gFe in treatments with high initial TCE concentrations (0.16 g TCE added).

4.1.2 Low ZVI Loading

TCE dechlorination stoichiometry was calculated based on chloride analysis as the end product of dechlorination. Estimates for the quantity of TCE dechlorinated per amount of ZVI are shown in Table 2 for each treatment condition. The dechlorination response was highly variable in treatments with low ZVI loading. Higher levels of dechlorination were observed in treatments incubated at 40^{o}C. Lack of significant dechlorination was not correlated with presence of SlurryPro. Lack of dechlorination activity was not systematic. Based on the results from the high ZVI loading, we believe that the low loading rate may have been close to a threshold of reactivity where small differences in particle reactivity of the ZVI caused a situation where TCE could not be effectively dechlorinated.

Table 2. Measured TCE dechlorination extent for low ZVI loading.

SlurryPro (%)	TCE (g)	Temperature (^{o}C)	gTCE/gFe (replicate 1)	gTCE/gFe (replicate 2)
--	0.22	20	0.0013	0.0015
0.02	0.22	20	0.0011	0.0012
--	0.02	20	0.0007	0.0007
0.02	0.02	20	0.0004	0.0004
--	0.22	40	0.0342	0.0056
0.02	0.22	40	0.0048	0.0040
--	0.02	40	0.0019	0.0011
0.02	0.02	40	0.0020	0.0014

4.2 Dechlorination Rate

4.2.1 High ZVI Loading

The dechlorination rate in experiments at the high ZVI loading rate was dependent on temperature, TCE concentration, and the presence of site sediment. Figures 2 and 3 illustrate the observed TCE dechlorination in treatments with high initial TCE concentration (0.16 g TCE added) at 20 and 40°C, respectively. Figures 4 and 5 illustrate observed TCE dechlorination in treatments with low initial TCE concentration (0.016 g TCE added) at 20 and 40°C, respectively. In treatments containing site sediments, the dechlorination rates appear to be attenuated compared to the water-only rates. Table 3 shows the dechlorination rate and extent derived for each treatment. Rates are computed as both a pseudo first-order rate coefficient and as a zero-order reaction. Comparing the first-order rate coefficients at the two TCE concentrations that were tested and examining the shape of the TCE concentration profile in Figure 2 demonstrates that the reaction rate is not strictly first order. However, comparing the zero-order rates for the two TCE concentrations that were tested demonstrates there is a concentration dependence to the reaction. Under the field test conditions, the groundwater concentrations will be controlled by the relative rate of reaction to the rate of mass transfer from nonaqueous phase liquid (NAPL) and sorbed phase TCE. The laboratory data will be used for comparison to field data in evaluating the overall processes that occur during the field test.

The zero-order reaction rates in SlurryPro range from about 80 to over 100% of the rates in water. Thus, the impact of SlurryPro on the ZVI reactions is deemed to be minimal. For treatments containing site sediments, reaction rates at 40°C are about 2.5 to 4 times faster than rates at 20°C. As such, the reaction rate is expected to be significantly enhanced by the heating process during the field test.

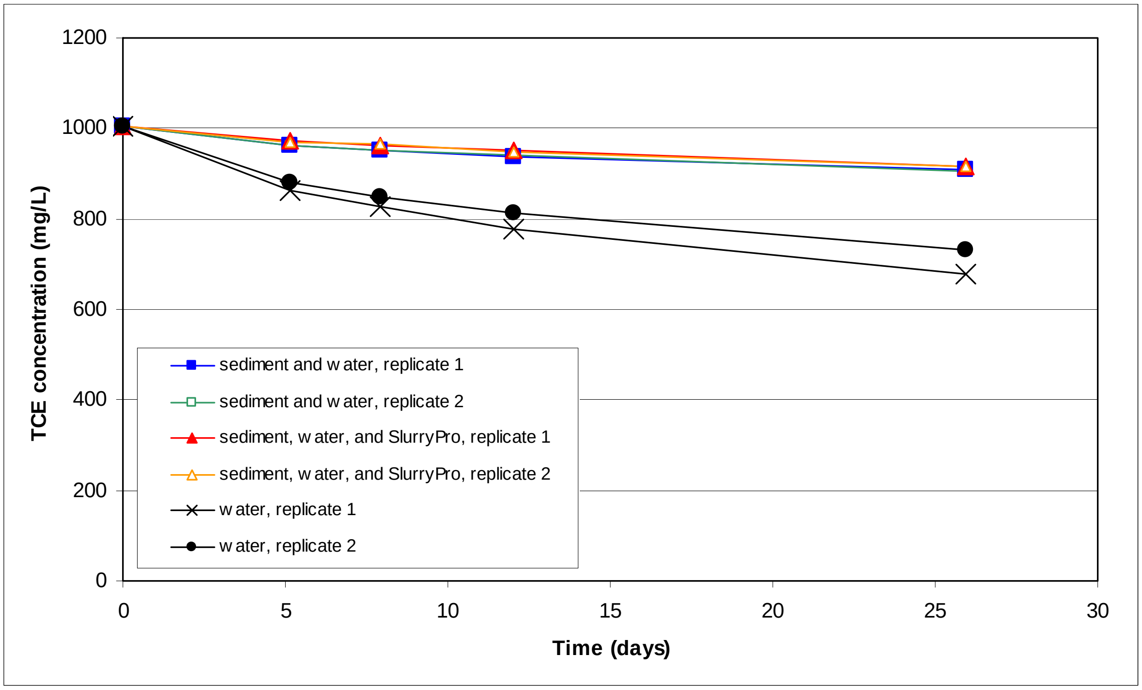

Figure 2. TCE concentration over time in experiments with high initial TCE concentrations (0.16 g TCE added) at 20°C. Note: Concentrations of TCE on the figure were computed from the added TCE mass and the chloride measurements assuming that all of the TCE is in the aqueous phase.

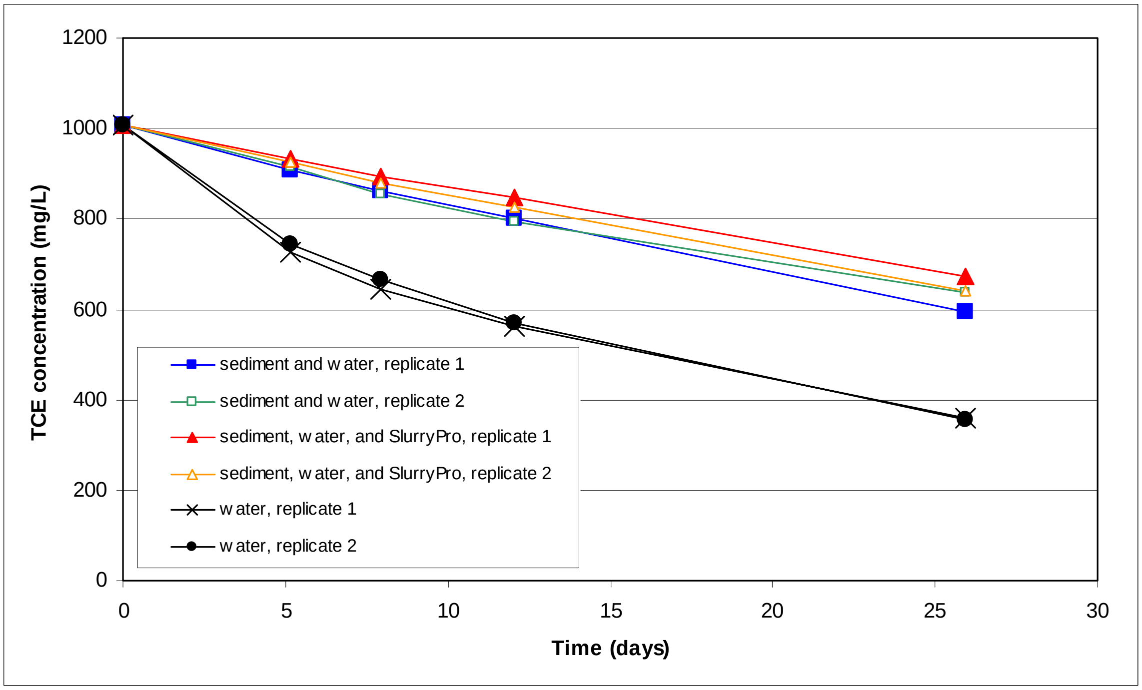

Figure 3. TCE concentration over time in experiments with high initial TCE concentrations (0.16 g TCE added) at 40°C. Note: Concentrations of TCE on the figure were computed from the added TCE mass and the chloride measurements assuming that all of the TCE is in the aqueous phase.

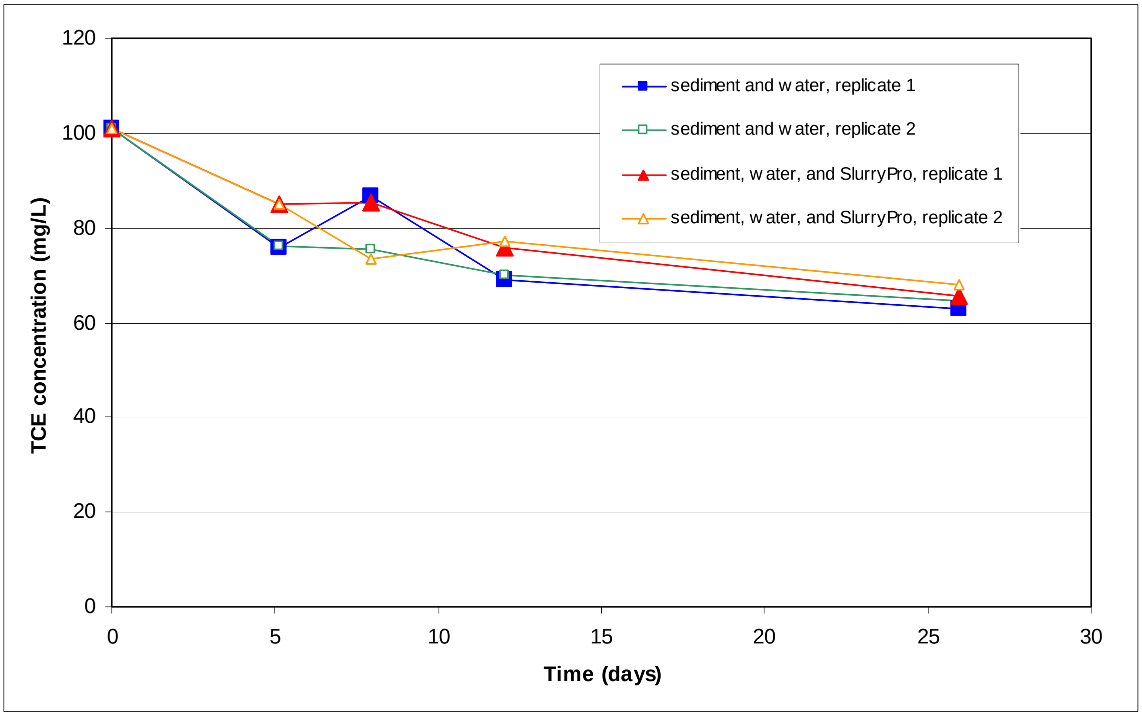

Figure 4. TCE concentration over time in experiments with low initial TCE concentrations (0.016 g TCE added) at 20°C. Note: Concentrations of TCE on the figure were computed from the added TCE mass and the chloride measurements assuming that all of the TCE is in the aqueous phase.

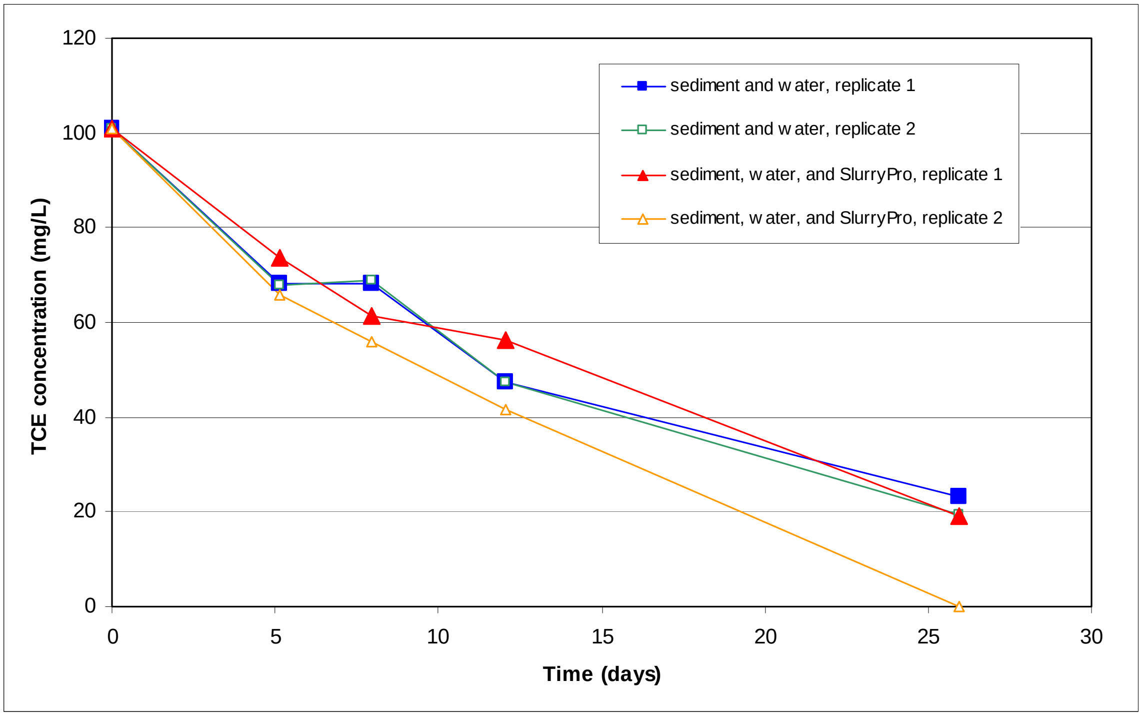

Figure 5. TCE concentration over time in experiments with low initial TCE concentrations (0.016 g TCE added) at 40^{o}C.

Table 3. Dechlorination rate and extent in high ZVI loading experiments.

Sediment (g)	SlurryPro (%)	TCE (g)	Temperature (^{o}C)	Replicate 1		Replicate 2	
				k value[a] (1/d)	g-TCE/d	k value[a] (1/d)	g-TCE/d
50	--	0.16	20	0.0040	0.0006	0.0040	0.0006
50	0.02	0.16	20	0.0037	0.0005	0.0037	0.0005
50	--	0.016	20	0.0182	0.0002	0.0172	0.0002
50	0.02	0.016	20	0.0166	0.0002	0.0153	0.0002
--	--	0.16	20	0.0151	0.0019	0.0122	0.0016
50	--	0.16	40	0.0204	0.0024	0.0176	0.0021
50	0.02	0.16	40	0.0154	0.0019	0.0174	0.0021
50	--	0.016	40	0.0565	0.0005	0.0635	0.0005
50	0.02	0.016	40	0.0638	0.0005	0.0733	0.0006
--	--	0.16	40	0.0398	0.0038	0.0399	0.0038

a. k value is the pseudo first order rate coefficient calculated from the $C=C_oe^{(-kt)}$ based on the initial TCE and the TCE dechlorinated after 26 days of incubation.

4.2.2 Low ZVI Loading

Because the dechlorination response was highly variable for low ZVI loading treatments, dechlorination rates were not calculated.

5. DISCUSSION RELATIVE TO TEST OBJECTIVES

The laboratory tests were conducted to 1) finalize selection of the polymer as the delivery mechanism for the ZVI, 2) determine injection parameters (i.e., quantity of ZVI/polymer addition), and 3) provide baseline reaction kinetics to assist in field data interpretation.

Laboratory tests indicate that presence of SlurryPro has only a minor effect on the rate and extent of dechlorination. Thus, delivery of the ZVI using the polymer is viable at the polymer concentrations shown to provide the best ZVI distribution in bench-scale wedge-shaped flow cell tests (Oostrom et al. 2007). Increasing the system temperature further minimizes the impact of the polymer on the dechlorination rate and extent catalyzed by the ZVI.

Data for the stoichiometry (i.e., extent) of dechlorination with ZVI are variable due to the variation in dechlorination response for the low ZVI loading treatments. However, these data, in conjunction with the observed responses at the high ZVI loading rate, provide information to support the injection design for the field test. The average stoichiometry for the low ZVI loading treatments at 40°C (most consistent data) and for the high level of initial TCE was 1.2 g-TCE/100 g-ZVI with a maximum value of 3.4 g-TCE/100 g-ZVI. Using a range from the average to the maximum stoichiometry value, 275 to 800 kg of ZVI would be required to dechlorinate 10 kg of TCE in the field test. The low end of the range of laboratory measured stoichiometry was not used in this estimate (e.g., 20°C and low initial TCE data) because the field test conditions will be primarily for the higher temperature and for high TCE mass loading (source zone). The calculated range of ZVI required for the field test can be delivered to the test zone using a weight percentage of ZVI in the injection fluid that is within the range tested in the previous bench-scale experiments (Oostrom et al. 2007). The ZVI injection concentration and target total ZVI mass will be evaluated based on the site characterization data. The injection design will need to balance:

- Uncertainties in the TCE mass estimate within the target zone,
- Uncertainty in the stoichiometry that will be obtained in the field,
- Material cost,
- Increased potential for injection problems with higher total ZVI mass to be injected, and
- Potential for phased injection, whereby the need for and quantity of a second ZVI injection can be determined based on the response observed from the initial injection (e.g., similar to reinjection procedures for bioremediation and other reagent-based treatments).

The dechlorination response was improved with increased temperature (40°C) in terms of reduced variability in low ZVI loading treatments and the overall rate of dechlorination. It is likely that in the field, dechlorination at ambient temperature (~12°C) will be minimal. However, dechlorination will be stimulated by increasing the temperature to 40°C and higher. The laboratory data provided rate information for comparison to data that will be collected during the field test.

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APPENDIX D
ANALYTICAL DATA

Table 1a. ISB Gore Analytical Results

Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ISB FluxA	26-Jan-09	0.25	1.00E-02	ND	ND	ND	ND	3.00E-02	1.06E+00	ND	4.21E+00
ISB FluxA	09-Mar-09	0.25	ND	ND	ND	ND	ND	2.50E-01	ND	ND	6.00E-02
ISB FluxA	9-Apr-09	0.25	ND	ND	ND	ND	ND	ND	6.30E-01	ND	5.50E-01
ISB FluxA	06-May-09	0.25	ND	ND	ND	ND	ND	ND	5.77E-01	ND	2.00E-02
ISB FluxA	9-Jul-09	0.25	1.57E-01	ND	ND	ND	ND	NA	9.23E-01	4.00E-02	1.90E+01
ISB FluxA	26-Aug-09	0.25	1.21E+00	ND	ND	ND	ND	NA	5.36E-01	1.45E-01	6.10E+01
ISB FluxA	18-Nov-09	0.25	ND	ND	ND	ND	ND	NA	2.15E-01	ND	1.84E-01
ISB FluxA	18-Dec-09	0.25	ND	ND	ND	ND	ND	NA	1.06E+00	ND	1.60E-02
ISB FluxA	24-Feb-10	0.25	ND	ND	ND	ND	ND	NA	6.83E-02	ND	4.10E-02
Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ISB FluxB	26-Jan-09	0.25	1.30E-01	ND	ND	ND	ND	9.00E-02	4.78E-01	ND	2.78E+01
ISB FluxB	09-Mar-09	0.25	ND	ND	ND	ND	ND	1.00E-02	ND	ND	1.59E+00
ISB FluxB	9-Apr-09	0.25	3.00E-02	ND	ND	ND	ND	3.00E-02	5.80E-01	ND	5.58E+00
ISB FluxB	06-May-09	0.25	ND	ND	ND	ND	ND	ND	9.01E-01	ND	2.22E+00
ISB FluxB	9-Jul-09	0.25	2.60E+00	ND	ND	ND	ND	NA	7.84E-01	2.73E-01	1.75E+02
ISB FluxB	26-Aug-09	0.25	1.22E-01	ND	ND	ND	ND	NA	4.97E-01	4.50E-02	1.81E+01
ISB FluxB	18-Nov-09	0.25	ND	ND	ND	ND	ND	NA	3.91E-01	ND	1.47E-01
ISB FluxB	18-Dec-09	0.25	ND	ND	ND	ND	ND	NA	1.36E+00	ND	6.93E-01
ISB FluxB	24-Feb-10	0.25	ND	ND	ND	ND	ND	NA	4.32E-02	ND	3.44E-01
Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ISB FluxC	26-Jan-09	0.25	1.00E-02	ND	ND	ND	ND	ND	4.95E-01	ND	2.90E+00
ISB FluxC	09-Mar-09	0.25	ND	ND	ND	ND	ND	1.70E-01	ND	ND	2.00E-02
ISB FluxC	9-Apr-09	0.25	ND	ND	ND	ND	ND	ND	3.50E-01	ND	1.06E+00
ISB FluxC	06-May-09	0.25	ND	ND	ND	ND	ND	ND	2.16E-01	ND	ND
ISB FluxC	9-Jul-09	0.25	6.00E-02	ND	ND	ND	ND	NA	4.78E-01	ND	1.17E+01
ISB FluxC	26-Aug-09	0.25	7.00E-02	ND	ND	ND	ND	NA	4.87E-01	ND	1.27E+01
ISB FluxC	18-Nov-09	0.25	ND	ND	ND	ND	ND	NA	3.85E-01	ND	9.68E-01
ISB FluxC	18-Dec-09	0.25	ND	ND	ND	ND	ND	NA	1.22E+00	ND	2.35E-01
ISB FluxC	24-Feb-10	0.25	ND	ND	ND	ND	ND	NA	ND	ND	1.40E-01
Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ISB-MW1	26-Jan-09	7	1.57E+01	ND	ND	ND	ND	6.20E-01	1.36E+01	3.70E-01	1.62E+02
ISB-MW1	09-Mar-09	7	1.32E+00	ND	ND	ND	ND	6.00E-02	ND	ND	1.48E+01
ISB-MW1	9-Apr-09	3	5.60E-01	ND	ND	ND	ND	3.00E-01	2.60E+00	1.60E-01	5.70E+01
ISB-MW1	06-May-09	3	2.56E+00	ND	ND	ND	ND	6.40E-01	1.32E+00	7.30E-01	1.16E+02
ISB-MW1	9-Jul-09	7	5.03E-01	ND	ND	ND	ND	NA	8.95E+00	4.60E-02	2.93E+01
ISB-MW1	26-Aug-09	7	1.18E+00	ND	ND	ND	ND	NA	6.12E+00	1.34E-01	4.88E+01
ISB-MW1	18-Nov-09	7	3.98E+00	ND	ND	ND	ND	NA	4.35E+00	2.88E-01	5.30E+01
ISB-MW1	18-Dec-09	7	6.92E+01	1.11E+01	ND	ND	ND	NA	4.06E+01	1.34E+00	1.86E+01
ISB-MW1	24-Feb-10	3	4.85E+01	3.38E+00	ND	ND	ND	NA	1.96E+00	4.28E-01	8.33E+01
Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)

ISB-MW2	26-Jan-09	7	2.89E+01	ND	ND	ND	ND	2.20E-01	5.32E+00	9.50E-01	4.37E+01
ISB-MW2	09-Mar-09	7	3.89E+00	ND	ND	ND	ND	4.00E-02	ND	1.00E-01	4.88E+00
ISB-MW2	9-Apr-09	3	3.82E+00	ND	ND	ND	ND	1.37E+00	3.30E+00	4.10E-01	1.51E+02
ISB-MW2	06-May-09	7	1.40E+00	ND	ND	ND	ND	ND	1.32E+01	ND	4.90E-01
ISB-MW2	9-Jul-09	3	2.27E+00	ND	ND	ND	ND	4.00E-01	7.75E-01	2.50E-01	5.65E+01
ISB-MW2	26-Aug-09	7	4.44E+00	ND	ND	ND	ND	NA	3.28E+00	3.93E-01	1.38E+02
ISB-MW2	18-Nov-09	7	9.92E+00	ND	ND	ND	ND	NA	3.50E+00	1.02E+00	1.43E+02
ISB-MW2	18-Dec-09	7	2.31E+01	ND	ND	ND	ND	NA	4.02E+00	2.55E+00	2.04E+02
ISB-MW2	24-Feb-10	7	8.69E+01	1.12E+01	ND	ND	ND	NA	2.83E+00	2.44E+00	2.77E+01
ISB-MW2	26-Jan-09	3	1.99E+01	ND	ND	ND	ND	NA	2.49E+00	2.00E-01	5.38E+01
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ISB-MW3	26-Jan-09	7	2.03E+00	ND	ND	ND	ND	1.90E-01	4.55E+00	1.00E-01	8.24E+01
ISB-MW3	09-Mar-09	7	1.21E+00	ND	ND	ND	ND	3.00E-02		3.00E-02	1.03E+01
ISB-MW3	9-Apr-09	3	4.28E+00	ND	ND	ND	ND	5.90E-01	5.30E-01	5.20E-01	1.83E+02
ISB-MW3	06-May-09	7	2.20E-01	ND	ND	ND	ND	ND	4.63E+01	ND	2.10E-01
ISB-MW3	9-Jul-09	3	8.50E-01	ND	ND	ND	ND	8.00E-02	9.61E-01	1.00E-01	3.25E+01
ISB-MW3	26-Aug-09	7	1.45E+00	ND	ND	ND	ND	NA	5.49E+00	1.14E-01	8.83E+01
ISB-MW3	18-Nov-09	7	2.23E+00	ND	ND	ND	ND	NA	7.46E+00	1.57E-01	6.04E+01
ISB-MW3	18-Dec-09	7	2.07E+01	5.79E-01	ND	ND	ND	NA	3.42E+00	3.63E-01	9.89E+01
ISB-MW3	24-Feb-10	7	1.23E+02	1.00E+02	ND	ND	ND	NA	2.35E+02	2.34E+01	3.38E+00
ISB-MW3	26-Jan-09	3	3.58E+00	ND	ND	ND	ND	NA	4.26E-01	5.80E-02	1.76E+01

Table 1b. ZVI Gore Analytical Results

Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ZVI FluxA	15-Apr-09	0.25	5.00E-02	ND	ND	ND	ND	1.30E-01	6.10E-01	ND	1.42E+01
ZVI FluxA	06-May-09	0.25	ND	ND	ND	ND	ND	ND	2.42E-01	ND	5.00E-02
ZVI FluxA	10-Jul-09	0.25	1.05E+00	ND	ND	ND	ND	ND	1.27E+00	1.79E-01	3.06E+01
ZVI FluxA	06-Aug-09	0.25	2.47E+00	ND	ND	ND	ND	ND	4.28E+00	2.66E-01	3.64E+01
ZVI FLUXA	05-Oct-09	0.25	6.38E-01	ND	ND	ND	ND	ND	3.90E+00	6.60E-02	7.85E+00
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ZVI FluxB	15-Apr-09	0.25	3.00E-02	ND	ND	ND	ND	3.00E-02	3.65E+00	ND	2.60E+00
ZVI FluxB	06-May-09	0.25	ND	ND	ND	ND	ND	ND	3.97E-01	ND	2.00E-02
ZVI FluxB	10-Jul-09	0.25	2.91E+00	ND	ND	ND	ND	ND	9.84E-01	1.27E-01	4.65E+01
ZVI FluxB	06-Aug-09	0.25	1.69E+01	ND	ND	ND	ND	ND	9.84E-01	3.68E-01	9.45E+01
ZVI FLUXB	05-Oct-09	0.25	2.87E+01	ND	ND	ND	ND	ND	4.57E+00	1.16E+00	1.00E+02
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ZVI FluxC	15-Apr-09	0.25	6.00E-02	ND	ND	ND	ND	2.00E-02	5.40E-01	ND	3.12E+00
ZVI FluxC	06-May-09	0.25	ND	ND	ND	ND	ND	ND	4.90E-01	ND	2.00E-02
ZVI FluxC	10-Jul-09	0.25	1.15E+00	ND	ND	ND	ND	ND	1.87E-01	1.04E-01	1.70E+02
ZVI FluxC	06-Aug-09	0.25	2.69E+00	ND	ND	ND	ND	ND	3.19E-01	2.30E-01	3.04E+02
ZVI FLUXC	05-Oct-09	0.25	2.92E-01	ND	ND	ND	ND	ND	8.91E+00	3.70E-02	5.00E+01
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ZVI-MW2	15-Apr-09	5	1.50E-01	ND	ND	ND	ND	5.00E-02	1.17E+00	ND	6.40E+00
ZVI-MW2	06-May-09	5	2.04E+00	ND	ND	ND	ND	4.70E-01	1.89E+00	9.00E-02	7.56E+01
ZVI-MW2	10-Jul-09	5	1.70E+00	ND	ND	ND	ND	ND	ND	3.30E-02	1.10E+01
ZVI-MW2	06-Aug-09	5	1.73E+00	ND	ND	ND	ND	ND	8.02E-02	3.00E-02	1.32E+01
ZVI-MW2	05-Oct-09	5	8.45E+00	ND	7.32E-01	1.81E+00	ND	ND	6.10E-01	2.57E-01	7.13E+01
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	ND	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ZVI-MW4	15-Apr-09	5.8	4.60E-01	ND	ND	ND	ND	3.00E-02	4.70E-01	ND	6.40E+00
ZVI-MW4	06-May-09	5.8	1.94E+01	ND	ND	ND	ND	2.20E-01	6.52E+00	6.10E-01	9.43E+01
ZVI-MW4	10-Jul-09	5.8	3.35E+00	ND	ND	ND	ND	ND	1.96E-01	7.60E-02	9.01E+00
ZVI-MW4	06-Aug-09	5.8	2.59E+02	1.15E+00	2.36E+00	3.55E+00	ND	ND	3.96E+01	2.70E+00	5.94E+01
ZVI-MW4	05-Oct-09	5.8	1.14E+02	1.37E+00	1.39E+00	3.08E+00	ND	ND	7.65E+01	3.99E+00	6.43E+01
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ZVI-MW6	15-Apr-09	5.5	7.00E-02	ND	ND	ND	ND	1.00E-02	8.80E-01	ND	3.80E-01
ZVI-MW6	06-May-09	5.5	1.16E+00	ND	ND	ND	ND	4.00E-02	4.09E-01	1.30E-01	1.40E+01
ZVI-MW6	10-Jul-09	5.5	8.57E-01	ND	ND	ND	ND	ND	1.84E-01	4.60E-02	4.36E+00
ZVI-MW6	06-Aug-09	5.5	9.42E-01	ND	ND	ND	ND	ND	ND	3.60E-02	2.29E+00
ZVI-MW6	05-Oct-09	5.5	8.04E+01	4.63E+00	ND	1.21E+00	ND	ND	3.01E+00	3.23E+00	5.30E+01

Table 1. Gore Analytical Results

Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ISB FluxA	26-Jan-09	0.25	1.00E-02	ND	ND	ND	ND	3.00E-02	1.06E+00	ND	4.21E+00
ISB FluxA	09-Mar-09	0.25	ND	ND	ND	ND	ND	2.50E-01	ND	ND	6.00E-02
ISB FluxA	9-Apr-09	0.25	ND	ND	ND	ND	ND	ND	6.30E-01	ND	5.50E-01
ISB FluxA	06-May-09	0.25	ND	ND	ND	ND	ND	ND	5.77E-01	ND	2.00E-02
ISB FluxA	9-Jul-09	0.25	1.57E-01	ND	ND	ND	ND	NA	9.23E-01	4.00E-02	1.90E+01
ISB FluxA	26-Aug-09	0.25	1.21E+00	ND	ND	ND	ND	NA	5.36E-01	1.45E-01	6.10E+01
ISB FluxA	18-Nov-09	0.25	ND	ND	ND	ND	ND	NA	2.15E-01	ND	1.84E-01
ISB FluxA	18-Dec-09	0.25	ND	ND	ND	ND	ND	NA	1.06E+00	ND	1.60E-02
ISB FluxA	24-Feb-10	0.25	ND	ND	ND	ND	ND	NA	6.83E-02	ND	4.10E-02
Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ISB FluxB	26-Jan-09	0.25	1.30E-01	ND	ND	ND	ND	9.00E-02	4.78E-01	ND	2.78E+01
ISB FluxB	09-Mar-09	0.25	ND	ND	ND	ND	ND	1.00E-02	ND	ND	1.59E+00
ISB FluxB	9-Apr-09	0.25	3.00E-02	ND	ND	ND	ND	3.00E-02	5.80E-01	ND	5.58E+00
ISB FluxB	06-May-09	0.25	ND	ND	ND	ND	ND	ND	9.01E-01	ND	2.22E+00
ISB FluxB	9-Jul-09	0.25	2.60E+00	ND	ND	ND	ND	NA	7.84E-01	2.73E-01	1.75E+02
ISB FluxB	26-Aug-09	0.25	1.22E-01	ND	ND	ND	ND	NA	4.97E-01	4.50E-02	1.81E+01
ISB FluxB	18-Nov-09	0.25	ND	ND	ND	ND	ND	NA	3.91E-01	ND	1.47E-01
ISB FluxB	18-Dec-09	0.25	ND	ND	ND	ND	ND	NA	1.36E+00	ND	6.93E-01
ISB FluxB	24-Feb-10	0.25	ND	ND	ND	ND	ND	NA	4.32E-02	ND	3.44E-01
Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ISB FluxC	26-Jan-09	0.25	1.00E-02	ND	ND	ND	ND	ND	4.95E-01	ND	2.90E+00
ISB FluxC	09-Mar-09	0.25	ND	ND	ND	ND	ND	1.70E-01	ND	ND	2.00E-02
ISB FluxC	9-Apr-09	0.25	ND	ND	ND	ND	ND	ND	3.50E-01	ND	1.06E+00
ISB FluxC	06-May-09	0.25	ND	ND	ND	ND	ND	ND	2.16E-01	ND	ND
ISB FluxC	9-Jul-09	0.25	6.00E-02	ND	ND	ND	ND	NA	4.78E-01	ND	1.17E+01
ISB FluxC	26-Aug-09	0.25	7.00E-02	ND	ND	ND	ND	NA	4.87E-01	ND	1.27E+01
ISB FluxC	18-Nov-09	0.25	ND	ND	ND	ND	ND	NA	3.85E-01	ND	9.68E-01
ISB FluxC	18-Dec-09	0.25	ND	ND	ND	ND	ND	NA	1.22E+00	ND	2.35E-01
ISB FluxC	24-Feb-10	0.25	ND	ND	ND	ND	ND	NA	ND	ND	1.40E-01
Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ISB-MW1	26-Jan-09	7	1.57E+01	ND	ND	ND	ND	6.20E-01	1.36E+01	3.70E-01	1.62E+02
ISB-MW1	09-Mar-09	7	1.32E+00	ND	ND	ND	ND	6.00E-02	ND	ND	1.48E+01
ISB-MW1	9-Apr-09	3	5.60E-01	ND	ND	ND	ND	3.00E-01	2.60E+00	1.60E-01	5.70E+01
ISB-MW1	06-May-09	3	2.56E+00	ND	ND	ND	ND	6.40E-01	1.32E+00	7.30E-01	1.16E+02
ISB-MW1	9-Jul-09	7	5.03E-01	ND	ND	ND	ND	NA	8.95E+00	4.60E-02	2.93E+01
ISB-MW1	26-Aug-09	7	1.18E+00	ND	ND	ND	ND	NA	6.12E+00	1.34E-01	4.88E+01
ISB-MW1	18-Nov-09	7	3.98E+00	ND	ND	ND	ND	NA	4.35E+00	2.88E-01	5.30E+01
ISB-MW1	18-Dec-09	7	6.92E+01	1.11E+01	ND	ND	ND	NA	4.06E+01	1.34E+00	1.86E+01

ISB-MW1	24-Feb-10	3	4.85E+01	3.38E+00	ND	ND	ND	NA	1.96E+00	4.28E-01	8.33E+01
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ISB-MW2	26-Jan-09	7	2.89E+01	ND	ND	ND	ND	2.20E-01	5.32E+00	9.50E-01	4.37E+01
ISB-MW2	09-Mar-09	7	3.89E+00	ND	ND	ND	ND	4.00E-02	ND	1.00E-01	4.88E+00
ISB-MW2	9-Apr-09	3	3.82E+00	ND	ND	ND	ND	1.37E+00	3.30E+00	4.10E-01	1.51E+02
ISB-MW2	06-May-09	7	1.40E+00	ND	ND	ND	ND	ND	1.32E+01	ND	4.90E-01
ISB-MW2	9-Jul-09	3	2.27E+00	ND	ND	ND	ND	4.00E-01	7.75E-01	2.50E-01	5.65E+01
ISB-MW2	26-Aug-09	7	4.44E+00	ND	ND	ND	ND	NA	3.28E+00	3.93E-01	1.38E+02
ISB-MW2	18-Nov-09	7	9.92E+00	ND	ND	ND	ND	NA	3.50E+00	1.02E+00	1.43E+02
ISB-MW2	18-Dec-09	7	2.31E+01	ND	ND	ND	ND	NA	4.02E+00	2.55E+00	2.04E+02
ISB-MW2	24-Feb-10	7	8.69E+01	1.12E+01	ND	ND	ND	NA	2.83E+00	2.44E+00	2.77E+01
ISB-MW2	26-Jan-09	3	1.99E+01	ND	ND	ND	ND	NA	2.49E+00	2.00E-01	5.38E+01
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ISB-MW3	26-Jan-09	7	2.03E+00	ND	ND	ND	ND	1.90E-01	4.55E+00	1.00E-01	8.24E+01
ISB-MW3	09-Mar-09	7	1.21E+00	ND	ND	ND	ND	3.00E-02		3.00E-02	1.03E+01
ISB-MW3	9-Apr-09	3	4.28E+00	ND	ND	ND	ND	5.90E-01	5.30E-01	5.20E-01	1.83E+02
ISB-MW3	06-May-09	7	2.20E-01	ND	ND	ND	ND	ND	4.63E+01	ND	2.10E-01
ISB-MW3	9-Jul-09	3	8.50E-01	ND	ND	ND	ND	8.00E-02	9.61E-01	1.00E-01	3.25E+01
ISB-MW3	26-Aug-09	7	1.45E+00	ND	ND	ND	ND	NA	5.49E+00	1.14E-01	8.83E+01
ISB-MW3	18-Nov-09	7	2.23E+00	ND	ND	ND	ND	NA	7.46E+00	1.57E-01	6.04E+01
ISB-MW3	18-Dec-09	7	2.07E+01	5.79E-01	ND	ND	ND	NA	3.42E+00	3.63E-01	9.89E+01
ISB-MW3	24-Feb-10	7	1.23E+02	1.00E+02	ND	ND	ND	NA	2.35E+02	2.34E+01	3.38E+00
ISB-MW3	26-Jan-09	3	3.58E+00	ND	ND	ND	ND	NA	4.26E-01	5.80E-02	1.76E+01

Table 1. ZVI GORE Results

Well	Collection Date	Sample Depth (ft)	cis-1,2-DCE(ug)	Vinyl Chloride (ug)	Ethane (ug)	Ethene (ug)	Acetylene (ug)	PCE (ug)	TPH (ug)	trans-1,2-DCE (ug)	TCE (ug)
ZVI FluxA	15-Apr-09	0.25	5.00E-02	ND	ND	ND	ND	1.30E-01	6.10E-01	ND	1.42E+01
ZVI FluxA	06-May-09	0.25	ND	ND	ND	ND	ND	ND	2.42E-01	ND	5.00E-02
ZVI FluxA	10-Jul-09	0.25	1.05E+00	ND	ND	ND	ND	ND	1.27E+00	1.79E-01	3.06E+01
ZVI FluxA	06-Aug-09	0.25	2.47E+00	ND	ND	ND	ND	ND	4.28E+00	2.66E-01	3.64E+01
ZVI FLUXA	05-Oct-09	0.25	6.38E-01	ND	ND	ND	ND	ND	3.90E+00	6.60E-02	7.85E+00
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ZVI FluxB	15-Apr-09	0.25	3.00E-02	ND	ND	ND	ND	3.00E-02	3.65E+00	ND	2.60E+00
ZVI FluxB	06-May-09	0.25	ND	ND	ND	ND	ND	ND	3.97E-01	ND	2.00E-02
ZVI FluxB	10-Jul-09	0.25	2.91E+00	ND	ND	ND	ND	ND	9.84E-01	1.27E-01	4.65E+01
ZVI FluxB	06-Aug-09	0.25	1.69E+01	ND	ND	ND	ND	ND	9.84E-01	3.68E-01	9.45E+01
ZVI FLUXB	05-Oct-09	0.25	2.87E+01	ND	ND	ND	ND	ND	4.57E+00	1.16E+00	1.00E+02
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**

ZVI FluxC	15-Apr-09	0.25	6.00E-02	ND	ND	ND	ND	2.00E-02	5.40E-01	ND	3.12E+00
ZVI FluxC	06-May-09	0.25	ND	ND	ND	ND	ND	ND	4.90E-01	ND	2.00E-02
ZVI FluxC	10-Jul-09	0.25	1.15E+00	ND	ND	ND	ND	ND	1.87E-01	1.04E-01	1.70E+02
ZVI FluxC	06-Aug-09	0.25	2.69E+00	ND	ND	ND	ND	ND	3.19E-01	2.30E-01	3.04E+02
ZVI FLUXC	05-Oct-09	0.25	2.92E-01	ND	ND	ND	ND	ND	8.91E+00	3.70E-02	5.00E+01
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ZVI-MW2	15-Apr-09	5	1.50E-01	ND	ND	ND	ND	5.00E-02	1.17E+00	ND	6.40E+00
ZVI-MW2	06-May-09	5	2.04E+00	ND	ND	ND	ND	4.70E-01	1.89E+00	9.00E-02	7.56E+01
ZVI-MW2	10-Jul-09	5	1.70E+00	ND	ND	ND	ND	ND	ND	3.30E-02	1.10E+01
ZVI-MW2	06-Aug-09	5	1.73E+00	ND	ND	ND	ND	ND	8.02E-02	3.00E-02	1.32E+01
ZVI-MW2	05-Oct-09	5	8.45E+00	ND	7.32E-01	1.81E+00	ND	ND	6.10E-01	2.57E-01	7.13E+01
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	ND	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ZVI-MW4	15-Apr-09	5.8	4.60E-01	ND	ND	ND	ND	3.00E-02	4.70E-01	ND	6.40E+00
ZVI-MW4	06-May-09	5.8	1.94E+01	ND	ND	ND	ND	2.20E-01	6.52E+00	6.10E-01	9.43E+01
ZVI-MW4	10-Jul-09	5.8	3.35E+00	ND	ND	ND	ND	ND	1.96E-01	7.60E-02	9.01E+00
ZVI-MW4	06-Aug-09	5.8	2.59E+02	1.15E+00	2.36E+00	3.55E+00	ND	ND	3.96E+01	2.70E+00	5.94E+01
ZVI-MW4	05-Oct-09	5.8	1.14E+02	1.37E+00	1.39E+00	3.08E+00	ND	ND	7.65E+01	3.99E+00	6.43E+01
Well	**Collection Date**	**Sample Depth (ft)**	**cis-1,2-DCE(ug)**	**Vinyl Chloride (ug)**	**Ethane (ug)**	**Ethene (ug)**	**Acetylene (ug)**	**PCE (ug)**	**TPH (ug)**	**trans-1,2-DCE (ug)**	**TCE (ug)**
ZVI-MW6	15-Apr-09	5.5	7.00E-02	ND	ND	ND	ND	1.00E-02	8.80E-01	ND	3.80E-01
ZVI-MW6	06-May-09	5.5	1.16E+00	ND	ND	ND	ND	4.00E-02	4.09E-01	1.30E-01	1.40E+01
ZVI-MW6	10-Jul-09	5.5	8.57E-01	ND	ND	ND	ND	ND	1.84E-01	4.60E-02	4.36E+00
ZVI-MW6	06-Aug-09	5.5	9.42E-01	ND	ND	ND	ND	ND	ND	3.60E-02	2.29E+00
ZVI-MW6	05-Oct-09	5.5	8.04E+01	4.63E+00	ND	1.21E+00	ND	ND	3.01E+00	3.23E+00	5.30E+01

Table 2. ISB and ZVI Soil Gas VOC Summa Results

ISB MW1

Date	Depth (ft bgs)	Temp (C)	PCE (ug/L)	TCE (ug/L)	cisDCE (ug/L)	transDCE (ug/L)	VC (ug/L)
27-Jan-09	7	10.11	ND	36.20814	1.836221	ND	ND
09-Mar-09	7	9.34	ND	22.69177	1.715688	ND	ND
10-Apr-09	3	9.57	0.628997	73.68825	1.0453	0.305228	ND
27-Aug-09	7	14.3	0.773309	111.5011	1.644959	0.324879	ND
27-Jan-10	7	23.2	ND	4.812786	4.387783	0.039889	0.138789
23-Feb-10	3	9	0.33662	90.87646	46.08611	0.255568	3.77932
24-Mar-10	3	11.9	ND	118.0619	11.19696	ND	ND
20-Apr-10	3	14.1	ND	145.0523	11.52273	ND	ND

ISB MW2

Date	Depth (ft bgs)	Temp (C)	PCE (ug/L)	TCE (ug/L)	cisDCE (ug/L)	transDCE (ug/L)	VC (ug/L)
27-Jan-09	7	9.92	ND	7.925846	2.046255	ND	ND
09-Mar-09	7	9.28	ND	20.99435	1.590487	ND	ND
10-Apr-09	3	10.43	1.068903	101.7205	2.667852	0.396009	ND
27-Aug-09	7	15.7	1.679042	260.7576	6.547945	0.572945	ND
20-Nov-09	7	28.1	ND	9.575399	82.40426	ND	1.264179
27-Jan-10	7	21.9	ND	70.60886	35.25693	ND	ND
23-Feb-10	3	8.3	0.861594	136.6537	28.56045	ND	ND
24-Mar-10	3	12	ND	140.5006	31.50632	ND	ND
20-Apr-10	3	13.1	ND	100.7717	18.99633	ND	ND

ISB MW3

Date	Depth (ft bgs)	Temp (C)	PCE (ug/L)	TCE (ug/L)	cisDCE (ug/L)	transDCE (ug/L)	VC (ug/L)
27-Jan-09	7	9.52	ND	17.00799	0.313645	ND	ND
09-Mar-09	7	9.18	0.2362	24.40748	3.098362	0.062805	ND
10-Apr-09	3	9.4	0.39336	96.41954	1.882672	0.305411	ND
27-Aug-09	7	19.6	ND	186.1202	2.180491	ND	ND
20-Nov-09	7	21.5	ND	ND	521.5481	ND	51.69985
27-Jan-10	7	13.1	ND	10.07717	4.542601	ND	0.127721
23-Feb-10	3	8.3	0.531316	96.79638	13.02021	0.117602	ND
24-Mar-10	3	12.6	ND	48.79153	153.064	ND	19.99129
20-Apr-10	3	12.5	ND	17.39158	57.93636	0.869045	ND

ZVI MW2

Date	Depth (ft bgs)	Temp (C)	PCE (ug/L)	TCE (ug/L)	cisDCE (ug/L)	transDCE (ug/L)	VC (ug/L)
09-Apr-09	5.5	9.78	ND	1472.671	31.75353	ND	ND
28-May-09	5.5	11.89	ND	1405.548	111.9735	ND	ND
10-Jul-09	5.5	25.6	20.96894	3969.495	435.2534	ND	ND
24-Jul-09	5.5	30.1	32.65261	4174.82	662.6826	ND	ND
05-Aug-09	5.5	35.5	37.97382	4880.598	842.5852	ND	ND
20-Aug-09	5.5	36.8	ND	5687.383	610.2191	ND	ND

10-Sep-09	5.5	35.9	ND	3889.054	328.9479	ND	ND
16-Oct-09	5.5	31.2	ND	2948.67	504.9257	ND	ND
12-Nov-09	5.5	25.6	ND	1984.747	474.8219	ND	ND
24-Mar-10	5.5	20	ND	1366.663	564.5411	ND	ND
ZVI MW4							
Date	**Depth (ft bgs)**	**Temp (C)**	**PCE (ug/L)**	**TCE (ug/L)**	**cisDCE (ug/L)**	**transDCE (ug/L)**	**VC (ug/L)**
09-Apr-09	5.5	9.51	ND	1700.859	79.45966	ND	ND
28-May-09	5.5	12.2	ND	1404.021	745.6793	6.213994	ND
10-Jul-09	5.5	28.7	14.05888	3928.728	1879.782	20.75593	ND
24-Jul-09	5.5	33.2	ND	2458.62	4244.556	57.8803	24.11679
05-Aug-09	5.5	39.6	ND	2715.751	6047.559	52.91614	ND
20-Aug-09	5.5	40.6	ND	970.4682	1130.303	ND	ND
10-Sep-09	5.5	41.4	ND	917.0526	2555.505	ND	ND
16-Oct-09	5.5	36.4	ND	776.5544	2673.158	ND	ND
12-Nov-09	5.5	28.6	ND	525.7743	1488.654	ND	ND
24-Mar-10	5.5	23.5	ND	1188.474	107591.2	ND	ND
ZVI MW5							
Date	**Depth (ft bgs)**	**Temp (C)**	**PCE (ug/L)**	**TCE (ug/L)**	**cisDCE (ug/L)**	**transDCE (ug/L)**	**VC (ug/L)**
09-Apr-09	5.5	9.4	ND	1588.087	54.3883	ND	ND
28-May-09	5.5	12.07	ND	955.1694	99.46922	ND	ND
10-Jul-09	5.5	28.7	ND	5149.819	1018.215	10.57377	ND
24-Jul-09	5.5	33.2	ND	5231.107	2238.038	33.18471	ND
05-Aug-09	5.5	39.6	ND	4970.337	2985.982	41.57697	ND
20-Aug-09	5.5	40.6	ND	9193.909	2938.788	ND	ND
10-Sep-09	5.5	41.4	ND	6113.684	1465.657	ND	ND
16-Oct-09	5.5	36.4	ND	2381.434	763.7595	ND	ND
12-Nov-09	5.5	28.6	ND	1433.93	54.84515	ND	ND
24-Mar-10	5.5	23.5	ND	410.5638	1753.338	ND	ND
ZVI MW6							
Date	**Depth (ft bgs)**	**Temp (C)**	**PCE (ug/L)**	**TCE (ug/L)**	**cisDCE (ug/L)**	**transDCE (ug/L)**	**VC (ug/L)**
09-Apr-09	5.5	8.81	1.146714	181.8754	4.19247	1.383515	0.007023
28-May-09	5.5	12.34	ND	162.7866	7.867199	0.910939	ND
10-Jul-09	5.5	28.7	ND	584.0001	101.8215	2.075593	ND
24-Jul-09	5.5	33.2	ND	680.0439	331.8471	5.016293	ND
05-Aug-09	5.5	39.6	ND	871.0901	491.3641	11.71715	ND
20-Aug-09	5.5	40.6	4.444142	970.4682	565.1516	10.92626	ND
10-Sep-09	5.5	41.4	ND	815.1579	450.9714	7.51619	ND
16-Oct-09	5.5	36.4	ND	264.0285	240.5842	ND	ND
12-Nov-09	5.5	28.6	ND	122.1496	168.4529	ND	ND
24-Mar-10	5.5	23.5	ND	59.42371	75.71234	ND	ND

ZVI MW7							
Date	Depth (ft bgs)	Temp (C)	PCE (ug/L)	TCE (ug/L)	cisDCE (ug/L)	transDCE (ug/L)	VC (ug/L)
09-Apr-09	5.5	9.16	2.934811	368.9764	6.699635	0.795582	ND
28-May-09	5.5	11.22	ND	225.4175	5.819715	ND	ND
10-Jul-09	5.5	23.7	ND	647.8219	7.167916	ND	ND
24-Jul-09	5.5	28.8	ND	175.142	ND	ND	ND
05-Aug-09	5.5	34.6	ND	67.69502	1.72851	ND	ND
20-Aug-09	5.5	35.9	1.307747	191.86	3.21298	ND	ND
10-Sep-09	5.5	33.6	0.988165	130.6071	3.314144	ND	ND
16-Oct-09	5.5	30.6	ND	147.7247	4.280888	ND	ND
12-Nov-09	5.5	25.1	ND	123.583	2.576264	ND	ND
24-Mar-10	5.5	18.7	ND	219.6402	6.480637	ND	ND

Table 1. Soil Gas Dissolved Gases Summa Results

ISB MW1						
Date	Depth (ft bgs)	Temp (C)	Methane (ug/L)	Ethane (ug/L)	Ethene (ug/L)	Acetylene (ug/L)
27-Jan-09	7	10.11	ND	ND	ND	ND
09-Mar-09	7	9.34	ND	ND	ND	ND
10-Apr-09	3	9.57	2.075513	ND	ND	ND
27-Aug-09	7	14.3	3.674449	ND	ND	ND
27-Jan-10	7	23.2	21.7806	ND	ND	ND
23-Feb-10	3	9	14557.94	ND	ND	ND
24-Mar-10	3	11.9	ND	ND	ND	ND
20-Apr-10	3	14.1	4.698398	ND	ND	ND
ISB MW2						
Date	Depth (ft bgs)	Temp (C)	Methane (ug/L)	Ethane (ug/L)	Ethene (ug/L)	Acetylene (ug/L)
27-Jan-09	7	9.92	ND	ND	ND	ND
09-Mar-09	7	9.28	ND	ND	ND	ND
10-Apr-09	3	10.43	2.276141	ND	ND	ND
27-Aug-09	7	15.7	4.604657	ND	ND	ND
20-Nov-09	7	28.1	162.3206	ND	ND	ND
27-Jan-10	7	21.9	5.502287	ND	ND	ND
23-Feb-10	3	8.3	ND	ND	ND	ND
24-Mar-10	3	12	ND	ND	ND	ND
20-Apr-10	3	13.1	1.913257	ND	ND	ND
ISB MW3						
Date	Depth (ft bgs)	Temp (C)	Methane (ug/L)	Ethane (ug/L)	Ethene (ug/L)	Acetylene (ug/L)
27-Jan-09	7	9.52	ND	ND	ND	ND
09-Mar-09	7	9.18	ND	ND	ND	ND
10-Apr-09	3	9.4	1.730635	ND	ND	ND

27-Aug-09	7	19.6	18.03963	ND	ND	ND
20-Nov-09	7	21.5	73020.87	ND	ND	ND
27-Jan-10	7	13.1	95.66284	ND	ND	ND
23-Feb-10	3	8.3	6.671611	ND	ND	ND
24-Mar-10	3	12.6	23957.56	ND	ND	ND
20-Apr-10	3	12.5	397.1499	ND	ND	ND
ZVI MW2						
Date	**Depth (ft bgs)**	**Temp (C)**	**Methane (ug/L)**	**Ethane (ug/L)**	**Ethene (ug/L)**	**Acetylene (ug/L)**
09-Apr-09	5.5	9.78	8.29589	7.253175	ND	ND
28-May-09	5.5	11.89	38.42757	7.970857	ND	ND
10-Jul-09	5.5	25.6	379.7352	9.935649	ND	ND
24-Jul-09	5.5	30.1	496.6502	15.70947	ND	ND
05-Aug-09	5.5	35.5	487.9611	43.92933	ND	ND
20-Aug-09	5.5	36.8	624.7472	35.46898	ND	ND
10-Sep-09	5.5	35.9	1898.686	652.1584	ND	ND
16-Oct-09	5.5	31.2	276.3477	ND	ND	ND
12-Nov-09	5.5	25.6	98.20737	ND	ND	ND
24-Mar-10	5.5	20	20.6839	ND	ND	ND
ZVI MW4						
Date	**Depth (ft bgs)**	**Temp (C)**	**Methane (ug/L)**	**Ethane (ug/L)**	**Ethene (ug/L)**	**Acetylene (ug/L)**
09-Apr-09	5.5	9.51	5.81267	ND	ND	ND
28-May-09	5.5	12.2	75.40073	24.40028	ND	ND
10-Jul-09	5.5	28.7	1166.385	41.27688	6.00424	ND
24-Jul-09	5.5	33.2	3575.451	179.4289	122.7858	ND
05-Aug-09	5.5	39.6	5691.213	492.1201	360.8195	24.35233455
20-Aug-09	5.5	40.6	3241.756	163.5172	599.4491	13.14880534
10-Sep-09	5.5	41.4	11192.92	337.8527	88.05798	4.237271372
16-Oct-09	5.5	36.4	5244.547	84.05173	ND	ND
12-Nov-09	5.5	28.6	4537.446	24.28856	ND	ND
24-Mar-10	5.5	23.5	791.2207	ND	ND	ND
ZVI MW5						
Date	**Depth (ft bgs)**	**Temp (C)**	**Methane (ug/L)**	**Ethane (ug/L)**	**Ethene (ug/L)**	**Acetylene (ug/L)**
09-Apr-09	5.5	9.4	8.307047	3.50177	ND	ND
28-May-09	5.5	12.07	41.83219	10.02152	ND	ND
10-Jul-09	5.5	28.7	2332.771	65.5574	19.25888	ND
24-Jul-09	5.5	33.2	2362.352	93.30305	34.60327	ND
05-Aug-09	5.5	39.6	3189.581	222.6258	109.3392	ND
20-Aug-09	5.5	40.6	6857.561	210.2364	64.30454	ND
10-Sep-09	5.5	41.4	6840.12	186.4015	27.17839	1.513311204
16-Oct-09	5.5	36.4	6065.983	97.07383	ND	ND

12-Nov-09	5.5	28.6	2009.44	ND	ND	ND
24-Mar-10	5.5	23.5	791.2207	14.82368	ND	ND
ZVI MW6						
Date	**Depth (ft bgs)**	**Temp (C)**	**Methane (ug/L)**	**Ethane (ug/L)**	**Ethene (ug/L)**	**Acetylene (ug/L)**
09-Apr-09	5.5	8.81	2.77481	ND	ND	ND
28-May-09	5.5	12.34	15.07275	ND	ND	ND
10-Jul-09	5.5	28.7	1231.185	20.63844	ND	ND
24-Jul-09	5.5	33.2	632.0887	13.15812	ND	ND
05-Aug-09	5.5	39.6	1250.816	43.35344	ND	ND
20-Aug-09	5.5	40.6	2181.951	37.37536	ND	ND
10-Sep-09	5.5	41.4	1741.121	11.30059	ND	ND
16-Oct-09	5.5	36.4	1137.372	ND	ND	ND
12-Nov-09	5.5	28.6	907.4893	ND	ND	ND
24-Mar-10	5.5	23.5	29.67078	ND	ND	ND
ZVI MW7						
Date	**Depth (ft bgs)**	**Temp (C)**	**Methane (ug/L)**	**Ethane (ug/L)**	**Ethene (ug/L)**	**Acetylene (ug/L)**
09-Apr-09	5.5	9.16	3.048507	ND	ND	ND
28-May-09	5.5	11.22	116.93	54.12335	ND	ND
10-Jul-09	5.5	23.7	118.6031	ND	ND	ND
24-Jul-09	5.5	28.8	62.83439	ND	ND	ND
05-Aug-09	5.5	34.6	298.7174	ND	ND	ND
20-Aug-09	5.5	35.9	62.02376	ND	ND	ND
10-Sep-09	5.5	33.6	50.37363	ND	ND	ND
16-Oct-09	5.5	30.6	14.16665	ND	ND	ND
12-Nov-09	5.5	25.1	63.6139	ND	ND	ND
24-Mar-10	5.5	18.7	27.47799	ND	ND	ND

Table 3. ISB Analytical Results: Carbon, Chloride, Temperature, Specific Conductivity

Well	Depth (ft bgs)	Collection Date	Chemical Oxygen Demand (mg/L)	Chloride (mg/L)	Temperature (C)	Specific Conductivity (uS/cm)
ISB-INJ	15	28-Jan-09	12	2.4	9.75	0.162
ISB-INJ	15	11-Feb-09	58	2.5	9.88	0.365
ISB-INJ	15	09-Mar-09	30	2.5	9.34	0.172
ISB-INJ	15	13-Apr-09	910	2.2	9.78	0.631
ISB-INJ	15	08-May-09	1000	2.6	NS	NS
ISB-INJ	15	02-Jul-09	1300	16	NS	NS
ISB-INJ	15	17-Aug-09	890	8.2	NS	NS
ISB-INJ	15	15-Oct-09	90	2.8	24.22	0.38
ISB-INJ	15	19-Nov-09	370	14	NS	NS
ISB-INJ	15	17-Dec-09	240	13	20.7	1.355
ISB-INJ	15	26-Jan-10	23	5.3	15.8	0.695
ISB-INJ	15	23-Feb-10	88	5.2	19.4	0.649
ISB-INJ	15	23-Mar-10	90	5	24.1	0.749
ISB-INJ	15	19-Apr-10	17	4.2	16.64	0.512
ISB-MW1	12	28-Jan-09	14	2.9	10.1	0.185
ISB-MW1	12	11-Feb-09	49	3.3	9.84	0.287
ISB-MW1	12	09-Mar-09	14	2.5	9.34	0.184
ISB-MW1	12	09-Apr-09	41	2.3	9.57	0.298
ISB-MW1	12	08-May-09	13	2.7	10.22	0.252
ISB-MW1	12	02-Jul-09	42	3.8	12.77	0.368
ISB-MW1	12	17-Aug-09	73	4.6	14.06	0.42
ISB-MW1	12	14-Oct-09	58	6	30.6	0.34
ISB-MW1	12	18-Nov-09	50	12	40.1	0.37
ISB-MW1	12	16-Dec-09	21	4.1	45.4	0.34
ISB-MW1	12	26-Jan-10	14	4.6	32.5	0.348
ISB-MW1	12	24-Feb-10	7	5.8	34.8	0.381
ISB-MW1	12	23-Mar-10	30	5.5	35.4	0.434
ISB-MW1	12	19-Apr-10	ND	5.9	26.79	0.279
ISB-MW1	17	28-Jan-09	9	2.5	10.64	0.187
ISB-MW1	17	11-Feb-09	71	3.5	10.42	0.26
ISB-MW1	17	09-Mar-09	19	2.9	9.35	0.22
ISB-MW1	17	09-Mar-09	19	2.7	9.35	0.22
ISB-MW1	17	09-Apr-09	60	7.1	10.05	0.348
ISB-MW1	17	08-May-09	24	4.6	9.99	0.302
ISB-MW1	17	02-Jul-09	74	7.2	11.96	0.467
ISB-MW1	17	02-Jul-09	70	7.2	11.96	0.467
ISB-MW1	17	17-Aug-09	260	9.4	13.09	0.691

ISB-MW1	17	17-Aug-09	250	9.2	13.09	0.691
ISB-MW1	17	14-Oct-09	85	6	31.8	0.416
ISB-MW1	17	18-Nov-09	130	8.5	41.9	0.454
ISB-MW1	17	16-Dec-09	92	6.8	47.7	0.52
ISB-MW1	17	26-Jan-10	39	9.4	36.7	0.548
ISB-MW1	17	24-Feb-10	47	8.2	39.3	0.576
ISB-MW1	17	23-Mar-10	73	9.5	39.1	0.663
ISB-MW1	17	23-Mar-10	80	9.5	39.1	0.663
ISB-MW1	17	19-Apr-10	9	8.3	29.14	0.256
ISB-MW1	22	28-Jan-09	12	2.4	12.24	0.172
ISB-MW1	22	11-Feb-09	170	2.7	10.6	0.249
ISB-MW1	22	09-Mar-09	30	2.9	9.84	0.229
ISB-MW1	22	09-Apr-09	48	8.1	10.07	0.358
ISB-MW1	22	08-May-09	26	6.5	10.2	0.331
ISB-MW1	22	02-Jul-09	86	9.2	12.3	0.53
ISB-MW1	22	17-Aug-09	270	12	12.95	0.853
ISB-MW1	22	14-Oct-09	50	3.8	25.8	0.346
ISB-MW1	22	18-Nov-09	120	6.6	32.6	0.444
ISB-MW1	22	18-Nov-09	120	7.1	32.6	0.444
ISB-MW1	22	16-Dec-09	160	9.3	39.7	0.665
ISB-MW1	22	26-Jan-10	79	12	32	0.692
ISB-MW1	22	24-Feb-10	47	11	33.4	0.643
ISB-MW1	22	23-Mar-10	83	10	32.9	0.688
ISB-MW1	22	19-Apr-10	17	9.8	28.45	0.490
ISB-MW2	12	28-Jan-09	11	3	10.77	0.194
ISB-MW2	12	11-Feb-09	100	4.6	9.92	0.284
ISB-MW2	12	09-Mar-09	23	3.4	9.76	0.222
ISB-MW2	12	09-Apr-09	100	8.6	10.43	0.38
ISB-MW2	12	08-May-09	32	7.2	9.76	0.284
ISB-MW2	12	02-Jul-09	44	7.3	13.01	0.38
ISB-MW2	12	17-Aug-09	120	8.6	14.05	0.522
ISB-MW2	12	15-Oct-09	88	9.8	28.6	0.409
ISB-MW2	12	18-Nov-09	110	17	36.3	0.491
ISB-MW2	12	17-Dec-09	130	16	42.4	0.553
ISB-MW2	12	27-Jan-10	79	18	30.3	0.585
ISB-MW2	12	24-Feb-10	92	17	32.5	0.683
ISB-MW2	12	22-Mar-10	170	22	33.3	0.74
ISB-MW2	12	19-Apr-10	72	31	29.42	0.560
ISB-MW2	17	28-Jan-09	9	2	10.48	0.188
ISB-MW2	17	11-Feb-09	40	3	10.27	0.279
ISB-MW2	17	11-Feb-09	51	3	10.27	0.279

ISB-MW2	17	09-Mar-09	23	2.8	9.78	0.225
ISB-MW2	17	09-Apr-09	100	7.9	10.35	0.401
ISB-MW2	17	08-May-09	47	6.7	9.96	0.334
ISB-MW2	17	02-Jul-09	65	6	12.39	0.424
ISB-MW2	17	17-Aug-09	120	7.9	12.77	0.566
ISB-MW2	17	15-Oct-09	95	9.7	29.5	0.484
ISB-MW2	17	15-Oct-09	90	9.8	29.5	0.484
ISB-MW2	17	18-Nov-09	140	17	39.2	0.54
ISB-MW2	17	17-Dec-09	180	15	45.7	0.673
ISB-MW2	17	27-Jan-10	110	17	36	6.45
ISB-MW2	17	27-Jan-10	130	17	36	6.45
ISB-MW2	17	24-Feb-10	97	14	38.1	0.732
ISB-MW2	17	24-Feb-10	110	14	38.1	0.732
ISB-MW2	17	22-Mar-10	240	14	38.9	0.869
ISB-MW2	17	19-Apr-10	100	3	31.62	0.679
ISB-MW2	17	19-Apr-10	99	3	31.62	0.679
ISB-MW2	22	28-Jan-09	ND	1.7	10.35	0.181
ISB-MW2	22	11-Feb-09	160	2.7	10.54	0.286
ISB-MW2	22	09-Mar-09	35	2.8	9.26	0.240
ISB-MW2	22	09-Apr-09	92	6.9	10.77	0.430
ISB-MW2	22	08-May-09	45	6.6	10.62	0.336
ISB-MW2	22	02-Jul-09	61	5.6	12.31	0.429
ISB-MW2	22	17-Aug-09	150	8.7	12.77	0.605
ISB-MW2	22	15-Oct-09	130	10	23	0.581
ISB-MW2	22	18-Nov-09	170	15	32.9	0.622
ISB-MW2	22	17-Dec-09	160	16	38.5	0.71
ISB-MW2	22	27-Jan-10	160	18	32.1	0.753
ISB-MW2	22	24-Feb-10	110	16	34	0.739
ISB-MW2	22	22-Mar-10	180	15	34.5	0.861
ISB-MW2	22	19-Apr-10	72	3.1	29.59	0.699
ISB-MW3	12	28-Jan-09	7	2.2	10.45	0.130
ISB-MW3	12	28-Jan-09	9.3	2.5	10.45	0.165
ISB-MW3	12	11-Feb-09	370	2.5	9.46	0.298
ISB-MW3	12	09-Mar-09	26	2.10	9.18	0.210
ISB-MW3	12	09-Apr-09	260	2	9.39	0.386
ISB-MW3	12	08-May-09	68	2.5	9.99	0.294
ISB-MW3	12	02-Jul-09	99	4	12.78	0.398
ISB-MW3	12	17-Aug-09	89	4.5	14.82	0.408
ISB-MW3	12	14-Oct-09	150	4.4	37.2	0.445
ISB-MW3	12	19-Nov-09	160	11	28.1	6.13
ISB-MW3	12	17-Dec-09	150	8.3	28.1	0.636

ISB-MW3	12	17-Dec-09	160	8.4	28.1	0.636
ISB-MW3	12	27-Jan-10	68	5.3	20.7	0.516
ISB-MW3	12	24-Feb-10	52	5.9	31.1	0.555
ISB-MW3	12	22-Mar-10	80	6.1	42.8	0.643
ISB-MW3	12	19-Apr-10	26	3.8	23.07	0.366
ISB-MW3	17	28-Jan-09	ND	1.8	10.58	0.175
ISB-MW3	17	28-Jan-09	ND	1.8	10.58	0.175
ISB-MW3	17	11-Feb-09	320	2.2	10.06	0.289
ISB-MW3	17	09-Mar-09	26	2.3	10.12	0.221
ISB-MW3	17	09-Apr-09	100	2.9	9.87	0.333
ISB-MW3	17	09-Apr-09	87	2.9	9.87	0.333
ISB-MW3	17	08-May-09	49	3	10.3	0.334
ISB-MW3	17	02-Jul-09	100	5.7	11.96	0.592
ISB-MW3	17	17-Aug-09	180	1.9	13.3	0.739
ISB-MW3	17	14-Oct-09	70	4	35.8	0.422
ISB-MW3	17	19-Nov-09	60	4.8	29.1	0.478
ISB-MW3	17	17-Dec-09	65	7.6	30.4	0.658
ISB-MW3	17	27-Jan-10	ND	6	24.7	0.601
ISB-MW3	17	25-Feb-10	24	6.1	36	0.522
ISB-MW3	17	22-Mar-10	90	8.1	52.9	0.731
ISB-MW3	17	19-Apr-10	9	6.7	26.77	0.478
ISB-MW3	22	28-Jan-09	12	2.2	10.52	0.180
ISB-MW3	22	11-Feb-09	360	2.10	10.34	0.275
ISB-MW3	22	09-Mar-09	26	2.1	10.05	0.223
ISB-MW3	22	09-Apr-09	64	2.1	9.99	0.299
ISB-MW3	22	08-May-09	34	2.6	10.42	0.293
ISB-MW3	22	02-Jul-09	76	4.3	11.77	0.461
ISB-MW3	22	17-Aug-09	170	1.2	13.41	0.664
ISB-MW3	22	14-Oct-09	60	3.5	24.4	0.416
ISB-MW3	22	19-Nov-09	55	5.1	24.2	0.547
ISB-MW3	22	17-Dec-09	60	7.8	26.3	0.685
ISB-MW3	22	27-Jan-10	39	6.4	22.8	0.688
ISB-MW3	22	25-Feb-10	20	5.9	30	0.653
ISB-MW3	22	22-Mar-10	43	7.5	38	0.844
ISB-MW3	22	19-Apr-10	9	9.6	25.70	0.694
ISB-MW4	15	28-Jan-09	21	2.6	9.78	0.165
ISB-MW4	15	11-Feb-09	12	2.4	9.82	0.190
ISB-MW4	15	09-Mar-09	20	2.8	9.35	0.178
ISB-MW4	15	10-Apr-09	16	2.2	9.03	0.24
ISB-MW4	15	07-May-09	ND	2.6	10	0.213
ISB-MW4	15	02-Jul-09	ND	2.5	12.83	0.235

ISB-MW4	15	17-Aug-09	15	3.2	14.28	0.298
ISB-MW4	15	15-Oct-09	25	4.4	15.1	0.324
ISB-MW4	15	19-Nov-09	13	1.6	18.2	0.277
ISB-MW4	15	16-Dec-09	16	2.6	20.9	0.282
ISB-MW4	15	26-Jan-10	23	3.1	20.5	0.282
ISB-MW4	15	23-Feb-10	9	5.1	20.3	0.279
ISB-MW4	15	23-Mar-10	20	3.3	20	0.344
ISB-MW4	15	19-Apr-10	6	3	19.45	0.251
ISB-MW5	15	28-Jan-09	ND	2.7	9.66	0.169
ISB-MW5	15	11-Feb-09	22	2.4	9.88	0.205
ISB-MW5	15	09-Mar-09	12	2.7	9.39	0.175
ISB-MW5	15	13-Apr-09	48	1.7	9.28	0.256
ISB-MW5	15	07-May-09	ND	2.6	10.06	0.22
ISB-MW5	15	07-May-09	6.4	2.6	10.06	0.22
ISB-MW5	15	02-Jul-09	ND	2.4	12.72	0.267
ISB-MW5	15	17-Aug-09	15	3.2	14.43	0.299
ISB-MW5	15	15-Oct-09	15	2.5	16	0.261
ISB-MW5	15	19-Nov-09	10	2.9	18.5	0.299
ISB-MW5	15	17-Dec-09	16	2.9	21.7	0.269
ISB-MW5	15	26-Jan-10	ND	3.2	19.7	3.14
ISB-MW5	15	25-Feb-10	7	3.4	19.7	0.33
ISB-MW5	15	23-Mar-10	27	3.8	19.1	0.368
ISB-MW5	15	19-Apr-10	12	3.2	18.09	0.253
ISB-MW6	15	28-Jan-09	12	2.4	10.15	0.167
ISB-MW6	15	11-Feb-09	18	2.5	10.05	0.208
ISB-MW6	15	09-Mar-09	12	2.2	9.58	0.184
ISB-MW6	15	10-Apr-09	34	1.8	9.38	0.244
ISB-MW6	15	07-May-09	6.4	2.5	9.82	0.225
ISB-MW6	15	02-Jul-09	32	2.3	12.85	0.25
ISB-MW6	15	17-Aug-09	15	3.2	14.61	0.309
ISB-MW6	15	15-Oct-09	28	2.5	15.45	0.265
ISB-MW6	15	19-Nov-09	10	3	19.3	0.319
ISB-MW6	15	17-Dec-09	14	2.9	20	0.283
ISB-MW6	15	26-Jan-10	ND	2.9	17.5	295
ISB-MW6	15	25-Feb-10	ND	3.3	17.5	0.336
ISB-MW6	15	23-Mar-10	33	4.1	17.2	0.402
ISB-MW6	15	19-Apr-10	6	3.2	14.63	0.241

Table 4. ISB Analytical Results Dissolved Gasses

well	depth	Collection Date	Methane (ug/L)	Ethane (ug/L)	Ethene (ug/L)	Acetylene (ug/L)
ISB-INJ	15	28-Jan-09	ND	ND	ND	ND
ISB-INJ	15	11-Feb-09	ND	ND	ND	ND
ISB-INJ	15	09-Mar-09	ND	ND	ND	ND
ISB-INJ	15	13-Apr-09	ND	ND	ND	ND
ISB-INJ	15	08-May-09	1.4 J	ND	ND	ND
ISB-INJ	15	02-Jul-09	260	0.3 JCOL	0.6 J	ND
ISB-INJ	15	17-Aug-09	6300	ND	ND	ND
ISB-INJ	15	15-Oct-09	12000	ND	ND	ND
ISB-INJ	15	19-Nov-09	17000	ND	ND	ND
ISB-INJ	15	17-Dec-09	23000	ND	ND	ND
ISB-INJ	15	26-Jan-10	15000	ND	ND	ND
ISB-INJ	15	23-Feb-10	17000	ND	ND	ND
ISB-INJ	15	23-Mar-10	16000	ND	ND	ND
ISB-INJ	15	19-Apr-10	20000	ND	ND	ND
ISB-MW1	12	28-Jan-09	1.2J	2.90J	1.20J	ND
ISB-MW1	12	11-Feb-09	1.9J	4.60J	5.20	0.45J
ISB-MW1	12	09-Mar-09	13	ND	ND	ND
ISB-MW1	12	09-Apr-09	17	0.48J	0.5J	ND
ISB-MW1	12	08-May-09	19	ND	ND	ND
ISB-MW1	12	02-Jul-09	810	ND	ND	ND
ISB-MW1	12	17-Aug-09	4000	ND	9.5 J	ND
ISB-MW1	12	14-Oct-09	11000	ND	11 J	ND
ISB-MW1	12	18-Nov-09	3400	ND	6.6 J	ND
ISB-MW1	12	16-Dec-09	6100	ND	ND	ND
ISB-MW1	12	26-Jan-10	16000	ND	ND	ND
ISB-MW1	12	24-Feb-10	15000	ND	ND	ND
ISB-MW1	12	23-Mar-10	12000	ND	30J	ND
ISB-MW1	12	19-Apr-10	11000	ND	23J	ND
ISB-MW1	17	26-Jan-09	1J	9.10	12.00	5.60
ISB-MW1	17	11-Feb-09	1.3J	6.40	9.80	ND
ISB-MW1	17	09-Mar-09	12	1.20J	1.40J	ND
ISB-MW1	17	09-Mar-09	15	1.10J	1.40J	ND
ISB-MW1	17	09-Apr-09	47	31	35	ND
ISB-MW1	17	08-May-09	110	8.7	9.1	ND
ISB-MW1	17	02-Jul-09	1500	9.8 J	12 J	ND
ISB-MW1	17	02-Jul-09	1400	9.6 J	12	ND
ISB-MW1	17	17-Aug-09	5500	22 J	30 J	ND
ISB-MW1	17	17-Aug-09	5900	24 J	32 J	ND
ISB-MW1	17	14-Oct-09	6500	ND	17 J	ND
ISB-MW1	17	18-Nov-09	7200	ND	16 J	ND

ISB-MW1	17	16-Dec-09	12000	ND	ND	ND
ISB-MW1	17	26-Jan-10	17000	ND	71 J	ND
ISB-MW1	17	24-Feb-10	16000	ND	50J	ND
ISB-MW1	17	23-Mar-10	14000	ND	22J	ND
ISB-MW1	17	23-Mar-10	14000	ND	38J	ND
ISB-MW1	17	19-Apr-10	16000	ND	ND	ND
ISB-MW1	22	28-Jan-09	0.46J	2.40J	ND	ND
ISB-MW1	22	11-Feb-09	1.3J	1.90J	2.40J	ND
ISB-MW1	22	09-Mar-09	18	0.99J	1.30J	ND
ISB-MW1	22	09-Apr-09	56	20	21	0.31
ISB-MW1	22	08-May-09	170	9	9.6	ND
ISB-MW1	22	02-Jul-09	1200	8.2 J	10	ND
ISB-MW1	22	17-Aug-09	4100	12 JCOL	15 J	ND
ISB-MW1	22	14-Oct-09	2800	ND	ND	ND
ISB-MW1	22	18-Nov-09	5800	ND	150	ND
ISB-MW1	22	18-Nov-09	5700	ND	130	ND
ISB-MW1	22	16-Dec-09	13000	ND	66 J	ND
ISB-MW1	22	26-Jan-10	19000	ND	130 J	ND
ISB-MW1	22	24-Feb-10	18000	13J	160J	ND
ISB-MW1	22	23-Mar-10	18000	64	130	ND
ISB-MW1	22	19-Apr-10	19000	89	150J	ND
ISB-MW2	12	26-Jan-09	1.3J	4.20J	5.10	1.30J
ISB-MW2	12	11-Feb-09	1.4J	5.20	6.80	0.32J
ISB-MW2	12	09-Mar-09	12	2.10J	2.60J	0.00
ISB-MW2	12	09-Apr-09	16	6.6	8.7	0.89
ISB-MW2	12	08-May-09	63	1.4 J	1.2 JCOL	ND
ISB-MW2	12	02-Jul-09	440	0.66 JCOL	0.99 J	ND
ISB-MW2	12	17-Aug-09	4300	ND	ND	ND
ISB-MW2	12	15-Oct-09	4900	ND	160	ND
ISB-MW2	12	18-Nov-09	1700	6 J	84	6.5 J
ISB-MW2	12	17-Dec-09	7800	15 J	80 J	ND
ISB-MW2	12	27-Jan-10	15000	ND	74 J	ND
ISB-MW2	12	24-Feb-10	13000	ND	110J	ND
ISB-MW2	12	22-Mar-10	11000	ND	77J	ND
ISB-MW2	12	19-Apr-10	14000	ND	82J	ND
ISB-MW2	17	26-Jan-09	0.73J	2.50J	3.70J	0.45J
ISB-MW2	17	11-Feb-09	0.92J	2.90J	4.80J	ND
ISB-MW2	17	11-Feb-09	0.88J	2.80J	4.60J	ND
ISB-MW2	17	09-Mar-09	7.9	1.10J	1.7J	ND
ISB-MW2	17	09-Apr-09	35	15	20	0.45
ISB-MW2	17	08-May-09	260	4.5 J	6.2	ND

ISB-MW2	17	02-Jul-09	710	3.1 JCOL	4.8 J	ND
ISB-MW2	17	17-Aug-09	4100	ND	ND	ND
ISB-MW2	17	15-Oct-09	6800	ND	530	ND
ISB-MW2	17	15-Oct-09	6400	ND	490	ND
ISB-MW2	17	18-Nov-09	5900	17 J	140	ND
ISB-MW2	17	17-Dec-09	11000	21 J	100	ND
ISB-MW2	17	27-Jan-10	17000	ND	130 J	ND
ISB-MW2	17	27-Jan-10	17000	ND	120 J	ND
ISB-MW2	17	24-Feb-10	15000	ND	130J	ND
ISB-MW2	17	24-Feb-10	15000	ND	130J	ND
ISB-MW2	17	22-Mar-10	14000	ND	100J	ND
ISB-MW2	17	19-Apr-10	17000	ND	69J	ND
ISB-MW2	17	19-Apr-10	16000	ND	97J	ND
ISB-MW2	22	26-Jan-09	0.48J	0.48J	ND	ND
ISB-MW2	22	11-Feb-09	0.61J	0.66J	0.66J	ND
ISB-MW2	22	09-Mar-09	12	0.95J	1.50J	ND
ISB-MW2	22	09-Apr-09	19	8.7	12	ND
ISB-MW2	22	08-May-09	250	3.9 J	5.1	ND
ISB-MW2	22	02-Jul-09	620	2.7 J	3.9 J	ND
ISB-MW2	22	17-Aug-09	3400	ND	ND	ND
ISB-MW2	22	15-Oct-09	8800	88 J	33 J	ND
ISB-MW2	22	18-Nov-09	9100	17 J	300	ND
ISB-MW2	22	17-Dec-09	14000	14 J	180 J	ND
ISB-MW2	22	27-Jan-10	16000	ND	330	ND
ISB-MW2	22	24-Feb-10	16000	28	340	ND
ISB-MW2	22	22-Mar-10	14000	92J	270	ND
ISB-MW2	22	19-Apr-10	17000	270	220	ND
ISB-MW3	12	27-Jan-09	0.32J	ND	ND	ND
ISB-MW3	12	11-Feb-09	0.45J	0.25J	ND	ND
ISB-MW3	12	09-Mar-09	ND	ND	ND	ND
ISB-MW3	12	09-Apr-09	0.36J	0.25J	0.64J	ND
ISB-MW3	12	08-May-09	13	ND	ND	ND
ISB-MW3	12	02-Jul-09	1600	ND	ND	ND
ISB-MW3	12	17-Aug-09	5500	ND	ND	ND
ISB-MW3	12	14-Oct-09	12000	ND	ND	ND
ISB-MW3	12	19-Nov-09	13000	ND	19 J	ND
ISB-MW3	12	17-Dec-09	18000	ND	290	ND
ISB-MW3	12	17-Dec-09	17000	ND	280	ND
ISB-MW3	12	27-Jan-10	24000	27 J	48 J	ND
ISB-MW3	12	24-Feb-10	17000	ND	37J	ND
ISB-MW3	12	22-Mar-10	12000	ND	41J	ND

ISB-MW3	12	19-Apr-10	20000	ND	ND	ND
ISB-MW3	17	26-Jan-09	1.3J	0.88J	0.48J	ND
ISB-MW3	17	26-Jan-09	1.4J	0.90J	0.49J	ND
ISB-MW3	17	11-Feb-09	1.4J	0.79J	0.69J	ND
ISB-MW3	17	09-Mar-09	21	0.86 J	0.88J	ND
ISB-MW3	17	09-Apr-09	170	2.1	2.3	ND
ISB-MW3	17	09-Apr-09	160	1.7	1.7	ND
ISB-MW3	17	08-May-09	1000	2.5 J	2 J	ND
ISB-MW3	17	02-Jul-09	1700	5.4 J	7.4 J	ND
ISB-MW3	17	17-Aug-09	4300	ND	ND	ND
ISB-MW3	17	14-Oct-09	10000	ND	ND	ND
ISB-MW3	17	19-Nov-09	14000	ND	ND	ND
ISB-MW3	17	17-Dec-09	19000	ND	ND	ND
ISB-MW3	17	27-Jan-10	24000	13 J	ND	ND
ISB-MW3	17	25-Feb-10	16000	ND	ND	ND
ISB-MW3	17	22-Mar-10	11000	14J	23J	ND
ISB-MW3	17	19-Apr-10	16000	13	ND	ND
ISB-MW3	22	27-Jan-09	2.9J	1.3J	1J	ND
ISB-MW3	22	11-Feb-09	2.5J	0.76J	0.5J	ND
ISB-MW3	22	09-Mar-09	51	0.74J	0.62J	ND
ISB-MW3	22	09-Apr-09	230	1.8	1.3	ND
ISB-MW3	22	08-May-09	870	1.7 J	1.4 J	ND
ISB-MW3	22	02-Jul-09	1800	ND	ND	ND
ISB-MW3	22	17-Aug-09	3800	ND	ND	ND
ISB-MW3	22	14-Oct-09	7300	ND	ND	ND
ISB-MW3	22	19-Nov-09	13000	ND	ND	ND
ISB-MW3	22	17-Dec-09	18000	ND	ND	ND
ISB-MW3	22	27-Jan-10	24000	ND	ND	ND
ISB-MW3	22	25-Feb-10	18000	ND	ND	ND
ISB-MW3	22	22-Mar-10	13000	ND	ND	ND
ISB-MW3	22	19-Apr-10	18000	16	ND	ND
ISB-MW4	15	28-Jan-09	ND	ND	ND	ND
ISB-MW4	15	11-Feb-09	1J	ND	ND	ND
ISB-MW4	15	09-Mar-09	16	ND	ND	ND
ISB-MW4	15	10-Apr-09	0.36	ND	ND	ND
ISB-MW4	15	07-May-09	1.3 J	ND	ND	ND
ISB-MW4	15	02-Jul-09	30	ND	ND	ND
ISB-MW4	15	17-Aug-09	340	ND	ND	ND
ISB-MW4	15	15-Oct-09	3100	ND	ND	ND
ISB-MW4	15	19-Nov-09	45	ND	ND	ND
ISB-MW4	15	16-Dec-09	390	ND	ND	ND

ISB-MW4	15	26-Jan-10	3900	ND	15 J	ND
ISB-MW4	15	23-Feb-10	3300	ND	ND	ND
ISB-MW4	15	23-Mar-10	3400	2.40J	26J	ND
ISB-MW4	15	19-Apr-10	4100	ND	ND	ND
ISB-MW5	15	26-Jan-09	ND	ND	ND	ND
ISB-MW5	15	11-Feb-09	4.3J	ND	ND	ND
ISB-MW5	15	09-Mar-09	15	ND	ND	ND
ISB-MW5	15	13-Apr-09	0.87J	ND	ND	ND
ISB-MW5	15	07-May-09	3 J	ND	ND	ND
ISB-MW5	15	07-May-09	3 J	ND	ND	ND
ISB-MW5	15	02-Jul-09	94	ND	ND	ND
ISB-MW5	15	17-Aug-09	720	ND	ND	ND
ISB-MW5	15	15-Oct-09	3700	ND	ND	ND
ISB-MW5	15	19-Nov-09	3400	ND	ND	ND
ISB-MW5	15	17-Dec-09	2400	ND	ND	ND
ISB-MW5	15	26-Jan-10	14000	ND	ND	ND
ISB-MW5	15	25-Feb-10	17000	ND	ND	ND
ISB-MW5	15	23-Mar-10	16000	ND	ND	ND
ISB-MW5	15	19-Apr-10	10000	ND	ND	ND
ISB-MW6	15	28-Jan-09	ND	ND	ND	ND
ISB-MW6	15	11-Feb-09	14	ND	ND	ND
ISB-MW6	15	09-Mar-09	44	ND	ND	ND
ISB-MW6	15	10-Apr-09	0.74J	ND	ND	ND
ISB-MW6	15	07-May-09	3 J	ND	ND	ND
ISB-MW6	15	02-Jul-09	57	ND	ND	ND
ISB-MW6	15	17-Aug-09	540	ND	ND	ND
ISB-MW6	15	15-Oct-09	4400	ND	ND	ND
ISB-MW6	15	19-Nov-09	1800	ND	ND	ND
ISB-MW6	15	17-Dec-09	5500	ND	ND	ND
ISB-MW6	15	26-Jan-10	13000	ND	ND	ND
ISB-MW6	15	25-Feb-10	17000	ND	ND	ND
ISB-MW6	15	23-Mar-10	18000	ND	ND	ND
ISB-MW6	15	19-Apr-10	4800	ND	ND	ND

Table 5. ISB Analytical Results Redox Parameters and pH

Well	Depth (ft bgs)	Collection Date	Sulfate (mg/L)	Ferrous Iron (mg/L)	Nitrate as N (mg/L)	Dissolved Oxygen (ppm)	ORP (Eh)	pH
ISB-INJ	15	28-Jan-09	22	0.42	2	2.98	-60.2	6.07
ISB-INJ	15	11-Feb-09	15	0.41	0.0048	0.15	112	9.61
ISB-INJ	15	09-Mar-09	10	NS	0.05	0.11	153	6.68
ISB-INJ	15	13-Apr-09	0.42	NS	0.0078 JH	0.07	-237	8.4
ISB-INJ	15	08-May-09	0.16 J	NS	ND	NS	NS	NS
ISB-INJ	15	02-Jul-09	0.88	2.3	HND	NS	NS	NS
ISB-INJ	15	17-Aug-09	ND	NS	0.43 J	NS	NS	NS
ISB-INJ	15	15-Oct-09	ND	2.5	ND	0.3	-96	6.31 HF
ISB-INJ	15	19-Nov-09	0.61 J	NS	ND	NS	NS	NS
ISB-INJ	15	17-Dec-09	ND	2.6	HND	0.74	53	6.64
ISB-INJ	15	26-Jan-10	1.1 J	NS	ND	0.48	31	6.05
ISB-INJ	15	23-Feb-10	0.64 J	2	ND	0.31	32	6.4
ISB-INJ	15	23-Mar-10	ND	4.5	ND	0.49	12	6.29
ISB-INJ	15	19-Apr-10	0.94 J	2.8	ND	0.26	36	6.10
ISB-MW1	12	28-Jan-09	19	NS	2.7	1.46	-106	6.2
ISB-MW1	12	11-Feb-09	17	5.4	0.0064	0.17	155	7.82
ISB-MW1	12	09-Mar-09	7.4	3.2	0.071	0.13	115	6.69
ISB-MW1	12	09-Apr-09	ND	NS	0.0048 JH	0.08	-82	6.35
ISB-MW1	12	08-May-09	0.18 J	NS	ND	0.11	-148	6.25
ISB-MW1	12	02-Jul-09	0.66 B	2.8	HND	0.22	-100	6.71
ISB-MW1	12	17-Aug-09	ND	2.8	ND	0.41	-88	6.27
ISB-MW1	12	14-Oct-09	0.42 J	3.2	ND	0.4	-95	6.39 HF
ISB-MW1	12	18-Nov-09	4.6	2.8	ND	0.4	-5	5.65
ISB-MW1	12	16-Dec-09	1 J	2.6	ND	0.42	20	5.56
ISB-MW1	12	26-Jan-10	0.42 J	NS	ND	0.24	25	5.8
ISB-MW1	12	24-Feb-10	0.4 J	2.5	ND	0.39	41	5.9
ISB-MW1	12	23-Mar-10	ND	2.3	ND	0.37	23	6.06
ISB-MW1	12	19-Apr-10	1.3	2.7	ND	0.21	11	6.19
ISB-MW1	12	19-May-10	NS	NS	NS	0.20	15	5.95
ISB-MW1	17	28-Jan-09	19	0.42	1.80	1.87	-67.6	6.16
ISB-MW1	17	11-Feb-09	15	1.80	ND	0.17	168	7.89
ISB-MW1	17	09-Mar-09	3.1	11	0.0087	0.28	87	6.5
ISB-MW1	17	09-Mar-09	3.1	11	0.0084	0.28	87	6.5
ISB-MW1	17	09-Apr-09	0.32 *	NS	0.012 JH	0.09	-78	6.39
ISB-MW1	17	08-May-09	0.18 J	NS	ND	0.1	-136	6.34
ISB-MW1	17	02-Jul-09	0.93 B	3.1	HND	0.22	-104	6.73
ISB-MW1	17	02-Jul-09	0.47 B	NS	HND	0.22	-104	6.73
ISB-MW1	17	17-Aug-09	ND	4.2	ND	0.39	-94	6.31
ISB-MW1	17	17-Aug-09	ND	NS	ND	0.39	-94	6.31

ISB-MW1	17	14-Oct-09	ND	3.4	HND	0.35	-105	6.41 HF
ISB-MW1	17	18-Nov-09	ND	3.1	ND	0.36	17	5.65
ISB-MW1	17	16-Dec-09	ND	2.2	ND	0.43	45	5.46
ISB-MW1	17	26-Jan-10	ND	NS	ND	0.28	41	5.77
ISB-MW1	17	24-Feb-10	ND	2.8	ND	0.34	50	5.87
ISB-MW1	17	23-Mar-10	ND	2.7	ND	0.36	28	6.04
ISB-MW1	17	23-Mar-10	ND	2.7	ND	0.36	28	6.04
ISB-MW1	17	19-Apr-10	1.2	3.0	ND	0.23	17	6.16
ISB-MW1	17	19-May-10	NS	NS	NS	0.19	14	5.95
ISB-MW1	22	28-Jan-09	14	0.032	1.90	2.19	-70.1	6.2
ISB-MW1	22	11-Feb-09	12	0.15	ND	0.15	191	7.92
ISB-MW1	22	09-Mar-09	0.91	7.7	0.0067	0.17	103	6.8
ISB-MW1	22	09-Apr-09	ND	NS	0.0047 JH	0.09	-74	6.37
ISB-MW1	22	08-May-09	0.17 J	NS	0.02 J	0.11	-125	6.33
ISB-MW1	22	02-Jul-09	0.95 B	3.1	HND	0.27	-103	6.68
ISB-MW1	22	17-Aug-09	ND	3.2	ND	0.38	-91	6.26
ISB-MW1	22	14-Oct-09	2.7	3	HND	0.57	-94	6.48 HF
ISB-MW1	22	18-Nov-09	ND	3.3	ND	0.32	16	5.75
ISB-MW1	22	18-Nov-09	ND	NS	ND	0.32	16	5.75
ISB-MW1	22	16-Dec-09	ND	2.8	ND	0.54	55	5.42
ISB-MW1	22	26-Jan-10	ND	NS	ND	0.29	52	5.74
ISB-MW1	22	24-Feb-10	ND	2.8	ND	0.25	43	5.89
ISB-MW1	22	23-Mar-10	ND	3.2	ND	0.46	32	6.12
ISB-MW1	22	19-Apr-10	0.51 J	3.2	ND	0.20	20	6.18
ISB-MW1	22	19-May-10	NS	NS	NS	0.13	10	6.00
ISB-MW2	12	28-Jan-09	19	0.29	1.90	1.62	-92.4	6.26
ISB-MW2	12	11-Feb-09	14	0.98	0.0054	0.24	157	7.82
ISB-MW2	12	09-Mar-09	3.3	6.9	0.0057	0.92	137	6.74
ISB-MW2	12	09-Apr-09	0.62 *	NS	0.014 J	0.08	160	6.46
ISB-MW2	12	08-May-09	0.22 J	NS	ND	0.22	-117	6.06
ISB-MW2	12	02-Jul-09	0.75 B	2.8	HND	0.21	-104	6.72
ISB-MW2	12	17-Aug-09	ND	2.6	ND	0.47	-82	6.08
ISB-MW2	12	15-Oct-09	ND	4.5	ND	0.23	-112	6.47 HF
ISB-MW2	12	18-Nov-09	2.9	3.2	ND	0.34	-2	5.72
ISB-MW2	12	17-Dec-09	0.69 J	2.8	ND	0.42	33	6.21
ISB-MW2	12	27-Jan-10	0.89 J	NS	ND	0.47	43	5.7
ISB-MW2	12	24-Feb-10	ND	2.6	ND	0.34	35	5.85
ISB-MW2	12	22-Mar-10	ND	2.4	ND	0.31	24	5.96
ISB-MW2	12	19-Apr-10	1.7	4.6	ND	0.22	25	5.98
ISB-MW2	12	19-May-10	NS	NS	NS	0.19	-2	5.91
ISB-MW2	17	28-Jan-09	18	0.44	2.1	2.38	-72	6.2

ISB-MW2	17	11-Feb-09	14	0.59	0.0047	0.18	174	7.84
ISB-MW2	17	11-Feb-09	14	0.62	0.0047	0.18	174	7.84
ISB-MW2	17	09-Mar-09	2.2	7.4	ND	1.58	118	6.78
ISB-MW2	17	09-Apr-09	0.41 *	NS	0.018 JH	0.05	155	6.45
ISB-MW2	17	08-May-09	0.17 J	NS	0.01 J	0.14	-123	6.27
ISB-MW2	17	02-Jul-09	0.53 B	2.1	HND	0.2	-106	6.79
ISB-MW2	17	17-Aug-09	ND	2.8	0.89 J	0.41	-94	6.32
ISB-MW2	17	15-Oct-09	ND	4.4	ND	0.31	-113	6.46 HF
ISB-MW2	17	15-Oct-09	ND	NS	HND	0.31	-113	6.46 HF
ISB-MW2	17	18-Nov-09	ND	3.1	ND	0.33	17	5.71
ISB-MW2	17	17-Dec-09	ND	2.8	ND	0.46	41	6.19
ISB-MW2	17	27-Jan-10	ND	NS	ND	0.45	45	5.73
ISB-MW2	17	27-Jan-10	ND	NS	ND	0.45	45	5.73
ISB-MW2	17	24-Feb-10	ND	3.2	ND	0.37	43	5.87
ISB-MW2	17	24-Feb-10	ND	3.2	ND	0.37	43	5.87
ISB-MW2	17	22-Mar-10	ND	2.7	ND	0.35	33	5.98
ISB-MW2	17	19-Apr-10	0.46 J	5.0	ND	0.20	29	6.07
ISB-MW2	17	19-Apr-10	0.43 J	5.0	ND	0.20	29	6.07
ISB-MW2	17	19-May-10	NS	NS	NS	0.20	-8	6.04
ISB-MW2	22	28-Jan-09	16	0.067	2.1	2.59	-79.1	6.17
ISB-MW2	22	11-Feb-09	12	0.71	ND	0.18	166	7.9
ISB-MW2	22	09-Mar-09	0.64	6.9	ND	0.91	102	6.44
ISB-MW2	22	09-Apr-09	0.36 *	NS	0.0065 JH	0.07	184	6.42
ISB-MW2	22	08-May-09	0.14 J	NS	0.01 J	0.1	-114	6.24
ISB-MW2	22	02-Jul-09	0.33	2.8	HND	0.18	-101	6.75
ISB-MW2	22	17-Aug-09	ND	2.2	ND	0.37	-85	6.29
ISB-MW2	22	15-Oct-09	0.57 J	3.4	ND	0.29	-105	6.46 HF
ISB-MW2	22	18-Nov-09	ND	1.1	ND	0.33	30	5.68
ISB-MW2	22	17-Dec-09	ND	2.4	ND	0.5	50	6.18
ISB-MW2	22	27-Jan-10	ND	NS	ND	0.44	48	5.68
ISB-MW2	22	24-Feb-10	ND	3.9	ND	0.31	46	5.82
ISB-MW2	22	22-Mar-10	ND	2.5	ND	0.29	32	5.98
ISB-MW2	22	19-Apr-10	0.67 J	3.0	ND	0.19	41	6.09
ISB-MW2	22	19-May-10	NS	NS	NS	0.20	5	5.90
ISB-MW3	12	28-Jan-09	22	ND	2.1	3.06	-109	6.1
ISB-MW3	12	11-Feb-09	16	0.1	ND	0.28	256	7.5
ISB-MW3	12	09-Mar-09	6.1	7.3	0.045	0.1	119	6.75
ISB-MW3	12	09-Apr-09	0.27 J*	NS	0.015 JH	0.09	-109	6.17
ISB-MW3	12	08-May-09	0.15 J	NS	ND	0.08	-128	6.23
ISB-MW3	12	02-Jul-09	0.42	2.6	HND	0.2	-94	6.71
ISB-MW3	12	17-Aug-09	ND	3.2	ND	0.33	-92	6.22

ISB-MW3	12	14-Oct-09	ND	2.2	HND	0.3	-100	6.28 HF
ISB-MW3	12	19-Nov-09	2.4	2.2	ND	0.23	12	6.15
ISB-MW3	12	17-Dec-09	ND	2.5	ND	0.42	41	6.25
ISB-MW3	12	17-Dec-09	ND	NS	ND	0.42	41	6.25
ISB-MW3	12	27-Jan-10	ND	NS	ND	0.36	14	5.82
ISB-MW3	12	24-Feb-10	ND	2.7	ND	0.3	14	6
ISB-MW3	12	22-Mar-10	ND	2.3	ND	0.27	15	6.15
ISB-MW3	12	19-Apr-10	ND	4.2	ND	0.23	39	6.13
ISB-MW3	12	19-May-10	NS	NS	NS	0.21	-3	5.99
ISB-MW3	17	28-Jan-09	14	ND	1.7	2.48	-64	6.24
ISB-MW3	17	28-Jan-09	14	ND	1.7	2.48	-64	6.24
ISB-MW3	17	11-Feb-09	9.4	0.051	0.007	0.24	201	7.61
ISB-MW3	17	09-Mar-09	3.2	8.5	0.01	0.42	112	6.73
ISB-MW3	17	09-Apr-09	0.67 *	NS	0.014 JH	0.1	-127	6.28
ISB-MW3	17	09-Apr-09	0.65 *	NS	0.015 JH	0.1	-127	6.28
ISB-MW3	17	08-May-09	0.17 J	NS	ND	0.09	-136	6.41
ISB-MW3	17	02-Jul-09	1.8	2.8	HND	0.2	-97	6.81
ISB-MW3	17	17-Aug-09	ND	4	ND	0.34	-95	6.26
ISB-MW3	17	14-Oct-09	0.4 J	2.6	HND	0.24	-116	6.52 HF
ISB-MW3	17	19-Nov-09	ND	2.3	ND	0.27	30	6.24
ISB-MW3	17	17-Dec-09	ND	2	ND	0.43	41	6.39
ISB-MW3	17	27-Jan-10	ND	NS	ND	0.38	28	5.93
ISB-MW3	17	25-Feb-10	ND	3.4	ND	0.44	12	6.13
ISB-MW3	17	22-Mar-10	ND	2.3	ND	0.31	0	6.15
ISB-MW3	17	19-Apr-10	ND	4.0	ND	0.23	29	6.15
ISB-MW3	17	19-May-10	NS	NS	NS	0.19	-9	6.07
ISB-MW3	22	28-Jan-09	8.7	1	1.2	2.5	-137	6.44
ISB-MW3	22	11-Feb-09	6	0.0.51	0.18	0.24	164	7.65
ISB-MW3	22	09-Mar-09	3.7	8.3	0.19	0.12	105	6.82
ISB-MW3	22	09-Apr-09	2.4 *	NS	0.018 J	0.12	-134	6.22
ISB-MW3	22	08-May-09	2	NS	0.01 J	0.09	-157	6.35
ISB-MW3	22	02-Jul-09	1.8	3.8	HND	0.2	-100	6.86
ISB-MW3	22	17-Aug-09	ND	3.8	0.46 J	0.35	-103	6.32
ISB-MW3	22	14-Oct-09	0.67 J	2	HND	0.3	-123	6.51 HF
ISB-MW3	22	19-Nov-09	ND	3	ND	0.23	22	6.31
ISB-MW3	22	17-Dec-09	ND	2.2	ND	0.47	38	6.39
ISB-MW3	22	27-Jan-10	ND	NS	ND	0.36	18	5.92
ISB-MW3	22	25-Feb-10	ND	3.5	ND	0.37	8	6.14
ISB-MW3	22	22-Mar-10	ND	3.4	ND	0.28	-3	6.22
ISB-MW3	22	19-Apr-10	0.47 J	3.4	ND	0.21	24	6.21
ISB-MW3	22	19-May-10	NS	NS	NS	0.20	-17	6.04

ISB-MW4	15	28-Jan-09	22	0.047	1.8	2.28	-77	6.05
ISB-MW4	15	11-Feb-09	16	0.066	0.0052	0.12	295	7.98
ISB-MW4	15	09-Mar-09	12	0.63	0.2	6.65	173	6.63
ISB-MW4	15	10-Apr-09	2.5 *	NS	0.016 J	2.45	-97	6.02
ISB-MW4	15	07-May-09	4.5	NS	0.01 J	0.12	-139	5.45
ISB-MW4	15	02-Jul-09	5 B	1.8	HND	0.23	-56	6.39
ISB-MW4	15	17-Aug-09	3.4	2.8	ND	0.33	-94	6.27
ISB-MW4	15	15-Oct-09	ND	2.2	ND	0.5	-72	6.51 HF
ISB-MW4	15	19-Nov-09	14	0	3.2	1.68	215	5.95
ISB-MW4	15	16-Dec-09	10	0.6	ND	0.46	188	5.37
ISB-MW4	15	26-Jan-10	7.1	NS	ND	0.39	65	5.72
ISB-MW4	15	23-Feb-10	0.8 J	1.9	ND	0.38	94	6.25
ISB-MW4	15	23-Mar-10	1.9	2.5	ND	0.39	30	6.20
ISB-MW4	15	19-Apr-10	5.6	2.2	ND	0.29	72	6.19
ISB-MW5	15	28-Jan-09	22	2.08	2.2	27.8	-40	6.06
ISB-MW5	15	11-Feb-09	15	0.51	0.0097	0.1	330	7.86
ISB-MW5	15	09-Mar-09	11	0.61	0.62	1.2	184	6.63
ISB-MW5	15	13-Apr-09	0.63	NS	0.017 JH	0.14	-121	6.18
ISB-MW5	15	07-May-09	2.1	NS	ND	0.09	-143	5.79
ISB-MW5	15	07-May-09	2	NS	ND	0.09	-143	5.79
ISB-MW5	15	02-Jul-09	3.1 B	2.6	HND	0.22	-95	6.62
ISB-MW5	15	17-Aug-09	3.2	2.8	ND	0.34	-101	6.25
ISB-MW5	15	15-Oct-09	ND	2.5	ND	0.37	-96	6.49 HF
ISB-MW5	15	19-Nov-09	3.3	2.6	ND	0.26	11	6.26
ISB-MW5	15	17-Dec-09	6.4	2.5	ND	0.41	25	6.28
ISB-MW5	15	26-Jan-10	ND	NS	ND	0.3	19	5.85
ISB-MW5	15	25-Feb-10	ND	3.2	ND	0.29	4	6.13
ISB-MW5	15	23-Mar-10	ND	3.5	ND	0.25	2	6.15
ISB-MW5	15	19-Apr-10	0.74 J	2.6	ND	0.22	12	6.19
ISB-MW6	15	28-Jan-09	18	0.067	1.9	1.84	-85	6.08
ISB-MW6	15	11-Feb-09	13	0.081	ND	0.09	347	7.83
ISB-MW6	15	09-Mar-09	9.4	1.1	0.011	0.14	150	6.68
ISB-MW6	15	10-Apr-09	ND	NS	0.0065 J	0.17	-113	6.06
ISB-MW6	15	07-May-09	1.5	NS	ND	0.08	-295	5.48
ISB-MW6	15	02-Jul-09	2.6 B	2.1	HND	0.24	-91	6.66
ISB-MW6	15	17-Aug-09	3.3	2.5	ND	0.33	-102	6.24
ISB-MW6	15	15-Oct-09	ND	2.5	ND	0.35	-103	6.49 HF
ISB-MW6	15	19-Nov-09	12	1	5.3	0.29	88	6.02
ISB-MW6	15	17-Dec-09	3.2	1.7	ND	0.37	12	6.31
ISB-MW6	15	26-Jan-10	ND	NS	ND	0.3	20	5.82
ISB-MW6	15	25-Feb-10	ND	2.7	ND	0.36	12	6.16

ISB-MW6	15	23-Mar-10	ND	2.5	ND	0.3	12	6.17
ISB-MW6	15	19-Apr-10	2.7	2.8	ND	0.19	8	6.18
ND: Non Detect NS: Not Sampled								

Table 6. ISB Analytical Results Chlorinated Ethenes

well	depth	Collection Date	PCE	TCE	cis-1,2-DCE	trans-1,2-DCE	Vinyl chloride
ISB-INJ	15	28-Jan-09	0.14	32	13	0.15	0.19
ISB-INJ	15	11-Feb-09	0.096J	85	18	0.51J	ND
ISB-INJ	15	09-Mar-09	0.086J	25	23	0.36J	ND
ISB-INJ	15	13-Apr-09	ND	3.9 B	17 B	0.19 J	1.2
ISB-INJ	15	08-May-09	ND	2	19	0.17 J	1.3
ISB-INJ	15	02-Jul-09	ND	1.9	43	1.1	2.3
ISB-INJ	15	17-Aug-09	ND	0.78 J	66	0.55 J	1.4
ISB-INJ	15	15-Oct-09	ND	2 B	79 B	0.25 J	9.2
ISB-INJ	15	19-Nov-09	ND	6.7	32	0.92 J	52
ISB-INJ	15	17-Dec-09	ND	0.45 J	4.8	0.25 J	8.8
ISB-INJ	15	26-Jan-10	ND	0.39 J	3.3	0.095 J	6.3
ISB-INJ	15	23-Feb-10	ND	0.72 J	4.8	0.13 J	4.9
ISB-INJ	15	23-Mar-10	ND	0.34 J	3.5	ND	5.4
ISB-INJ	15	19-Apr-10	*ND	0.3 J	2.3	0.096 J	4.3
ISB-MW1	12	28-Jan-09	3.5	14000	430	9.1	1.4*
ISB-MW1	12	11-Feb-09	2.1	10000B	1400	13	1.2
ISB-MW1	12	09-Mar-09	0.24J	560	250	3.7	2.1
ISB-MW1	12	09-Apr-09	ND	66 B	620 B	6.3	4.9
ISB-MW1	12	08-May-09	ND	46	180	2.2	0.83 J
ISB-MW1	12	02-Jul-09	ND	60	520	5.3	1.8
ISB-MW1	12	17-Aug-09	ND	27	430	5	8.7
ISB-MW1	12	14-Oct-09	0.38 J	2700 B	5100 B	46	81
ISB-MW1	12	18-Nov-09	0.23 J	720 H	8800 H	92	40
ISB-MW1	12	16-Dec-09	0.27 J	1600 B	1300	8	5.9
ISB-MW1	12	26-Jan-10	ND	260	2500	7.1	21
ISB-MW1	12	24-Feb-10	0.11 J	180 B	1800 B	8	150
ISB-MW1	12	23-Mar-10	ND	69	610	5.4	110
ISB-MW1	12	19-Apr-10	0.17 J	310	2100	20	230
ISB-MW1	17	26-Jan-09	0.88J	4600	190	1.4	2.2*
ISB-MW1	17	11-Feb-09	0.51J	3100B	1900	12	1.7
ISB-MW1	17	09-Mar-09	0.46J	1200	1200	19	3
ISB-MW1	17	09-Mar-09	0.45J	1200	1200	16	3
ISB-MW1	17	09-Apr-09	0.9 J	5600 B	12000 B	84	38
ISB-MW1	17	08-May-09	0.23 J	650	4500 B	30	8.5
ISB-MW1	17	02-Jul-09	ND	310	7700	120	ND
ISB-MW1	17	02-Jul-09	ND	380	6900	70	9.4
ISB-MW1	17	17-Aug-09	0.078 J	380	6300	54	18
ISB-MW1	17	17-Aug-09	ND	380	6500	60	15
ISB-MW1	17	14-Oct-09	0.35 J	1700 B	4200 B	38	62
ISB-MW1	17	18-Nov-09	ND	1100 H	12000 H	110	89

ISB-MW1	17	16-Dec-09	0.88 J	5200 B	6300	19	44
ISB-MW1	17	26-Jan-10	0.32 J	3400	8400	46	460
ISB-MW1	17	24-Feb-10	0.092 J	520 B	2500 B	7.7	82
ISB-MW1	17	23-Mar-10	ND	960	3300	33	55
ISB-MW1	17	23-Mar-10	ND	830	3300	35	57
ISB-MW1	17	19-Apr-10	0.73 J	5300	8500	54	110
ISB-MW1	22	28-Jan-09	0.87J	2900B	73	0.61J	0.43J
ISB-MW1	22	11-Feb-09	0.54J	3100B	400	3.7	0.52J
ISB-MW1	22	09-Mar-09	0.54J	2000	1600	28	11
ISB-MW1	22	09-Apr-09	0.9 J	4400 B	15000 B	130	49
ISB-MW1	22	08-May-09	0.28 J	930	7800	69	18
ISB-MW1	22	02-Jul-09	0.23 J	830 H	13000 H	130 H	16
ISB-MW1	22	17-Aug-09	0.42 J	2100	12000	91	17
ISB-MW1	22	14-Oct-09	0.23 J	50 B	900 B	6.7	63
ISB-MW1	22	18-Nov-09	ND	57	4000 H	45	550 H
ISB-MW1	22	18-Nov-09	ND	69 H	4700 H	46	570 H
ISB-MW1	22	16-Dec-09	0.17 J	360 B	8600	22	140
ISB-MW1	22	26-Jan-10	0.13 J	450	9600	58	660
ISB-MW1	22	24-Feb-10	0.13 J	140	3300 B	19	290
ISB-MW1	22	23-Mar-10	ND	53	3200	47	410
ISB-MW1	22	19-Apr-10	0.12 J	100	3600	30	780
ISB-MW2	12	26-Jan-09	5.7	19000B	4100	65	3*
ISB-MW2	12	11-Feb-09	4.9	25000	7500	89	2
ISB-MW2	12	09-Mar-09	3.5	11000	4200	73	3.8
ISB-MW2	12	09-Apr-09	12	38000 B	17000 B	330	43
ISB-MW2	12	08-May-09	3.5	8100	11000 B	140	10
ISB-MW2	12	02-Jul-09	0.93 J	2300	9500	130	4.5
ISB-MW2	12	17-Aug-09	0.83 J	2800	8200	85	13
ISB-MW2	12	15-Oct-09	2.8	13000 B	11000 B	140	780
ISB-MW2	12	18-Nov-09	11	26000 H	19000 H	190 H	440 H
ISB-MW2	12	17-Dec-09	22	42000 B	20000	85	150
ISB-MW2	12	27-Jan-10	18	32000	24000	330	360
ISB-MW2	12	24-Feb-10	7.3	12000	14000	52	190
ISB-MW2	12	22-Mar-10	3.5	9400	23000	120	170
ISB-MW2	12	19-Apr-10	17	36000	57000 B	220	280
ISB-MW2	17	26-Jan-09	0.94J	6300B	530	4.5	0.7J*
ISB-MW2	17	11-Feb-09	0.9J	7600B	1400	12	0.78J
ISB-MW2	17	11-Feb-09	0.84J	7200B	1300	13	0.69J
ISB-MW2	17	09-Mar-09	0.87J	4900	1900	30	3.5
ISB-MW2	17	09-Apr-09	1.9	16000 B	16000 B	120	54
ISB-MW2	17	08-May-09	0.68 J	5000	10000 B	89	17

ISB-MW2	17	02-Jul-09	ND	670	9000	91	9.9
ISB-MW2	17	17-Aug-09	ND	73	5400	30	38
ISB-MW2	17	15-Oct-09	0.42 J	730 B	8200 B	85	270
ISB-MW2	17	15-Oct-09	0.44 J	730 B	8300 B	83	260
ISB-MW2	17	18-Nov-09	0.96 J	4500 H	22000 H	150 H	680 H
ISB-MW2	17	17-Dec-09	0.37 J	3100 B	14000	47	150
ISB-MW2	17	27-Jan-10	0.79 J	4900	19000	160	600
ISB-MW2	17	27-Jan-10	0.91 J	5300	18000	130	610
ISB-MW2	17	24-Feb-10	0.29 J	580	7500	31	200
ISB-MW2	17	24-Feb-10	0.27 J	670 B	7300	25	230
ISB-MW2	17	22-Mar-10	ND	180	9100	120	190
ISB-MW2	17	19-Apr-10	0.59 J	1700	17000 B	67	210
ISB-MW2	17	19-Apr-10	0.63 J	1800	16000 B	87	200
ISB-MW2	22	26-Jan-09	0.69J	3700B	170	1.2	0.2J*
ISB-MW2	22	11-Feb-09	0.39J	3400B	420	5.7	0.26J
ISB-MW2	22	09-Mar-09	0.52J	2400	1900	29	16
ISB-MW2	22	09-Apr-09	0.64 J	5000 B	13000 B	100	72
ISB-MW2	22	08-May-09	0.097 J	790	10000 B	77	23
ISB-MW2	22	02-Jul-09	ND	160	4700	150	10
ISB-MW2	22	17-Aug-09	ND	140	3300	29	10
ISB-MW2	22	15-Oct-09	0.27 J	280 B	8500 B	79	420
ISB-MW2	22	18-Nov-09	ND	120	19000 H	160	4100 H
ISB-MW2	22	17-Dec-09	0.4 J	5500 B	33000	51	1000
ISB-MW2	22	27-Jan-10	0.53 J	4100	16000	160	790
ISB-MW2	22	24-Feb-10	0.072 J	220 B	6800	23	440
ISB-MW2	22	22-Mar-10	ND	160	8500	120	310
ISB-MW2	22	19-Apr-10	0.14 J	390	9200 B	35	330
ISB-MW3	12	27-Jan-09	0.21J	170B	25	0.26J	0.17J*
ISB-MW3	12	11-Feb-09	0.12J	370B	38	0.57J	0.16J
ISB-MW3	12	09-Mar-09	0.1J	230	140	2.2	ND
ISB-MW3	12	09-Apr-09	ND	39 B	180 B	2	7
ISB-MW3	12	08-May-09	0.12 J	5.9	54 B	0.56 J	1.3
ISB-MW3	12	02-Jul-09	ND	5.3	100	0.88 J	1.8
ISB-MW3	12	17-Aug-09	ND	4.5	94	1	0.71 J
ISB-MW3	12	14-Oct-09	ND	40	780 B	5.8	25
ISB-MW3	12	19-Nov-09	ND	300	5200	34	540
ISB-MW3	12	17-Dec-09	ND	55	760	5.4	470
ISB-MW3	12	17-Dec-09	ND	51	760	5.5	470
ISB-MW3	12	27-Jan-10	ND	4.2	38	1.5	23
ISB-MW3	12	24-Feb-10	0.091 J	190 B	200 B	1.7	37
ISB-MW3	12	22-Mar-10	ND	1000	710	5.7	90

ISB-MW3	12	19-Apr-10	*ND	4.7	88	0.73 J	37
ISB-MW3	17	26-Jan-09	0.36J	1800B	94	0.96J	0.2J*
ISB-MW3	17	26-Jan-09	0.31J	1700B	95	0.97J	0.19J*
ISB-MW3	17	11-Feb-09	0.16J	1700B	150	2.4	ND
ISB-MW3	17	09-Mar-09	0.38J	2600	430	4.3	2
ISB-MW3	17	09-Apr-09	0.87 J	10000 B	2500 B	28	14
ISB-MW3	17	09-Apr-09	0.89 J	10000 B	2600 B	29	15
ISB-MW3	17	08-May-09	0.25 J	1900	910 B	13	3.6
ISB-MW3	17	02-Jul-09	0.13 J	1300	7000	65	5.8
ISB-MW3	17	17-Aug-09	0.067 J	750	1100	12	1.9
ISB-MW3	17	14-Oct-09	0.27 J	360 B	390 B	4.8	12
ISB-MW3	17	19-Nov-09	ND	820	1800	7.4	88
ISB-MW3	17	17-Dec-09	ND	57	300	1.7	53
ISB-MW3	17	27-Jan-10	ND	210	200	1.4	39
ISB-MW3	17	25-Feb-10	0.071 J	570 B	230 B	1.3	36
ISB-MW3	17	22-Mar-10	ND	160	160	0.86 J	26
ISB-MW3	17	19-Apr-10	*ND	8.9	34	0.63 J	17
ISB-MW3	22	27-Jan-09	0.067J	82B	16	0.22J	0.14J
ISB-MW3	22	11-Feb-09	0.082J	130B	36	0.33J	0.093J
ISB-MW3	22	09-Mar-09	0.074J	150	70	0.83J	3.2
ISB-MW3	22	09-Apr-09	0.1 J	600 B	180	2.1	2.9
ISB-MW3	22	08-May-09	ND	11	74 B	0.68 J	3.8
ISB-MW3	22	02-Jul-09	ND	32	300	2.4 J	3.7
ISB-MW3	22	17-Aug-09	ND	2.8	92	1.1	1.4
ISB-MW3	22	14-Oct-09	ND	4.6 B	110 B	0.59 J	8.7
ISB-MW3	22	19-Nov-09	ND	0.53 J	39	0.65 J	35
ISB-MW3	22	17-Dec-09	ND	0.47 J	25	0.68 J	30
ISB-MW3	22	27-Jan-10	ND	1.4	10	0.62 J	26
ISB-MW3	22	25-Feb-10	ND	4.9 B	14 B	0.56 J	23
ISB-MW3	22	22-Mar-10	ND	4.9	17	0.38 J	20
ISB-MW3	22	19-Apr-10	*ND	0.37 J	3.2	0.6 J	13
ISB-MW4	15	28-Jan-09	0.11J	38B	29	0.21J	0.39J
ISB-MW4	15	11-Feb-09	0.073J	60	23	0.33J	0.17J
ISB-MW4	15	09-Mar-09	ND	19	28	0.34J	2.1
ISB-MW4	15	10-Apr-09	ND	4.1	25	0.22 J	0.33 J
ISB-MW4	15	07-May-09	ND	12	24	0.21 J	0.22 J
ISB-MW4	15	02-Jul-09	ND	15	39	1.5	ND
ISB-MW4	15	17-Aug-09	ND	4.7	32	0.22 J	ND
ISB-MW4	15	15-Oct-09	0.21 J	4.5	2300 B	17	47
ISB-MW4	15	19-Nov-09	0.35 J	280	48	0.71 J	1.6
ISB-MW4	15	16-Dec-09	0.17 J	93 B	65	0.32 J	2.4

ISB-MW4	15	26-Jan-10	ND	20	340	1.6	52
ISB-MW4	15	23-Feb-10	ND	4.5	99	0.89 J	31
ISB-MW4	15	23-Mar-10	ND	3.1	89	0.94 J	68
ISB-MW4	15	19-Apr-10	*ND	7.5	180	1.1	43
ISB-MW5	15	26-Jan-09	0.12J	35B	23	0.19J	0.22J
ISB-MW5	15	11-Feb-09	ND	57	23	0.3J	0.39J
ISB-MW5	15	09-Mar-09	ND	22	31	0.28J	2.1
ISB-MW5	15	13-Apr-09	ND	3.4 B	25 B	0.24 J	0.46 J
ISB-MW5	15	07-May-09	ND	4.5	21	0.21 J	0.32 J
ISB-MW5	15	07-May-09	ND	4.2	22	0.26 J	0.26 J
ISB-MW5	15	02-Jul-09	ND	2.3	24	2.3	ND
ISB-MW5	15	17-Aug-09	ND	2.3	22	0.2 J	ND
ISB-MW5	15	15-Oct-09	ND	1.1 B	30 B	ND	0.79 J
ISB-MW5	15	19-Nov-09	ND	8.3	78	0.35 J	3.3
ISB-MW5	15	17-Dec-09	ND	2.5	27	0.16 J	2.9
ISB-MW5	15	26-Jan-10	ND	0.35 J	14	0.21 J	16
ISB-MW5	15	25-Feb-10	ND	0.44 J B	11 B	0.24 J	11
ISB-MW5	15	23-Mar-10	ND	0.38 J	9.4	ND	11
ISB-MW5	15	19-Apr-10	*ND	1.2	8.1	0.14 J	8
ISB-MW6	15	28-Jan-09	0.12J	33B	23	0.19J	0.27J
ISB-MW6	15	11-Feb-09	0.11J	48	21	0.3J	1.1
ISB-MW6	15	09-Mar-09	ND	23	26	0.44J	3.5
ISB-MW6	15	10-Apr-09	ND	1.8 B	21 B	0.21 J	0.49 J
ISB-MW6	15	07-May-09	ND	2.9	18	0.2 J	0.34 J
ISB-MW6	15	02-Jul-09	ND	2.1	19	1.6	ND
ISB-MW6	15	17-Aug-09	ND	1.9	23	ND	ND
ISB-MW6	15	15-Oct-09	ND	1.1 B	34 B	0.073 J	0.78 J
ISB-MW6	15	19-Nov-09	ND	85	54	0.28 J	1 J
ISB-MW6	15	17-Dec-09	ND	1.5	26	0.14 J	1.7
ISB-MW6	15	26-Jan-10	ND	0.37 J	14	0.1 J	6.5
ISB-MW6	15	25-Feb-10	ND	0.29 J B	12 B	0.14 J	7.9
ISB-MW6	15	23-Mar-10	ND	0.13 J	8.4	ND	8.7
ISB-MW6	15	19-Apr-10	*ND	3.1	12	0.07 J	3.7

Table 7. ZVI Analytical Results Dissolved Gasses

well	depth	Collection Date	Methane	Ethane	Ethene	Chloride	Acetylene
	ft		ug/L	ug/L	ug/L	mg/L	ug/L
ZVI-INJ	13	13-Apr-09	3.8	4.3	7.4	4.3	0.33
ZVI-INJ	13	22-Apr-09	96	79	60	2.91	ND
ZVI-INJ	13	28-Apr-09	78	62	46	3.05	0.44J
ZVI-INJ	13	07-May-09	71	31	26	3.2	2.3J
ZVI-INJ	13	29-May-09	93	21	20	2.8	0.67J
ZVI-INJ	13	18-Jun-09	160	62	90	4B	0.94J
ZVI-INJ	13	26-Jun-09	470	44	55	3.1	ND
ZVI-INJ	13	01-Jul-09	1700	68	130	4.5	ND
ZVI-INJ	13	10-Jul-09	2900	63COL	160	6.9	3.9JCOL
ZVI-INJ	13	15-Jul-09	1400	59	180	8.4	5.9J
ZVI-INJ	13	23-Jul-09	1600	58	140	9.7	7.4J
ZVI-INJ	13	28-Jul-09	610	38	95	11	7
ZVI-INJ	13	06-Aug-09	1000	43	86	16	5.4J
ZVI-INJ	13	14-Aug-09	1100	44	73	13	11
ZVI-INJ	13	19-Aug-09	1500	48J	64	9.7	8.4J
ZVI-INJ	13	27-Aug-09	3300	66	70	6.3	6.2J
ZVI-INJ	13	10-Sep-09	3400	57	56	6.7	ND
ZVI-INJ	13	16-Oct-09	5300	76	40J	4.5	ND
ZVI-INJ	13	29-Oct-09	5700	97	110	32	ND
ZVI-INJ	13	12-Nov-09	5400	160	200	56	ND
ZVI-INJ	13	26-Mar-10	5300H	120H	210H	12	ND
ZVI-MW1	13	13-Apr-09	ND	ND	ND	2.4	ND
ZVI-MW1	13	21-Apr-09	93	88	100	3.47	ND
ZVI-MW1	13	28-Apr-09	140	110	86	3.81	
ZVI-MW1	13	07-May-09	57	35	26	2.9	ND
ZVI-MW1	13	07-May-09	63	37	27	2.9	ND
ZVI-MW1	13	28-May-09	80	38	24	2.8	ND
ZVI-MW1	13	18-Jun-09	170	70	73	3.1	ND
ZVI-MW1	13	26-Jun-09	850	60	79	3.1	ND
ZVI-MW1	13	01-Jul-09	1800	95	200	4.9	ND
ZVI-MW1	13	01-Jul-09	1900	98	200	5	ND
ZVI-MW1	13	10-Jul-09	5000	62	120	4.1	ND
ZVI-	13	15-Jul-09	3600	60	120	4.5	ND

MW1							
ZVI-MW1	13	23-Jul-09	2800	71COL	120	4.9	ND
ZVI-MW1	13	28-Jul-09	1800	52	100	6	ND
ZVI-MW1	13	07-Aug-09	3100	86	93	5.8	14J
ZVI-MW1	13	14-Aug-09	3100	76COL	74	5.2	ND
ZVI-MW1	13	20-Aug-09	4300	84	67	4.1	ND
ZVI-MW1	13	20-Aug-09	3900	78	63	4	ND
ZVI-MW1	13	26-Aug-09	5500	85	65	3.6	ND
ZVI-MW1	13	10-Sep-09	6800	96J	79J	4.4	ND
ZVI-MW1	13	16-Oct-09	4200	49J	16J	2.8	ND
ZVI-MW1	13	29-Oct-09	6100	55	30J	5.7	ND
ZVI-MW1	13	10-Nov-09	6700	85	44J	20	ND
ZVI-MW1	13	10-Nov-09	6500	83	43J	20	ND
ZVI-MW1	13	26-Mar-10	1500H	35H	13H	3.3	ND
ZVI-MW1	13	26-Mar-10					
ZVI-MW2	13	09-Apr-09	ND	ND	ND	1.8	ND
ZVI-MW2	13	21-Apr-09	79	66	59	2.93	ND
ZVI-MW2	13	28-Apr-09	98	68	43	2.98	
ZVI-MW2	13	07-May-09	83	32	22	2.7	ND
ZVI-MW2	13	28-May-09	100	11	8.6	2.6	ND
ZVI-MW2	13	18-Jun-09	150	15	14	2.7	ND
ZVI-MW2	13	26-Jun-09	290	32	29	2.6	ND
ZVI-MW2	13	02-Jul-09	910	31	36	2.3	ND
ZVI-MW2	13	09-Jul-09	2200	21J	32	2.5	ND
ZVI-MW2	13	15-Jul-09	1600	18J	30	3	ND
ZVI-MW2	13	15-Jul-09	1500	18J	29	3	ND
ZVI-MW2	13	23-Jul-09	3000	30J	40J	3.2	ND
ZVI-	13	28-Jul-09	3900	75	94	3.3	ND

MW2							
ZVI-MW2	13	05-Aug-09	3200	53	60	2.8	ND
ZVI-MW2	13	14-Aug-09	2400	42COL	37	3	ND
ZVI-MW2	13	19-Aug-09	2900	54	48J	3	ND
ZVI-MW2	13	26-Aug-09	2400	48	33	2.4	ND
ZVI-MW2	13	09-Sep-09	1900	33	20J	3	ND
ZVI-MW2	13	16-Oct-09	2400	27	ND	2.8	ND
ZVI-MW2	13	29-Oct-09	1800	20J	5.5J	4.6	ND
ZVI-MW2	13	10-Nov-09	400	6.7	3.8J	9.2	ND
ZVI-MW2	13	25-Mar-10	6300	84J	9.7J	3.6	ND
ZVI-MW3	10	10-Apr-09	ND	ND	ND	2.3	ND
ZVI-MW3	10	21-Apr-09	69	65	64	2.98	ND
ZVI-MW3	10	22-Apr-09					
ZVI-MW3	10	28-Apr-09	91	64	41	2.86	
ZVI-MW3	10	28-Apr-09	87	61	39	2.87	
ZVI-MW3	10	07-May-09	70	40	28	3	0.59J
ZVI-MW3	10	29-May-09	85	21	16	2.6	ND
ZVI-MW3	10	18-Jun-09	110	63	70	4.7	0.89J
ZVI-MW3	10	26-Jun-09	160	50	64	5.3	0.82J
ZVI-MW3	10	01-Jul-09	610	55	92	9.3	2.1J
ZVI-MW3	10	09-Jul-09	910	41	96	6.8	2.4J
ZVI-MW3	10	15-Jul-09	3600	51	98	3.9	31J
ZVI-MW3	10	23-Jul-09	680	17	38	3.9	14
ZVI-MW3	10	28-Jul-09	1700	49	130	47	4.5J
ZVI-MW3	10	28-Jul-09	1800	49	130	47	4.6J
ZVI-MW3	10	06-Aug-09	2700	53COL	78	6	ND
ZVI-MW3	10	14-Aug-09	420	14	22	5.6	1.4J
ZVI-	10	19-Aug-09	2700	57	52	3.3	ND

MW3							
ZVI-MW3	10	26-Aug-09	2600	60	47	3.5	ND
ZVI-MW3	10	10-Sep-09	3600	62	29J	5.1	ND
ZVI-MW3	10	15-Oct-09					
ZVI-MW3	10	29-Oct-09					
ZVI-MW3	10	12-Nov-09	1500	31	9.1J	33	ND
ZVI-MW3	10	25-Mar-10	1500	21J	2.4J	3.5	ND
ZVI-MW4	13	09-Apr-09	ND	ND	ND	1.7	ND
ZVI-MW4	13	21-Apr-09	100	95	88	3.53	ND
ZVI-MW4	13	21-Apr-09	100	97	89	3.47	ND
ZVI-MW4	13	28-Apr-09	94	75	56	3.26	
ZVI-MW4	13	07-May-09	73	46	32	3.2	ND
ZVI-MW4	13	28-May-09	64	41	32	3.1	0.79J
ZVI-MW4	13	18-Jun-09	130	73	71	3.4	ND
ZVI-MW4	13	18-Jun-09	160	85	79	3.5	ND
ZVI-MW4	13	26-Jun-09	380	110	120	4	ND
ZVI-MW4	13	02-Jul-09	990	100	190	5.7	ND
ZVI-MW4	13	09-Jul-09	3100	97	230	10	ND
ZVI-MW4	13	15-Jul-09	4800	91	260	9.8	ND
ZVI-MW4	13	23-Jul-09	6300	110	280	7.6	ND
ZVI-MW4	13	23-Jul-09	6500	110	310	7.7	ND
ZVI-MW4	13	28-Jul-09	2900	100	280	34	ND
ZVI-MW4	13	05-Aug-09	2200	85	220	20	1.6J
ZVI-MW4	13	14-Aug-09	1900	86	160	12	2.7J
ZVI-MW4	13	19-Aug-09	450	35	49	4.2	7.8
ZVI-MW4	13	27-Aug-09	1200	42	52	3.1	ND
ZVI-MW4	13	09-Sep-09	830	21	24	3.5	1.9J
ZVI-	13	09-Sep-09	810	19	22	3.5	1.6J

MW4							
ZVI-MW4	13	16-Oct-09				6	
ZVI-MW4	13	16-Oct-09				5.9	
ZVI-MW4	13	29-Oct-09					
ZVI-MW4	13	10-Nov-09	2000	38COL	33	20	ND
ZVI-MW4	13	25-Mar-10	1100	17J	6.2J	3.3	ND
ZVI-MW5	13	10-Apr-09	ND	ND	ND	2.5	ND
ZVI-MW5	13	21-Apr-09	100	87	81	3.47	ND
ZVI-MW5	13	28-Apr-09	82	61	45	3.13	
ZVI-MW5	13	07-May-09	77	55	42	4	4.1J
ZVI-MW5	13	29-May-09	53	33	25	3	ND
ZVI-MW5	13	18-Jun-09	180	43COL	39	3	ND
ZVI-MW5	13	26-Jun-09	34	2.1J	2.1J	3.2	ND
ZVI-MW5	13	01-Jul-09	1100	25	31	3	ND
ZVI-MW5	13	09-Jul-09	2400	49	120	6.6	ND
ZVI-MW5	13	15-Jul-09	2200	31	56	4.4	ND
ZVI-MW5	13	23-Jul-09	3500	58	110	5.4	ND
ZVI-MW5	13	28-Jul-09	2900	47COL	77	17	ND
ZVI-MW5	13	06-Aug-09	4000	63	85	5.6	ND
ZVI-MW5	13	14-Aug-09	3600	54COL	55	4.2	ND
ZVI-MW5	13	14-Aug-09	3300	54	58	4.2	ND
ZVI-MW5	13	19-Aug-09	4100	63	57	4.1	ND
ZVI-MW5	13	27-Aug-09	5700	73	56	4.1	ND
ZVI-MW5	13	27-Aug-09	6000	75	56	4.1	ND
ZVI-MW5	13	09-Sep-09	8000	74J	45J	4.5	ND
ZVI-MW5	13	16-Oct-09	8000	75J	17J	3.8	ND
ZVI-MW5	13	29-Oct-09	5800	53	10J	5.3	ND
ZVI-	13	10-Nov-09	7400	54J	14J	17	ND

MW5							
ZVI-MW5	13	25-Mar-10	1200	14J	2.4J	2.8	ND
ZVI-MW6	13	13-Apr-09	0.95	ND	ND	2.2	ND
ZVI-MW6	13	21-Apr-09	130	100	93	3.19	ND
ZVI-MW6	13	28-Apr-09	100	58	41	3	
ZVI-MW6	13	07-May-09	58	34	24	3.3	ND
ZVI-MW6	13	28-May-09	30	3.7J	3.4J	2.6	0.63J
ZVI-MW6	13	18-Jun-09	37	11COL	11	2.6	ND
ZVI-MW6	13	26-Jun-09	500	31COL	34	3	ND
ZVI-MW6	13	01-Jul-09	510	31	44	3.4	ND
ZVI-MW6	13	10-Jul-09	1600	26	44	5.2	ND
ZVI-MW6	13	10-Jul-09	1600	27COL	45	0.96	ND
ZVI-MW6	13	15-Jul-09	1700	26	45	5.8	ND
ZVI-MW6	13	23-Jul-09	3500	62	97	4.4	ND
ZVI-MW6	13	28-Jul-09	1600	46	100	9.7	ND
ZVI-MW6	13	06-Aug-09	4000	72COL	96	6.2	ND
ZVI-MW6	13	14-Aug-09	4500	63	64	4.6	ND
ZVI-MW6	13	20-Aug-09	6600	62	52	3.7	ND
ZVI-MW6	13	27-Aug-09	8100	68J	56J	3.8	ND
ZVI-MW6	13	10-Sep-09	7200	58J	41J	4.2	ND
ZVI-MW6	13	15-Oct-09	8800	ND	150	3.3	ND
ZVI-MW6	13	29-Oct-09	9000	94J	82J	8.9	ND
ZVI-MW6	13	10-Nov-09	4400	88	48J	21	ND
ZVI-MW6	13	26-Mar-10	490H	4.4JH	22H	2.9	ND
ZVI-MW7	13	13-Apr-09	ND	ND	ND	2.3	ND
ZVI-MW7	13	13-Apr-09			ND	2.3	
ZVI-MW7	13	13-Apr-09	ND	ND	ND		ND
ZVI-	13	22-Apr-09	80	67	52	2.84	ND

MW7							
ZVI-MW7	13	28-Apr-09	64	33	22	2.89	
ZVI-MW7	13	07-May-09	59	15	10	2.7	ND
ZVI-MW7	13	29-May-09	95	3.6J	3.3J	2.6	ND
ZVI-MW7	13	29-May-09	93	3.3J	3.2J	2.8	ND
ZVI-MW7	13	18-Jun-09	150	15	13	2.6	ND
ZVI-MW7	13	26-Jun-09	270	24	21	2.7	ND
ZVI-MW7	13	26-Jun-09	250	23	20	2.6	ND
ZVI-MW7	13	02-Jul-09	330	18	18	2.6	ND
ZVI-MW7	13	10-Jul-09	2400	27	37	2.4	ND
ZVI-MW7	13	15-Jul-09	840	15	32	3.1	1.6J
ZVI-MW7	13	24-Jul-09	1700	19JCOL	27	3.5	ND
ZVI-MW7	13	28-Jul-09	2200	23J	33	3.2	ND
ZVI-MW7	13	06-Aug-09	3800	46J	45J	3.4	ND
ZVI-MW7	13	14-Aug-09	2400	31	26	2.8	ND
ZVI-MW7	13	19-Aug-09	1800	25JCOL	17J	2.6	ND
ZVI-MW7	13	26-Aug-09	1700	25COL	14J	2.3	ND
ZVI-MW7	13	10-Sep-09	2600	37J	18J	2.5	ND
ZVI-MW7	13	16-Oct-09	1700	24J	6.3J	2.4	ND
ZVI-MW7	13	29-Oct-09	3600	38J	10J	4.2	ND
ZVI-MW7	13	29-Oct-09	3400	40J	11J	4.2	ND
ZVI-MW7	13	12-Nov-09	3400	56	18J	8.3	ND
ZVI-MW7	13	26-Mar-10	65Hp	ND	ND	2.5	ND
ZVI-MW8	13	10-Apr-09	ND	ND	ND	2.4	ND
ZVI-MW8	13	21-Apr-09	47	30	22	2.79	ND
ZVI-MW8	13	28-Apr-09	33	9.5	5.8	2.79	
ZVI-MW8	13	07-May-09	43	6.3	4.2J	2.7	ND
ZVI-	13	28-May-09	73	ND	ND	2.5	ND

MW8							
ZVI-MW8	13	18-Jun-09	150	0.43	0.67JCOL	2.4	ND
ZVI-MW8	13	26-Jun-09	160	1.2JCOL	1.3J	2.4	ND
ZVI-MW8	13	01-Jul-09	99	0.8JCOL	0.91J	2.2	ND
ZVI-MW8	13	09-Jul-09	0.54JCHI		ND	2.3	ND
ZVI-MW8	13	15-Jul-09	0.94JCHI		ND	2.2	ND
ZVI-MW8	13	23-Jul-09	23	1J	1.7J	3.1	ND
ZVI-MW8	13	28-Jul-09	18		ND	3	ND
ZVI-MW8	13	06-Aug-09	130	1.3H	0.66J	3.2	ND
ZVI-MW8	13	06-Aug-09	130	1JCOL	ND	3.1	ND
ZVI-MW8	13	14-Aug-09	100	0.43J	ND	2.7	ND
ZVI-MW8	13	19-Aug-09	39	0.39	ND	2.6	ND
ZVI-MW8	13	26-Aug-09	360	5.8	3.5J	2.3	ND
ZVI-MW8	13	10-Sep-09	380	6.1	3.1J	2.4	ND
ZVI-MW8	13	16-Oct-09	2.7JCOL	ND	ND	2.3	ND
ZVI-MW8	13	29-Oct-09	610	ND	ND	3.1	ND
ZVI-MW8	13	12-Nov-09	6.4COL	ND	ND	5.7	ND
ZVI-MW8	13	25-Mar-10	630	ND	ND	2.4	ND
ZVI-MW9	13	13-Apr-09	ND	ND	ND	2.2	ND
ZVI-MW9	13	22-Apr-09	ND	ND	ND	2.6	ND
ZVI-MW9	13	28-Apr-09				2.67	
ZVI-MW9	13	07-May-09	ND	ND	ND	2.6	ND
ZVI-MW9	13	28-May-09	ND	ND	ND	2.4	ND
ZVI-MW9	13	18-Jun-09	0.97J	ND	ND	2.6B	ND
ZVI-MW9	13	26-Jun-09	303J	ND	ND	3.1	ND
ZVI-MW9	13	02-Jul-09	2.9J	ND	ND	2.5	ND
ZVI-MW9	13	10-Jul-09	0.66JCHI	ND	ND	2.3	ND
ZVI-	13	15-Jul-09	ND	ND	ND	2.2	ND

MW9							
ZVI-MW9	13	24-Jul-09	50	ND	0.42J	3.5	ND
ZVI-MW9	13	28-Jul-09	160	ND	1.3J	4.6	ND
ZVI-MW9	13	07-Aug-09	610	0.52	2J	3.8	ND
ZVI-MW9	13	14-Aug-09	880	0.91	4.3J	3.6	ND
ZVI-MW9	13	20-Aug-09	1100	1.3J	5.8J	3.6	ND
ZVI-MW9	13	27-Aug-09	2600	4J	14J	3.7	ND
ZVI-MW9	13	10-Sep-09	2900	4.1J	12J	4.3	ND
ZVI-MW9	13	15-Oct-09	3100		4.1J	3.9	ND
ZVI-MW9	13	29-Oct-09	4200		ND	6.5	ND
ZVI-MW9	13	12-Nov-09	2400		ND	8.8	ND
ZVI-MW9	13	25-Mar-10	920H	6.2JH	ND	2.3	ND

Table 8. ZVI Analytical Results Redox Parameters

well	depth	Collection Date	Bromide	Sulfate	Nitrate as N	Dissolved oxygen	Ferrous Iron
	ft		mg/L	mg/L	mg/L	mg/L	mg/L
ZVI-INJ	13	13-Apr-09	0.069J	23	0.28H	0.22	NS
ZVI-INJ	13	22-Apr-09	0.65	11	ND	0.1	3.8
ZVI-INJ	13	28-Apr-09	ND	10.7	NS	0.06	2.4
ZVI-INJ	13	07-May-09	0.52	7.3	ND	0.07	2.4
ZVI-INJ	13	29-May-09	0.04J	1	ND	0.11	3.6
ZVI-INJ	13	18-Jun-09	0.06J*B	1.1B	HND	0.14	5.85
ZVI-INJ	13	26-Jun-09	ND	0.29J	ND	0.2	NS
ZVI-INJ	13	01-Jul-09	ND	0.4B	HND	0.15	NS
ZVI-INJ	13	10-Jul-09	0.08J	0.32	ND	0.21	0.2
ZVI-INJ	13	15-Jul-09	ND	ND	HND	0.14	NS
ZVI-INJ	13	23-Jul-09	ND	ND	ND	0.17	NS
ZVI-INJ	13	28-Jul-09	ND	ND	ND	0.15	NS
ZVI-INJ	13	06-Aug-09	0.2J*	ND	ND		NS
ZVI-INJ	13	14-Aug-09	ND	0.45J	ND	0.19	NS
ZVI-INJ	13	19-Aug-09	ND	ND	ND	0.32	NS
ZVI-INJ	13	27-Aug-09	ND	ND	ND	0.14	3.4
ZVI-INJ	13	10-Sep-09	ND	ND	ND	0.2	NS
ZVI-INJ	13	16-Oct-09	ND	0.87J	ND	0.3	0.6
ZVI-INJ	13	29-Oct-09	0.26J	0.85J	ND	0.29	NS
ZVI-INJ	13	12-Nov-09	0.76	6.2	0.36J	0.15	1.6
ZVI-INJ	13	26-Mar-10	ND	ND	ND	0.27	0.4
ZVI-MW1	13	13-Apr-09	0.038J	13	0.55H	0.26	NS
ZVI-MW1	13	21-Apr-09	3.37	7.82	ND	0.09	2.8
ZVI-MW1	13	28-Apr-09	1.31	7.42	NS	0.08	2.5
ZVI-MW1	13	07-May-09	0.41B	7	ND	0.1	4.2
ZVI-MW1	13	07-May-09	0.43B	7.2	ND	0.1	NS
ZVI-MW1	13	28-May-09	0.12J	0.57	ND	0.1	4
ZVI-MW1	13	18-Jun-09	0.02J	0.69	0.01JH	0.11	4.65
ZVI-MW1	13	26-Jun-09	0.02J	0.09J	ND	0.17	NS
ZVI-MW1	13	01-Jul-09	0.04J	0.36B	HND	0.1	NS
ZVI-MW1	13	01-Jul-09	ND	0.37B	HND	0.1	NS
ZVI-MW1	13	10-Jul-09	0.13J	0.13J	ND	0.17	1.5
ZVI-MW1	13	15-Jul-09	ND	ND	ND	0.16	NS
ZVI-MW1	13	23-Jul-09	ND	ND	ND	0.15	NS
ZVI-MW1	13	28-Jul-09	0.23J	ND	ND	0.18	NS
ZVI-MW1	13	07-Aug-09	*ND	ND	ND	0.32	1.1
ZVI-MW1	13	14-Aug-09	ND	0.4J	ND	0.18	NS

ZVI-MW1	13	20-Aug-09	ND	ND	ND	0.2	NS
ZVI-MW1	13	20-Aug-09	ND	ND	ND	0.2	NS
ZVI-MW1	13	26-Aug-09	ND	ND	HND	0.32	0.8
ZVI-MW1	13	10-Sep-09	ND	ND	ND	0.35	NS
ZVI-MW1	13	16-Oct-09	ND	ND	ND	1.82	NS
ZVI-MW1	13	29-Oct-09	ND	ND	ND	0.63	NS
ZVI-MW1	13	10-Nov-09	0.64	13	0.32J	0.23	2.5
ZVI-MW1	13	10-Nov-09	0.66	13	0.3J	0.23	NS
ZVI-MW1	13	26-Mar-10	ND	4.6	ND	0.31	3
ZVI-MW1	13	26-Mar-10	ND	5	ND	0.31	3
ZVI-MW2	13	09-Apr-09	ND	ND	1.2	0.32	NS
ZVI-MW2	13	21-Apr-09	0.46	9.38	ND	0.19	NS
ZVI-MW2	13	28-Apr-09	ND	9.23	NS	0.18	3
ZVI-MW2	13	07-May-09	0.04JB	8.1	ND	0.1	2.6
ZVI-MW2	13	28-May-09	0.02J	0.8	ND	0.36	3.8
ZVI-MW2	13	18-Jun-09	ND	0.85	HND	0.19	4.4
ZVI-MW2	13	26-Jun-09	0.05J	0.07J	ND	0.24	NS
ZVI-MW2	13	02-Jul-09	ND	0.27JB	HND	0.25	NS
ZVI-MW2	13	09-Jul-09	0.03J	2.4	ND	0.27	3.3
ZVI-MW2	13	15-Jul-09	ND	7.8	ND	0.22	NS
ZVI-MW2	13	15-Jul-09	ND	8.2	ND	0.22	NS
ZVI-MW2	13	23-Jul-09	ND	1.3	ND	0.21	NS
ZVI-MW2	13	28-Jul-09	ND	ND	ND	0.26	NS
ZVI-MW2	13	05-Aug-09	*ND	ND	HND	0.46	2.8
ZVI-MW2	13	14-Aug-09	ND	2.2	ND	0.25	NS
ZVI-MW2	13	19-Aug-09	ND	1.9	ND	0.27	NS
ZVI-MW2	13	26-Aug-09	ND	1.4	HND	0.27	2.9
ZVI-MW2	13	09-Sep-09	ND	4.5	ND	0.44	NS
ZVI-MW2	13	16-Oct-09	ND	6.8	ND	0.67	1
ZVI-MW2	13	29-Oct-09	ND	26	ND	0.39	NS
ZVI-MW2	13	10-Nov-09	ND	23	2.8	0.33	0.8
ZVI-MW2	13	25-Mar-10	ND	8.7	ND	0.3	2.6
ZVI-MW3	10	10-Apr-09	ND	NS	1.2	0.29	NS
ZVI-MW3	10	21-Apr-09	1.06	9.57	ND	0.18	3.8
ZVI-MW3	10	28-Apr-09	ND	9.46	NS	0.11	4
ZVI-MW3	10	28-Apr-09	ND	9.43	NS	0.11	NS
ZVI-MW3	10	07-May-09	0.25B	6.6	ND	0.12	3.4
ZVI-MW3	10	29-May-09	0.02J	0.18J	ND	0.22	3.8
ZVI-MW3	10	18-Jun-09	0.39	0.07J	HND	0.14	4.5
ZVI-MW3	10	26-Jun-09	ND	0.11J	ND	0.27	NS

ZVI-MW3	10	01-Jul-09	ND	0.43B	HND	0.21	NS
ZVI-MW3	10	09-Jul-09	0.16	0.78	ND	0.24	2.9
ZVI-MW3	10	15-Jul-09	ND	2.8	ND	0.23	NS
ZVI-MW3	10	23-Jul-09	ND	0.71J	ND	0.35	NS
ZVI-MW3	10	28-Jul-09	0.38J	7.6	ND	0.24	NS
ZVI-MW3	10	28-Jul-09	ND	7.5	ND	0.24	NS
ZVI-MW3	10	06-Aug-09	*ND	0.45J	ND	0.57	3.5
ZVI-MW3	10	14-Aug-09	ND	1.7	ND	0.83	NS
ZVI-MW3	10	19-Aug-09	ND	0.45J	ND	0.39	NS
ZVI-MW3	10	26-Aug-09	ND	0.47J	HND	0.99	2
ZVI-MW3	10	10-Sep-09	ND	1.7	ND	3.14	NS
ZVI-MW3	10	15-Oct-09	NS	NS	NS	NA	NS
ZVI-MW3	10	29-Oct-09	NS	NS	NS	NA	NS
ZVI-MW3	10	12-Nov-09	0.59J	48	2.4	0.94	0.8
ZVI-MW3	10	25-Mar-10	ND	11	ND	0.35	2.6
ZVI-MW4	13	09-Apr-09	ND	NS	1.2	0.25	NS
ZVI-MW4	13	21-Apr-09	1.58	10.5	ND	0.08	3.8
ZVI-MW4	13	28-Apr-09	0.47	9.45	NS	0.06	2.6
ZVI-MW4	13	07-May-09	0.31B	7.5	ND	0.12	4.2
ZVI-MW4	13	28-May-09	0.1J	0.73	ND	0.08	4.4
ZVI-MW4	13	18-Jun-09	ND	0.09J	HND	0.15	2.8
ZVI-MW4	13	18-Jun-09	0.02J	0.59	HND	0.15	NS
ZVI-MW4	13	26-Jun-09	0.33	0.06J	0.01J	0.2	NS
ZVI-MW4	13	02-Jul-09	ND	0.34B	HND	0.19	NS
ZVI-MW4	13	09-Jul-09	0.22	0.09J	0.07	0.2	3
ZVI-MW4	13	15-Jul-09	ND	ND	ND	0.11	NS
ZVI-MW4	13	23-Jul-09	ND	ND	ND	0.19	NS
ZVI-MW4	13	23-Jul-09	ND	ND	ND	0.19	NS
ZVI-MW4	13	28-Jul-09	ND	ND	ND	0.18	NS
ZVI-MW4	13	05-Aug-09	0.24J*	ND	HND	0.32	4.5
ZVI-MW4	13	14-Aug-09	0.29J	ND	ND	0.23	NS
ZVI-MW4	13	19-Aug-09	ND	ND	ND	0.15	NS
ZVI-MW4	13	27-Aug-09	ND	ND	ND	0.27	2.9
ZVI-MW4	13	09-Sep-09	ND	ND	ND	0.98	NS
ZVI-MW4	13	09-Sep-09	ND	ND	ND	0.98	NS
ZVI-MW4	13	16-Oct-09	ND	1.5	ND	0.83	NS
ZVI-MW4	13	16-Oct-09	ND	1.4	ND	0.83	NS
ZVI-MW4	13	29-Oct-09	NS	NS	ND	0.42	NS
ZVI-MW4	13	10-Nov-09	0.41J	6.5	ND	1.71	2.4

ZVI-MW4	13	25-Mar-10	ND	9.3	ND	0.39	2.8
ZVI-MW5	13	10-Apr-09	0.022J	NS	1.1	0.33	NS
ZVI-MW5	13	21-Apr-09	2.14	10.7	ND	0.15	3
ZVI-MW5	13	28-Apr-09	ND	9.22	NS	0.16	3
ZVI-MW5	13	07-May-09	0.38B	8.8	ND	0.12	7
ZVI-MW5	13	29-May-09	0.06J	0.42	ND	0.21	4.6
ZVI-MW5	13	18-Jun-09	ND	0.33	HND	0.22	3.2
ZVI-MW5	13	26-Jun-09	0.09J	0.5	ND	0.31	NS
ZVI-MW5	13	01-Jul-09	ND	0.66B	HND	0.23	NS
ZVI-MW5	13	09-Jul-09	0.14J	0.96	ND	0.27	4
ZVI-MW5	13	15-Jul-09	ND	1.9	HND	0.27	NS
ZVI-MW5	13	23-Jul-09	ND	0.53J	ND	0.38	NS
ZVI-MW5	13	28-Jul-09	0.2J	0.99J	ND	0.31	NS
ZVI-MW5	13	06-Aug-09	*ND	0.49J	ND	0.33	3
ZVI-MW5	13	14-Aug-09	ND	0.51J	ND	0.36	NS
ZVI-MW5	13	14-Aug-09	ND	0.65J	ND	0.36	NS
ZVI-MW5	13	19-Aug-09	0.28J	ND	ND	0.34	NS
ZVI-MW5	13	27-Aug-09	ND	ND	ND	0.44	2.4
ZVI-MW5	13	27-Aug-09	ND	ND	ND	0.44	NS
ZVI-MW5	13	09-Sep-09	ND	ND	ND	0.47	NS
ZVI-MW5	13	16-Oct-09	ND	1.5	ND	0.5	2.3
ZVI-MW5	13	29-Oct-09	ND	8.4	ND	0.49	NS
ZVI-MW5	13	10-Nov-09	0.49J	9.1	0.34	0.33	2.8
ZVI-MW5	13	25-Mar-10	ND	10	ND	0.39	2.8
ZVI-MW6	13	13-Apr-09	0.039J	10	0.72	0.15	NS
ZVI-MW6	13	21-Apr-09	2.51	9.92	ND	0.1	2.8
ZVI-MW6	13	28-Apr-09	0.44	9.41	NS	0.11	2.8
ZVI-MW6	13	07-May-09	0.27B	8.9	ND	0.1	3.6
ZVI-MW6	13	28-May-09	0.14J	4.4	ND	0.13	4.5
ZVI-MW6	13	18-Jun-09	ND	4.7	HND	0.26	3
ZVI-MW6	13	26-Jun-09	ND	2.7	ND	0.27	NS
ZVI-MW6	13	01-Jul-09	ND	2.3B	HND	0.18	NS
ZVI-MW6	13	10-Jul-09	0.14J	2.2	ND	0.23	3.5
ZVI-MW6	13	10-Jul-09	ND	0.4	ND	0.23	NS
ZVI-MW6	13	15-Jul-09	ND	3.2	HND	0.15	NS
ZVI-MW6	13	23-Jul-09	ND	ND	ND	0.21	NS
ZVI-MW6	13	28-Jul-09	0.36J	0.52J	ND	0.3	NS
ZVI-MW6	13	06-Aug-09	*ND	ND	ND	0.27	3.8
ZVI-MW6	13	14-Aug-09	ND	ND	ND	0.24	NS
ZVI-MW6	13	20-Aug-09	ND	3.6	ND	0.27	NS

ZVI-MW6	13	27-Aug-09	ND	1.1J	ND	0.24	2.8
ZVI-MW6	13	10-Sep-09	ND	ND	ND	0.34	NS
ZVI-MW6	13	15-Oct-09	ND	ND	ND	0.33	0.6
ZVI-MW6	13	29-Oct-09	ND	2	ND	0.33	NS
ZVI-MW6	13	10-Nov-09	0.69	26	0.91	0.2	2.6
ZVI-MW6	13	26-Mar-10	ND	3.5	ND	0.3	2.6
ZVI-MW7	13	13-Apr-09	0.027J	10	0.88H	0.32	NS
ZVI-MW7	13	13-Apr-09	0.029J	10	0.87H	0.32	NS
ZVI-MW7	13	22-Apr-09	ND	9.48	ND	0.18	2.8
ZVI-MW7	13	28-Apr-09	ND	9.64	NS	0.08	3
ZVI-MW7	13	07-May-09	0.11JB	8.6	ND	0.09	4
ZVI-MW7	13	29-May-09	0.12J	2.1	ND	0.1	2.2
ZVI-MW7	13	29-May-09	0.11JB	2	0.03J	0.1	NS
ZVI-MW7	13	18-Jun-09	ND	2.3	HND	0.33	3
ZVI-MW7	13	26-Jun-09	ND	1.8	ND	0.4	NS
ZVI-MW7	13	26-Jun-09	ND	1.5	ND	0.4	NS
ZVI-MW7	13	02-Jul-09	ND	0.81B	HND	0.18	NS
ZVI-MW7	13	10-Jul-09	ND	2.5	0.03J	0.18	2.4
ZVI-MW7	13	15-Jul-09	ND	8.6	HND	0.21	NS
ZVI-MW7	13	24-Jul-09	ND	1J	ND	0.42	NS
ZVI-MW7	13	28-Jul-09	ND	0.51J	ND	0.27	NS
ZVI-MW7	13	06-Aug-09	*ND	1J	ND	0.41	3
ZVI-MW7	13	14-Aug-09	ND	2.9	ND	0.51	NS
ZVI-MW7	13	19-Aug-09	ND	6.7	ND	0.37	NS
ZVI-MW7	13	26-Aug-09	ND	3.7	HND	0.37	2.2
ZVI-MW7	13	10-Sep-09	ND	2.8	ND	0.42	NS
ZVI-MW7	13	16-Oct-09	ND	6.2	ND	0.34	3.8
ZVI-MW7	13	29-Oct-09	ND	15	ND	0.38	NS
ZVI-MW7	13	29-Oct-09	ND	15	ND	0.38	NS
ZVI-MW7	13	12-Nov-09	ND	20	0.42J	0.36	3.2
ZVI-MW7	13	26-Mar-10	ND	14	ND	0.34	2.8
ZVI-MW8	13	10-Apr-09	ND	NS	1.1	0.31	NS
ZVI-MW8	13	21-Apr-09	ND	9.9	ND	0.25	2.8
ZVI-MW8	13	28-Apr-09	ND	9.61	NS	0.25	3
ZVI-MW8	13	07-May-09	0.2B	10	0.01J	0.25	4
ZVI-MW8	13	28-May-09	ND	9.3	0.16	0.19	0.03
ZVI-MW8	13	18-Jun-09	ND	8	0.01JH	0.25	1.5
ZVI-MW8	13	26-Jun-09	ND	7.4	0.01J	0.38	NS
ZVI-MW8	13	01-Jul-09	ND	6.6B	HND	0.6	NS
ZVI-MW8	13	09-Jul-09	0.15	7.8	0.56	2.53	0.2

ZVI-MW8	13	15-Jul-09	0.27J	8.3	0.61JH	3.79	NS
ZVI-MW8	13	23-Jul-09	ND	6.6	ND	0.6	NS
ZVI-MW8	13	28-Jul-09	ND	7.2	ND	0.8	NS
ZVI-MW8	13	06-Aug-09	*ND	3.9	ND	0.75	2.8
ZVI-MW8	13	06-Aug-09	*ND	3.7	ND	0.75	NS
ZVI-MW8	13	14-Aug-09	ND	5.5	ND	0.36	NS
ZVI-MW8	13	19-Aug-09	ND	6.7	ND	0.34	NS
ZVI-MW8	13	26-Aug-09	ND	5.3	HND	0.35	2.2
ZVI-MW8	13	10-Sep-09	ND	5.4	ND	0.7	NS
ZVI-MW8	13	16-Oct-09	ND	7.3	ND	0.79	NS
ZVI-MW8	13	29-Oct-09	ND	2.5	0.38J	0.42	NS
ZVI-MW8	13	12-Nov-09	0.4J	18	5.7	0.75	0
ZVI-MW8	13	25-Mar-10	ND	18	ND	0.33	2.1
ZVI-MW9	13	13-Apr-09	0.026J	10	0.9H	0.92	NS
ZVI-MW9	13	22-Apr-09	ND	10.1	0.96	0.9	0.1
ZVI-MW9	13	28-Apr-09	ND	10.1	NS	0.98	0
ZVI-MW9	13	07-May-09	0.19	11	0.59	0.71	0.2
ZVI-MW9	13	28-May-09	ND	9.9	0.43	0.82	0
ZVI-MW9	13	18-Jun-09	*ND	9.7B	0.13HB	0.18	0.25
ZVI-MW9	13	26-Jun-09	0.08J	0.09J	0.21	0.36	NS
ZVI-MW9	13	02-Jul-09	ND	8B	0.2H	0.35	NS
ZVI-MW9	13	10-Jul-09	ND	7.8	0.41	2.35	0.2
ZVI-MW9	13	15-Jul-09	ND	8.2	0.42JH	2.83	NS
ZVI-MW9	13	24-Jul-09	ND	6.4	ND	0.37	NS
ZVI-MW9	13	28-Jul-09	ND	1.5	ND	0.27	NS
ZVI-MW9	13	07-Aug-09	*ND	2.7	HND	0.43	4.4
ZVI-MW9	13	14-Aug-09	ND	2.2	ND	0.34	NS
ZVI-MW9	13	20-Aug-09	0.22J	3.7	ND	0.32	NS
ZVI-MW9	13	27-Aug-09	ND	0.95J	ND	0.29	4.4
ZVI-MW9	13	10-Sep-09	ND	0.76J	ND	0.2	NS
ZVI-MW9	13	15-Oct-09	0.22J	1.7	ND	0.38	3
ZVI-MW9	13	29-Oct-09	0.26J	0.41J	ND	0.35	NS
ZVI-MW9	13	12-Nov-09	0.33J	19	ND	0.55	3.4
ZVI-MW9	13	25-Mar-10	ND	10	0.54J	0.61	0

Table 9. ZVI Analytical Results Chlorinated Ethenes

well	depth	Collection Date	PCE	TCE	cis-1,2-DCE	trans-1,2-DCE	Vinyl chloride
	ft		ug/L	ug/L	ug/L	ug/L	ug/L
ZVI-INJ	13	13-Apr-09	5.5	25000B	3200	22	2.8
ZVI-INJ	13	22-Apr-09	1.5	810	88	1.3	ND
ZVI-INJ	13	28-Apr-09	0.99J	580	300	2J	0.9J
ZVI-INJ	13	07-May-09	0.28JND	260	380	1.9	2
ZVI-INJ	13	29-May-09	ND	38	470	1.5	2
ZVI-INJ	13	18-Jun-09	0.19J	51	1200	8	4
ZVI-INJ	13	26-Jun-09	0.19J	39	420	2.5	2.1
ZVI-INJ	13	01-Jul-09	HND	73H	850H	.95JH	2.6H
ZVI-INJ	13	10-Jul-09	ND	100	550	1.2	1.6
ZVI-INJ	13	15-Jul-09	0.15J	85	480	20	1.7
ZVI-INJ	13	23-Jul-09	0.39JB	170	820	2.6	1.1
ZVI-INJ	13	28-Jul-09	0.35J	110	740	2.7	0.87J
ZVI-INJ	13	06-Aug-09	0.47J	150	900	2.1	0.24J
ZVI-INJ	13	14-Aug-09	0.97J	400	1000	3.6	ND
ZVI-INJ	13	19-Aug-09	0.78J	160	430	2	ND
ZVI-INJ	13	27-Aug-09	0.72J	170	380	1.5	ND
ZVI-INJ	13	10-Sep-09	0.72J	150	320	.86J	ND
ZVI-INJ	13	16-Oct-09	0.52J	110	180	ND	ND
ZVI-INJ	13	29-Oct-09	0.42J	140	370	ND	0.68J
ZVI-INJ	13	12-Nov-09	0.41J	130	620	0.44J	1
ZVI-INJ	13	26-Mar-10	0.27J	27	1400	0.37J	2.9
ZVI-MW1	13	13-Apr-09	0.21J	140B	69B	1	ND
ZVI-MW1	13	21-Apr-09	0.89	650	410	5	ND
ZVI-MW1	13	28-Apr-09	0.56J	150	770	6.6	ND
ZVI-MW1	13	07-May-09	ND	11	140	0.94J	1.3
ZVI-MW1	13	07-May-09	ND	9.4	76	0.68J	1.2
ZVI-MW1	13	28-May-09	ND	10	330	1.2	1J
ZVI-MW1	13	18-Jun-09	ND	9.1	340	3.1	1.2
ZVI-MW1	13	26-Jun-09	ND	4.9	170	1.7	1.7
ZVI-MW1	13	01-Jul-09	HND	25	1000	1.4H	3.3H
ZVI-MW1	13	01-Jul-09	HND	24	930	1.5H	3.3H
ZVI-MW1	13	10-Jul-09	ND	27	600	1.9	2.5
ZVI-MW1	13	15-Jul-09	ND	20	640	22	1.3
ZVI-MW1	13	23-Jul-09	0.089JB	34	710	1.9	0.77J
ZVI-MW1	13	28-Jul-09	ND	30	510	1.6	0.35J
ZVI-MW1	13	07-Aug-09	0.19J	110	530	1.3	0.29J
ZVI-MW1	13	14-Aug-09	0.28J	250	520	1.9	0.19J
ZVI-MW1	13	20-Aug-09	0.31J	380	190	1.2	ND

ZVI-MW1	13	20-Aug-09	0.32J	350	160	1.1	ND
ZVI-MW1	13	26-Aug-09	0.94J	660	270	2	ND
ZVI-MW1	13	10-Sep-09	0.37J	500	340	4.2	0.2J
ZVI-MW1	13	16-Oct-09	0.32J	150	180	1.9	ND
ZVI-MW1	13	29-Oct-09	0.3J	260	380	3	0.58J
ZVI-MW1	13	10-Nov-09	0.4J	710	490	3.1	1.8
ZVI-MW1	13	10-Nov-09	0.4J	630	450	3.7	1.9
ZVI-MW1	13	26-Mar-10	0.36J	110	260	0.63J	1.7
ZVI-MW1	13	26-Mar-10	0.35J	110	260	0.62J	1.6
ZVI-MW2	13	09-Apr-09	0.11J	46B	17B	0.12J	ND
ZVI-MW2	13	21-Apr-09	0.39	230	63	0.58	ND
ZVI-MW2	13	28-Apr-09	0.24J	85	110	0.84J	ND
ZVI-MW2	13	07-May-09	0.19J	59	49	0.48J	1.6
ZVI-MW2	13	28-May-09	ND	15	85	0.13J	2.4
ZVI-MW2	13	18-Jun-09	ND	10	62	0.54J	2
ZVI-MW2	13	26-Jun-09	ND	1.8	63	0.58J	1.7
ZVI-MW2	13	02-Jul-09	ND	5.7	100	12	2.6
ZVI-MW2	13	09-Jul-09	ND	7	240	6	0.89J
ZVI-MW2	13	15-Jul-09	ND	46	470	16	0.38J
ZVI-MW2	13	15-Jul-09	0.082J	47	480	12	0.38J
ZVI-MW2	13	23-Jul-09	ND	9.6	240	0.57J	1.3
ZVI-MW2	13	28-Jul-09	ND	2.2	140	0.39J	0.32J
ZVI-MW2	13	05-Aug-09	ND	4.2	140	0.37J	0.25J
ZVI-MW2	13	14-Aug-09	ND	20	110	0.45J	ND
ZVI-MW2	13	19-Aug-09	ND	28	220	0.37J	ND
ZVI-MW2	13	26-Aug-09	2	510	160	0.67J	ND
ZVI-MW2	13	09-Sep-09	1.6	300	100	0.38J	ND
ZVI-MW2	13	16-Oct-09	0.58J	380	150	0.53J	ND
ZVI-MW2	13	29-Oct-09	0.58J	270	160	0.47J	ND
ZVI-MW2	13	10-Nov-09	1.1	610	130	0.35J	ND
ZVI-MW2	13	25-Mar-10	1.6	290	240	0.37J	0.88J
ZVI-MW3	10	10-Apr-09	0.34J	260B	33B	0.34J	ND
ZVI-MW3	10	21-Apr-09	1.1	740	69	0.79	ND
ZVI-MW3	10	28-Apr-09	0.25J	100	61	0.57J	ND
ZVI-MW3	10	28-Apr-09	0.29J	130	72	0.59J	ND
ZVI-MW3	10	07-May-09	0.22J	93	320	2.4	0.88J
ZVI-MW3	10	29-May-09	ND	32	190	0.47J	1.6
ZVI-MW3	10	18-Jun-09	0.29J	79	900	8.1	1.6
ZVI-MW3	10	26-Jun-09	0.36J	120	960	8	2.3
ZVI-MW3	10	01-Jul-09	0.13JH	300H	2000H	3.2H	3.2H
ZVI-MW3	10	09-Jul-09	0.28J	580	2800	4.4	2.2

ZVI-MW3	10	15-Jul-09	1.6	690	670	16	0.62J
ZVI-MW3	10	23-Jul-09	0.79J	500	590	1.8	1.2
ZVI-MW3	10	28-Jul-09	1.6	760	3800	17	5.2
ZVI-MW3	10	28-Jul-09	1.5	830	3900	16	5.2
ZVI-MW3	10	06-Aug-09	.43J	580	1000	2.2	0.9J
ZVI-MW3	10	14-Aug-09	6.8	6600	950	5.4	0.52J
ZVI-MW3	10	19-Aug-09	2.6	1500	410	2.2	ND
ZVI-MW3	10	26-Aug-09	0.71J	410	400	0.96J	ND
ZVI-MW3	10	10-Sep-09	0.84J	460	130	4.9	ND
ZVI-MW3	10	29-Oct-09	0.82J	1800	240	0.32J	ND
ZVI-MW3	10	12-Nov-09	0.89J	1100	260	0.95J	ND
ZVI-MW3	10	25-Mar-10	2.6	1300	620	1.2	ND
ZVI-MW4	13	09-Apr-09	0.2J	120B	31B	0.31J	ND
ZVI-MW4	13	21-Apr-09	2.5	2800	340	3.1	ND
ZVI-MW4	13	21-Apr-09	3.2	2700	340	3	ND
ZVI-MW4	13	28-Apr-09	0.84J	360	640	5	1.3J
ZVI-MW4	13	07-May-09	0.27J	100	660	4.7	1.5
ZVI-MW4	13	28-May-09	ND	45	990	3.8	1.3
ZVI-MW4	13	18-Jun-09	ND	32	840	7.5	2.8
ZVI-MW4	13	18-Jun-09	0.088J	33	790	9.2	2.1
ZVI-MW4	13	26-Jun-09	ND	8.7	990	6.5	3.3
ZVI-MW4	13	02-Jul-09	ND	15	1800	3	5.5
ZVI-MW4	13	09-Jul-09	ND	3.2	3600	20	8.4
ZVI-MW4	13	15-Jul-09	ND	11	3200	89	12
ZVI-MW4	13	23-Jul-09	ND	17	1600	4.5	9.2
ZVI-MW4	13	23-Jul-09	ND	18	2400	3.7	13
ZVI-MW4	13	28-Jul-09	ND	26	3100	23	6.8
ZVI-MW4	13	05-Aug-09	ND	18	3200	10	8.8
ZVI-MW4	13	14-Aug-09	ND	95	2200	5	8.7
ZVI-MW4	13	19-Aug-09	1.1	860	2800E	14	2.9
ZVI-MW4	13	27-Aug-09	1.2	450	2500E	12	6.8
ZVI-MW4	13	09-Sep-09	0.49J	400	2400	13	2.4
ZVI-MW4	13	09-Sep-09	0.47J	400	2400	16	2.5
ZVI-MW4	13	29-Oct-09	0.5J	950	1300	2.2	ND
ZVI-MW4	13	10-Nov-09	0.68J	850	850	2.7	0.42J
ZVI-MW4	13	25-Mar-10	0.16J	22	630	1	16
ZVI-MW5	13	10-Apr-09	1.6	1100B	100B	1.4	0.45J
ZVI-MW5	13	21-Apr-09	3	2500	450	4.9	ND
ZVI-MW5	13	28-Apr-09	1.2J	620	510	4J	1.1J
ZVI-MW5	13	07-May-09	1J	780	1000	6	1.8
ZVI-MW5	13	29-May-09	ND	35	870	2.5	1.4

ZVI-MW5	13	18-Jun-09	ND	63	280	4.4	1.7
ZVI-MW5	13	26-Jun-09	ND	30	520	3.6	2.4
ZVI-MW5	13	01-Jul-09	HND	51	440	1.1H	2.1H
ZVI-MW5	13	09-Jul-09	ND	59	1700	4.7	4.6
ZVI-MW5	13	15-Jul-09	ND	47	1300	35	2.7
ZVI-MW5	13	23-Jul-09	ND	52	1600	2.6	3.2
ZVI-MW5	13	28-Jul-09	0.15J	89	2400	19	3.2
ZVI-MW5	13	06-Aug-09	0.27J	170	700	1.8	0.97J
ZVI-MW5	13	14-Aug-09	0.53J	640	1200	3.7	0.87J
ZVI-MW5	13	14-Aug-09	0.63J	580	1000	4.8	0.9J
ZVI-MW5	13	19-Aug-09	0.6J	400	1500E	3.5	ND
ZVI-MW5	13	27-Aug-09	2.9	1600	760	4	0.88J
ZVI-MW5	13	27-Aug-09	2.7	1500	710	3.8	0.82J
ZVI-MW5	13	09-Sep-09	1.7	620	450	3.9	0.6J
ZVI-MW5	13	16-Oct-09	0.6J	340	250	3.2	ND
ZVI-MW5	13	29-Oct-09	2	1800	550	4.5	ND
ZVI-MW5	13	10-Nov-09	1.7	1100	400	2	0.42J
ZVI-MW5	13	25-Mar-10	0.41J	160	480	0.74J	2.9
ZVI-MW6	13	13-Apr-09	0.13J	79B	25B	0.39J	0.26J
ZVI-MW6	13	21-Apr-09	0.83	500	240	3.7	ND
ZVI-MW6	13	28-Apr-09	0.39J	98	230	2	3
ZVI-MW6	13	07-May-09	ND	15	200	1.5	2.2
ZVI-MW6	13	28-May-09	ND	39	170	1.3	1.8
ZVI-MW6	13	18-Jun-09	0.069J	39	170	3	2.7
ZVI-MW6	13	26-Jun-09	0.086J	46	440	5.5	7.7
ZVI-MW6	13	01-Jul-09	HND	74H	1200B	4.6H	25H
ZVI-MW6	13	10-Jul-09	ND	36	2000	9.2	28
ZVI-MW6	13	10-Jul-09	ND	35	2100	8.9	27
ZVI-MW6	13	15-Jul-09	ND	29	3100	130	36
ZVI-MW6	13	23-Jul-09	ND	11	1400	5.3	37
ZVI-MW6	13	28-Jul-09	0.11J	72	3100	26	48
ZVI-MW6	13	06-Aug-09	ND	28	690	3.9	12
ZVI-MW6	13	14-Aug-09	ND	32	450	2.7	6.4
ZVI-MW6	13	20-Aug-09	ND	68	190	2.2	3.2
ZVI-MW6	13	27-Aug-09	ND	67	280	3.9	3.1
ZVI-MW6	13	10-Sep-09	ND	68	280	4.5	1.6
ZVI-MW6	13	15-Oct-09	ND	71B	170B	3.4	1.3
ZVI-MW6	13	29-Oct-09	ND	140	350	3.2	1.7
ZVI-MW6	13	10-Nov-09	0.25J	250	250	1.9	1
ZVI-MW6	13	26-Mar-10	0.12J	7.4	94	1.1	83
ZVI-MW7	13	13-Apr-09	J	51B	24	0.2J	ND

ZVI-MW7	13	13-Apr-09	ND	50B	24B	0.2J	ND
ZVI-MW7	13	13-Apr-09	ND	51B	24B	0.2J	ND
ZVI-MW7	13	22-Apr-09	ND	68	50	0.67	ND
ZVI-MW7	13	28-Apr-09	ND	17	26	0.21J	1.3
ZVI-MW7	13	07-May-09	ND	7.1	28	0.22J	1.7
ZVI-MW7	13	29-May-09	ND	4.5	74	ND	2.1
ZVI-MW7	13	29-May-09	ND	4.4	70	0.085J	2.2
ZVI-MW7	13	18-Jun-09	ND	5.4	35	0.25J	2
ZVI-MW7	13	26-Jun-09	ND	4.3	29	0.34J	1.7
ZVI-MW7	13	26-Jun-09	ND	3.9	31	0.27J	1.8
ZVI-MW7	13	02-Jul-09	ND	3.5	25	3.4	2.9
ZVI-MW7	13	10-Jul-09	ND	13	90B	0.32J	0.69
ZVI-MW7	13	15-Jul-09	ND	63	250	13	0.61
ZVI-MW7	13	24-Jul-09	ND	8.8	120	0.4J	0.53
ZVI-MW7	13	28-Jul-09	ND	3.7	120	0.37J	ND
ZVI-MW7	13	06-Aug-09	ND	5.4	92	0.36J	0.094
ZVI-MW7	13	14-Aug-09	ND	8.6	150	0.53J	ND
ZVI-MW7	13	19-Aug-09	ND	15	83	0.12J	ND
ZVI-MW7	13	26-Aug-09	ND	19	95	0.17J	ND
ZVI-MW7	13	10-Sep-09	ND	24	240	0.67J	ND
ZVI-MW7	13	16-Oct-09	ND	24	41	ND	ND
ZVI-MW7	13	29-Oct-09	0.37J	400	300	0.8J	1.3
ZVI-MW7	13	29-Oct-09	0.36J	390	280	0.74J	1.2
ZVI-MW7	13	12-Nov-09	0.39J	460	240	0.53J	1.6
ZVI-MW7	13	26-Mar-10	0.18J	34	20	ND	
ZVI-MW8	13	10-Apr-09	ND	18B	15B	0.066J	ND
ZVI-MW8	13	21-Apr-09	ND	39	18	0.18	ND
ZVI-MW8	13	28-Apr-09	ND	30	19	0.13J	1.2
ZVI-MW8	13	07-May-09	0.11J	54	19	0.14J	1.7
ZVI-MW8	13	28-May-09	ND	26	14	ND	2.1
ZVI-MW8	13	18-Jun-09	ND	34	20	0.53J	2.3
ZVI-MW8	13	26-Jun-09	0.15J	77	32	0.15J	2.5
ZVI-MW8	13	01-Jul-09	0.17J	97	37	6	2.1
ZVI-MW8	13	09-Jul-09	ND	68	8.3B	ND	ND
ZVI-MW8	13	15-Jul-09	ND	79	9.5	0.61J	ND
ZVI-MW8	13	23-Jul-09	0.17J	110	51	0.2J	ND
ZVI-MW8	13	28-Jul-09	0.22J	150	37	ND	ND
ZVI-MW8	13	06-Aug-09	0.12J	63	66	0.27J	ND
ZVI-MW8	13	06-Aug-09	0.1J	53	52	0.23J	ND
ZVI-MW8	13	14-Aug-09	0.1J	61	43	0.17J	ND
ZVI-MW8	13	19-Aug-09	0.16J	92	35	ND	ND

ZVI-MW8	13	26-Aug-09	0.6J	83	33	ND	ND
ZVI-MW8	13	10-Sep-09	0.16J	110	21	0.11J	ND
ZVI-MW8	13	16-Oct-09	0.095J	89	11	ND	ND
ZVI-MW8	13	29-Oct-09	ND	79	96	ND	0.42
ZVI-MW8	13	12-Nov-09	0.7J	770	67	0.42J	ND
ZVI-MW8	13	25-Mar-10	0.69J	400	87	ND	ND
ZVI-MW9	13	13-Apr-09	0.087J	49B	10B	0.54J	ND
ZVI-MW9	13	22-Apr-09	0.21	57	15	0.57	0.13
ZVI-MW9	13	28-Apr-09	ND	41	12	0.39J	ND
ZVI-MW9	13	07-May-09	0.13J	50	9.5	0.54J	ND
ZVI-MW9	13	28-May-09	ND	31	9.7	ND	ND
ZVI-MW9	13	18-Jun-09	ND	19	7.6	.28J	ND
ZVI-MW9	13	26-Jun-09	ND	26	8.3	0.18J	ND
ZVI-MW9	13	02-Jul-09	ND	27	8.4	1.5	ND
ZVI-MW9	13	10-Jul-09	ND	94	13B	0.61J	ND
ZVI-MW9	13	15-Jul-09	0.12J	89	10	0.79J	ND
ZVI-MW9	13	24-Jul-09	0.16JB	79	21	0.64J	1
ZVI-MW9	13	28-Jul-09	ND	23	60	0.61J	0.39J
ZVI-MW9	13	07-Aug-09	ND	24	77	0.9J	6.6
ZVI-MW9	13	14-Aug-09	ND	13	130	1.7	16
ZVI-MW9	13	20-Aug-09	ND	16	140	1.7	17
ZVI-MW9	13	27-Aug-09	ND	14	380	4.2	30
ZVI-MW9	13	10-Sep-09	ND	19	520	5.4	28
ZVI-MW9	13	15-Oct-09	0.23J	34	360B	4.6	18
ZVI-MW9	13	29-Oct-09	ND	45	390	4.3	11
ZVI-MW9	13	12-Nov-09	ND	60	200	2.8	8.9
ZVI-MW9	13	25-Mar-10	0.21J	37	7.9	0.15J	ND