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Demonstration of In Situ Dehalogenation of DNAPL through Injection of Emulsified Zero-Valent Iron at Launch Complex 34 in Cape Canaveral Air Force Station, Florida

Innovative Technology Evaluation Report

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Demonstration of In Situ Dehalogenation of DNAPL through Injection of Emulsified Zero-Valent Iron at Launch Complex 34 in Cape Canaveral Air Force Station, Florida

Final Innovative Technology Evaluation Report

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Sally Gutierrez, Director
National Risk Management Research Laboratory

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Executive Summary

The purpose of this project was to evaluate the technical and cost performance of emulsified zero-valent iron (EZVI) technology when applied to DNAPL contaminants in the saturated zone. This demonstration was conducted at Launch Complex 34, Cape Canaveral Air Force Station, FL, where chlorinated volatile organic compounds (CVOCs), mainly trichloroethylene (TCE), are present in the subsurface as DNAPL. Smaller amounts of dichloroethylene (DCE) and vinyl chloride (VC) also are present as a result of the natural degradation of TCE.

The EZVI project was conducted under the National Aeronautics and Space Administration (NASA) Small Business Technology Transfer Research (STTR) Program. The Small Business Concern is GeoSyntec Consultants (GeoSyntec) and the Research Institution is the University of Central Florida (UCF). This EZVI demonstration was independently evaluated under the United States Environmental Protection Agency's (U.S. EPA's) Superfund Innovative Technology Evaluation Program (the SITE Program).

EZVI can be used to enhance the destruction of chlorinated DNAPL in source zones by creating intimate contact between the DNAPL and the nanoscale iron particles. The EZVI is composed of surfactant, biodegradable oil, water, and zero-valent iron particles, which form emulsion particles (or micelles) that contain the iron particles in water surrounded by an oil-liquid membrane. Because the exterior oil membrane of the emulsion particles has similar hydrophobic properties as the DNAPL, the emulsion is miscible with the DNAPL (i.e., the phases can mix). It has been demonstrated in laboratory experiments conducted at UCF that DNAPL compounds (e.g., TCE) diffuse through the oil membrane of the emulsion particle and undergo reductive dechlorination facilitated by the zero-valent iron particles in the interior aqueous phase. The final byproducts (nonchlorinated hydrocarbons) from the dehalogenation reaction then can diffuse out of the emulsion into the surrounding aqueous phase.

The main dehalogenation reaction pathways occurring at the iron surface require excess electrons produced from the corrosion of the zero-valent iron. Hydrogen gas also is produced, as well as OH^- that results in an increase in the pH of the surrounding water. The degradation of TCE also occurs via a ß-elimination reaction where TCE is converted to chloroacetylene followed by a dehalogenation reaction to acetylene, and then to ethene and ethane. It has been shown in laboratory studies that complete dehalogenation occurs within the micelles. TCE is continually degraded within the emulsion particle, maintaining a concentration gradient across the oil membrane, and thus a driving force for TCE molecules to continue to enter into the micelle.

Based on pre-demonstration groundwater and soil sampling by Battelle, a test plot for EZVI of 15 ft long × 9.5 ft wide × 26 ft deep was identified; this plot consists of the upper portion of the surficial aquifer known as the Upper Sand Unit. The Upper Sand Unit is underlain by the Middle Fine-Grained Unit, which constitutes somewhat of a hydraulic barrier to the Lower Sand Unit below. These three stratigraphic units constitute the surficial aquifer. The Lower Clay Unit forms a thin aquitard under the surficial aquifer. The EZVI treatment was targeted at depths of 16 to 24 ft bgs in the Upper Sand Unit, where most of the DNAPL appeared to be present within the target depths. The layout of the pilot test area for application of the EZVI technology at Launch Complex 34 included: (1) injection and extraction wells that were used to maintain hydraulic control over the test area; (2) a row of upgradient monitoring wells to allow characterization of groundwater upgradient of the treatment zone; (3) a row of downgradient monitoring wells to allow characterization of the groundwater downgradient of the treatment zone; and (4) the location of multilevel iron emulsion injection points to allow injection of the EZVI into the subsurface.

Prior to beginning the EZVI demonstration, GeoSyntec recirculated groundwater from the extraction wells to the injection wells for three weeks to establish steady state flow conditions. At the end of the three-week recirculation period, one round of groundwater samples was collected to measure the baseline mass flux of TCE. The recirculation system then was shut down, and the EZVI was injected inside the plot to begin the demonstration. The process was repeated after the EZVI treatment to estimate the post-demonstration TCE mass flux from the DNAPL source in the plot.

During the field demonstration, a total of 661 gal of EZVI, containing 77 lb of nanoscale iron, was injected into the Upper Sand Unit. Pressure pulse technology (PPT) was used by Wavefront Environmental to inject the EZVI; this injection technology involves periodic (e.g., one pulse per second) hydraulic excitations to dilate pores and facilitate movement of the injected fluid in the aquifer. The EZVI was injected into the test plot through directional PPT injection wells located along the edges of the plot (with well screens open only in the direction of the treatment plot interior). Approximately 1,627 gal of water was injected along with the EZVI as part of the PPT implementation.

Performance assessment activities for the EZVI demonstration included pre-demonstration investigations, installation of wells, operation, monitoring, and post-treatment evaluation. Battelle conducted detailed soil and groundwater characterization activities to establish the DNAPL distribution and mass inside the test cell. Geosyntec conducted the mass flux measurements. The objectives of the performance assessment were to:

- Determine changes in total TCE (dissolved and free-phase) and DNAPL mass in the test plot and the change in groundwater TCE flux due to the EZVI treatment;
- Determine changes in aquifer quality due to the EZVI treatment;
- Determine the fate of TCE, the primary DNAPL contaminant; and,
- Determine operating requirements and cost of the EZVI technology.

Changes in Total TCE and DNAPL Mass and Mass Flux

Detailed pre-demonstration and post-demonstration soil sampling was the main tool for estimating changes in total TCE and DNAPL mass in the plot due to the EZVI injection. The majority of the pre-demonstration DNAPL mass was found in the western and southern portions of the plot in the Upper Sand Unit. The rest of the plot appeared to contain mostly dissolved-phase TCE. The soil sampling results were evaluated using both linear interpolation and kriging to obtain mass estimates for the entire treatment zone (i.e., Upper Sand Unit). Linear interpolation indicated that, before the EZVI treatment, 17.8 kg of total TCE (both DNAPL and dissolved-phase TCE) were present in the treatment zone; 3.8 kg of the total TCE mass was present as DNAPL. After the EZVI treatment, the estimated total TCE mass in the plot declined to 2.6 kg, of which 0.6 kg was DNAPL. Linear interpolation indicated that the total TCE and DNAPL masses in the plot declined by 86% and 84%, respectively.

Kriging of the soil data indicated that the total TCE mass in the target zone before EZVI treatment ranged from 10 to 46 kg, with an average of 28 kg. After EZVI treatment, the total TCE mass in the plot ranged from 2.5 to 21 kg, with an average of 11.7 kg. The decline in TCE mass due to the EZVI treatment ranged from 22 to 100%, with an estimated average decline of 58%. Because few data points were available for DNAPL estimation, only the total TCE data were subjected to kriging. These estimated TCE mass ranges are based on an 80% confidence level and incorporate the uncertainty and spatial variability in the data. The linear interpolation estimates are within the range of the kriging estimates. These results indicate that the EZVI injection caused a significant decrease in total TCE and DNAPL mass in the target treatment zone.

In measurements conducted by the vendor, mass flux of dissolved TCE in groundwater, as measured in the extraction transect on the downgradient side of the plot, declined from 1,826 to 810 mmoles/day due to the EZVI treatment. During the same period, mass flux of *cis*-1,2-DCE increased from 83 to 438 mmoles/ day; mass flux of VC increased from 0 to 143 mmoles/day; and mass flux of ethene increased from 0 to 69 mmoles/day. These results show that the EZVI treatment reduced the mass flux of TCE emanating from the DNAPL source in the target plot, indicating that the DNAPL source was contributing less TCE to the plume. The decrease in TCE mass flux could have been caused either by a decrease in the total TCE/DNAPL mass in the plot, or through dissolution (and sequestration) of total TCE/DNAPL in the vegetable oil component of the EZVI. The mass flux of TCE degradation products increased, indicating that some TCE was being degraded, either through biotic or abiotic means. The increase in *cis*-1,2-DCE and VC mass fluxes may be attributed primarily to biologically induced reductive dehalogenation caused by the vegetable oil, and secondarily to abiotic reduction caused by the iron. The increase in ethene can be attributed to either abiotic (zero-valent iron-driven) or biologically-driven reactions.

Changes in Aquifer Quality

The dissolved TCE level in the treatment plot groundwater declined considerably, from 1,180,000 µg/L (close to saturation) before the EZVI treatment to 8,800 µg/L afterward. This indicates that there was a considerable decline in dissolved TCE levels due to EZVI treatment. Levels of *cis*-1,2-DCE increased tenfold from 16,900 µg/L to 169,000 µg/L, and VC levels increased sharply from below detection to 21,600 µg/L. These increases in the degradation products match the increases seen in the mass flux measurements and indicate degradation of TCE through biological and abiotic mechanisms.

Oxidation-reduction potential (ORP) and dissolved oxygen (DO) decreased slightly after the EZVI injection. These changes can be attributed to the anaerobic conditions generated by either the vegetable oil or iron components of EZVI. Groundwater pH remained relatively stable (close to neutral), with a slight increase. Generally, addition of zero-valent iron to an aquifer generates very high pH (up to 10 or 11); however, in this case, the action of the nanoscale iron could have remained muted as it was sequestered in the oil.

Calcium, magnesium, and alkalinity levels in the treatment plot remained relatively constant, indicating that the effect of the nanoscale iron was relatively muted in the bulk aquifer. Chloride levels in well PA-23 in the center of the plot remained relatively constant, but chloride levels measured at discrete depths using a Waterloo Profiler®

showed a slight increasing trend; this indicates that some TCE was completely mineralized through biotic or abiotic mechanisms. Anomalously, both total and dissolved iron concentrations in the groundwater were relatively high before EZVI treatment and declined after the treatment.

Sulfate levels dropped considerably, indicating the presence of sulfate-reducing bacteria in the aquifer. Somewhat anomalously, total organic carbon (TOC) levels decreased, possibly due to mass transfer of dissolved organic matter from the water phase to the oil phase. At the same time, biological oxygen demand (BOD) levels increased, indicating that the oil is a contributing nutrient source for microbes in the aquifer. An increase in methane levels in the aquifer also indicates increased microbial activity. Polymerase chain reaction (PCR) analysis conducted by the vendor indicated the presence of an active *Dehalococcoides* population, which is probably contributing to the sequential degradation of TCE and daughter products.

Slug tests conducted before and after EZVI treatment did not indicate any changes in aquifer permeability; the addition of the EZVI did not affect the hydraulic properties of the aquifer.

Long-term groundwater monitoring results were collected in December 2003 and March 2004, and suggest that the EZVI treatment had a long-lasting effect on CVOCs in the subsurface. TCE, *cis*-1,2-DCE, and (eventually) VC levels declined sharply in the one year following EZVI injection. Ethene level was substantially increased. This may suggest that the remaining EZVI in the treatment plot area continued to dechlorinate TCE in and around the test area for several months after the demonstration due to biotic and abiotic mechanisms.

Fate of TCE/DNAPL in the Aquifer

The decrease in total TCE and DNAPL mass in the test plot can be attributed to several possible causes:

- Biologically mediated degradation of TCE, as indicated by the increases in *cis*-1,2-DCE and VC, the increases in dissolved ethene and methane, and the slight increase in chloride. The decreases in ORP, DO, and sulfate in the aquifer all indicate heightened microbial activity, probably induced by the vegetable oil component of the EZVI.
- Abiotic degradation of TCE due to reaction with the nanoscale iron. The increase in ethene and chloride, the slight decrease in ORP, and the slight increase in pH indicate the presence of zero-valent iron activity in water containing TCE, *cis*-1,2-DCE, and VC could partly indicate abiotic degradation reactions involving iron.
- Dissolution into the vegetable oil phase. Vegetable oil can induce mass transfer of dissolved-phase TCE from the water phase to the oil phase. In addition, DNAPL itself can dissolve in the oil phase upon contact. The sequestration of dissolved and DNAPL TCE in the oil phase may have contributed to a reduction in the mass flux of TCE from the test plot.
- Migration of DNAPL outside the test plot. Monitoring wells were installed around and below the test plot to monitor migration. In addition, soil cores were collected in the Middle Fine-Grained Unit and Lower Sand Unit as well. These data did not indicate that any significant migration of DNAPL outside the test plot occurred due to the EZVI injection.

Operating Requirements and Cost

As indicated by the changes in the aquifer chemistry, the EZVI injection was implemented with relative success, given the highly viscous nature of the emulsion. After initial evaluation of different delivery methods, PPT was used to inject the EZVI into the aquifer. The entire operation was relatively smooth and successful. Additional testing of the delivery method may be needed in the future to improve the distribution of the EZVI in the aquifer. The need to use the water recirculation system to help distribute the EZVI should be re-examined, as a significant amount of water was required to be treated aboveground before it could be reinjected.

A cost comparison between short-term source treatment with EZVI and long-term source/plume containment with an equivalent pump-and-treat system indicates that the EZVI treatment is cost-competitive.

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Contents

Appendices

Figures

Tables

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Acronyms and Abbreviations

2D	two-dimensional
3D	three-dimensional
ACL	alternative concentration limit
ARAR	applicable or relevant and appropriate requirement
ARS	ARS Technologies
bgs	below ground surface
BOD	biological oxygen demand
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CVOC	chlorinated volatile organic compound
CWA	Clean Water Act
DCE	dichloroethylene
DNAPL	dense, nonaqueous-phase liquid
DO	dissolved oxygen
EEW	EZVI extraction well
EIW	EZVI injection well
EZVI	emulsified zero-valent iron
FDEP	(State of) Florida Department of Environmental Protection
FRTR	Federal Remediation Technology Roundtable
GAC	granulated activated carbon
gpm	gallon(s) per minute
HSWA	Hazardous and Solid Waste Amendments
ISCO	in situ chemical oxidation
IW	injection well
LAI	liquid atomization injection
LCS	laboratory control spike(s)
LRPCD	Land Remediation and Pollution Control Division
MB	method blank(s)
MCL	maximum contaminant level
MS	matrix spike(s)
MSD	matrix spike duplicate(s)

msl	mean sea level
mV	millivolts
MYA	million years ago
NA	not available; not analyzed
N/A	not applicable
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
ND	not detected
NPDES	National Pollutant Discharge Elimination System
O&M	operation and maintenance
O.D.	outside diameter
ORD	Office of Research and Development
ORP	oxidation-reduction potential
OSHA	Occupational Safety and Health Administration
OW	observation well
PCE	tetrachloroethylene
PCR	polymerase chain reaction
PLFA	phospholipid fatty acid
POTW	publicly owned treatment works
PPT	pressure pulse technology
psi	pounds per square inch
PV	present value
PVC	polyvinyl chloride
QA	quality assurance
QAPP	Quality Assurance Project Plan
QC	quality control
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RI/FS	Remedial Investigation/Feasibility Study
RPD	relative percent difference
SARA	Superfund Amendments and Reauthorization Act
SB	soil boring
SDWA	Safe Drinking Water Act
SI/E	steam injection/extraction
SIP	State Implementation Plan
SITE	Superfund Innovative Technology Evaluation (Program)
STTR	Small Business Technology Transfer Research (Program)
TCA	trichloroethane
TCE	trichloroethylene
TDS	total dissolved solids
TOC	total organic carbon
UCF	University of Central Florida
UIC	Underground Injection Control
U.S. EPA	United States Environmental Protection Agency
VC	vinyl chloride
VOA	volatile organic analysis
WP	Waterloo Profiler®

1. Introduction

This report presents the project field demonstration of emulsified zero-valent iron (EZVI) technology for treatment of a dense, nonaqueous-phase liquid (DNAPL) source zone at Launch Complex 34, Cape Canaveral Air Force Station, FL.

1.1 Project Background

The goal of the project was to evaluate the technical and cost performance of the nanoscale EZVI technology when applied to a DNAPL source zone. The chlorinated volatile organic compound (CVOC) trichloroethylene (TCE) is present as a DNAPL source in the aquifer at Launch Complex 34. Smaller amounts of dissolved *cis*-1,2-dichloroethylene (*cis*-1,2-DCE) and vinyl chloride (VC) also are present in the groundwater as a result of the natural degradation of TCE.

The field application of EZVI technology began at Launch Complex 34 in June 2002 and ended in January 2003. Performance assessment activities were conducted before, during, and after the field application.

1.1.1 Project Organization

The EZVI project was conducted under the National Aeronautics and Space Administration (NASA) Small Business Technology Transfer Research (STTR) Program. The STTR Program awards contracts to small business concerns in partnership with nonprofit research institutions for cooperative research and development. The goal of the STTR Program is to facilitate the transfer of technology developed by a research institution through the entrepreneurship of a small business. For this project, STTR funding was awarded to GeoSyntec Consultants (GeoSyntec) as the small business concern in partnership with the University of Central Florida (UCF) as the nonprofit research institution. The NASA Contracting Officer's Technical Representative provided a project management role for NASA. Figure 1-1 summarizes the project organization for the EZVI demonstration.

1.1.2 Performance Assessment

The EZVI technology demonstration is being independently evaluated under the United States Environmental Protection Agency's (U.S. EPA's) Superfund Innovative Technology Evaluation (SITE) Program.

The U.S. EPA contracted Battelle to plan, conduct, and report on the detailed site characterization at Launch Complex 34 and perform an independent performance assessment for the demonstration of the EZVI technology. Battelle also was responsible for providing quality assurance (QA) oversight for the performance assessment activities. Before the field demonstration, Battelle prepared a Quality Assurance Project Plan (QAPP) that was reviewed by all project stakeholders. This QAPP was based on the general guidelines provided by the U.S. EPA's SITE Program for test plan preparation, quality assurance, and data analysis (Battelle, 2002a).

1.1.3 The SITE Program

The performance assessment planning, field implementation, and data analysis and reporting for the EZVI demonstration followed the general guidance provided by the U.S. EPA's SITE Program. The SITE Program was established by U.S. EPA's Office of Solid Waste and Emergency Response and the Office of Research and Development (ORD) in response to the 1986 Superfund Amendments and Reauthorization Act, which recognized a need for an "Alternative or Innovative Treatment Technology Research and Demonstration Program." ORD's National Risk Management Research Laboratory in the Land Remediation and Pollution Control Division (LRPCD), headquartered in Cincinnati, OH, administers the SITE Program. This program encourages the development and implementation of (1) innovative treatment technologies for hazardous waste site remediation, and (2) innovative monitoring and measurement tools.

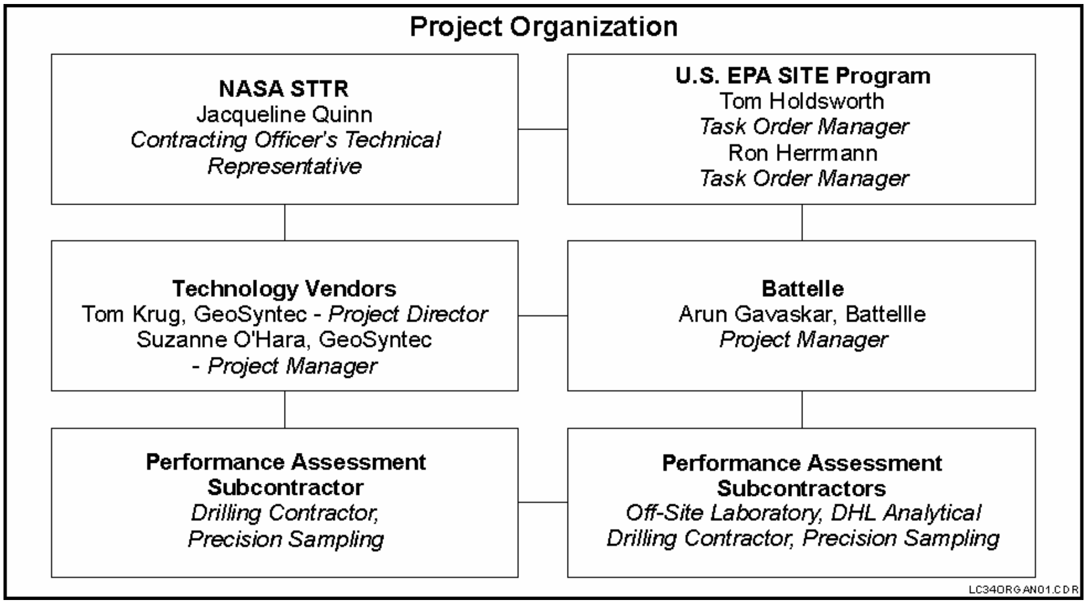


Figure 1-1. Project Organization for the EZVI Demonstration at Launch Complex 34

In the SITE Program, a field demonstration is used to gather engineering and cost data on the innovative technology so that potential users can assess the technology's applicability to a particular site. Data collected during the field demonstration are used to assess the performance of the technology, the potential need for pre- and post-processing of the waste, applicable types of wastes and waste matrices, potential operating problems, and approximate capital and operating costs.

U.S. EPA provides guidelines on the preparation of an Innovative Technology Evaluation Report at the end of the field demonstration. These reports evaluate all available information on the technology and analyze its overall applicability to other site characteristics, waste types, and waste matrices. Testing procedures, performance and cost data, and quality assurance and quality standards also are presented. This report on the EZVI technology demonstration at Launch Complex 34 is based on these general guidelines.

1.2 The DNAPL Problem

Figure 1-2 illustrates the formation of a DNAPL source zone at a chlorinated solvent release site. When solvent is released into the ground due to previous use or disposal practices, it travels downward through the vadose zone to the water table. Because many chlorinated solvents are denser than water, the solvent continues its downward migration through the saturated zone (assuming sufficient volume of solvent is involved) until it encounters a low-permeability layer or aquitard, on which it may form a pool. During its downward migration, the solvent leaves a trace of residual solvent in the soil pores. Many chlorinated solvents are only sparingly soluble in water; therefore, they can persist as a separate phase for several years (or decades). This free-phase solvent is called DNAPL.

DNAPL in pools often can be mobilized toward extraction wells when a strong hydraulic gradient is imposed; this solvent is called mobile DNAPL. In contrast, residual DNAPL is DNAPL trapped in pores that cannot be mobilized toward extraction wells, regardless of the strength of the applied gradient. Residual DNAPLs form as DNAPL pools dissolve in groundwater over time, leaving behind residual DNAPL in the soil structure. At most sites DNAPL pools are rare, as DNAPL is often present in residual form.

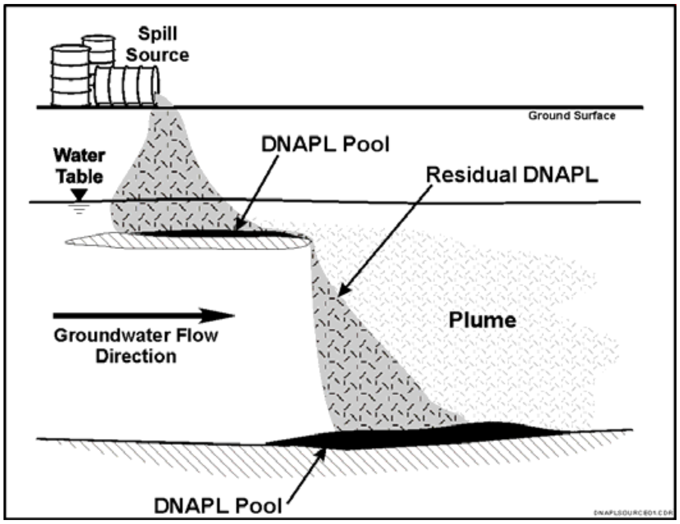


Figure 1-2. Simplified Depiction of the Formation of a DNAPL Source Zone in the Subsurface

As long as DNAPL is present in the aquifer, a plume of dissolved solvent is generated. DNAPL therefore constitutes a secondary source that keeps replenishing the plume long after the primary source (leaking aboveground or buried drums, drain pipes, vadose zone soil, etc.) has been removed. Because DNAPL persists for many decades or centuries, the resulting plume also persists for many years. As recently as five years ago, DNAPL sources were difficult to find and most remedial approaches focused on plume treatment or plume control. In recent years, efforts to identify DNAPL sources have been successful at many chlorinated solvent-contaminated sites. The focus is now shifting from plume control to DNAPL source removal or treatment.

Pump-and-treat systems have been the conventional treatment approach at DNAPL sites and these systems have proven useful as an interim remedy to control the progress of the *plume* beyond a property boundary or other compliance point. However, pump-and-treat systems are not economical for *DNAPL* remediation. Pools of DNAPL that can be pumped and treated above ground are rare. Residual DNAPL is immobile and does not migrate toward extraction wells. As with plume control, the effectiveness and cost of DNAPL remediation with pump and treat is governed by the time (decades) required for slow dissolution of the DNAPL source in the groundwater flow. An innovative approach is required to address the DNAPL problem.

1.3 The Demonstration Site

Launch Complex 34, the site selected for this demonstration, is located at Cape Canaveral Air Force Station, FL (see Figure 1-3). Launch Complex 34 was used as a launch site for Saturn rockets from 1960 to 1968. Historical records and worker accounts suggest that rocket engines were cleaned on the launch pad with chlorinated organic solvents such as TCE. Other rocket parts were cleaned on racks at the western portion of the

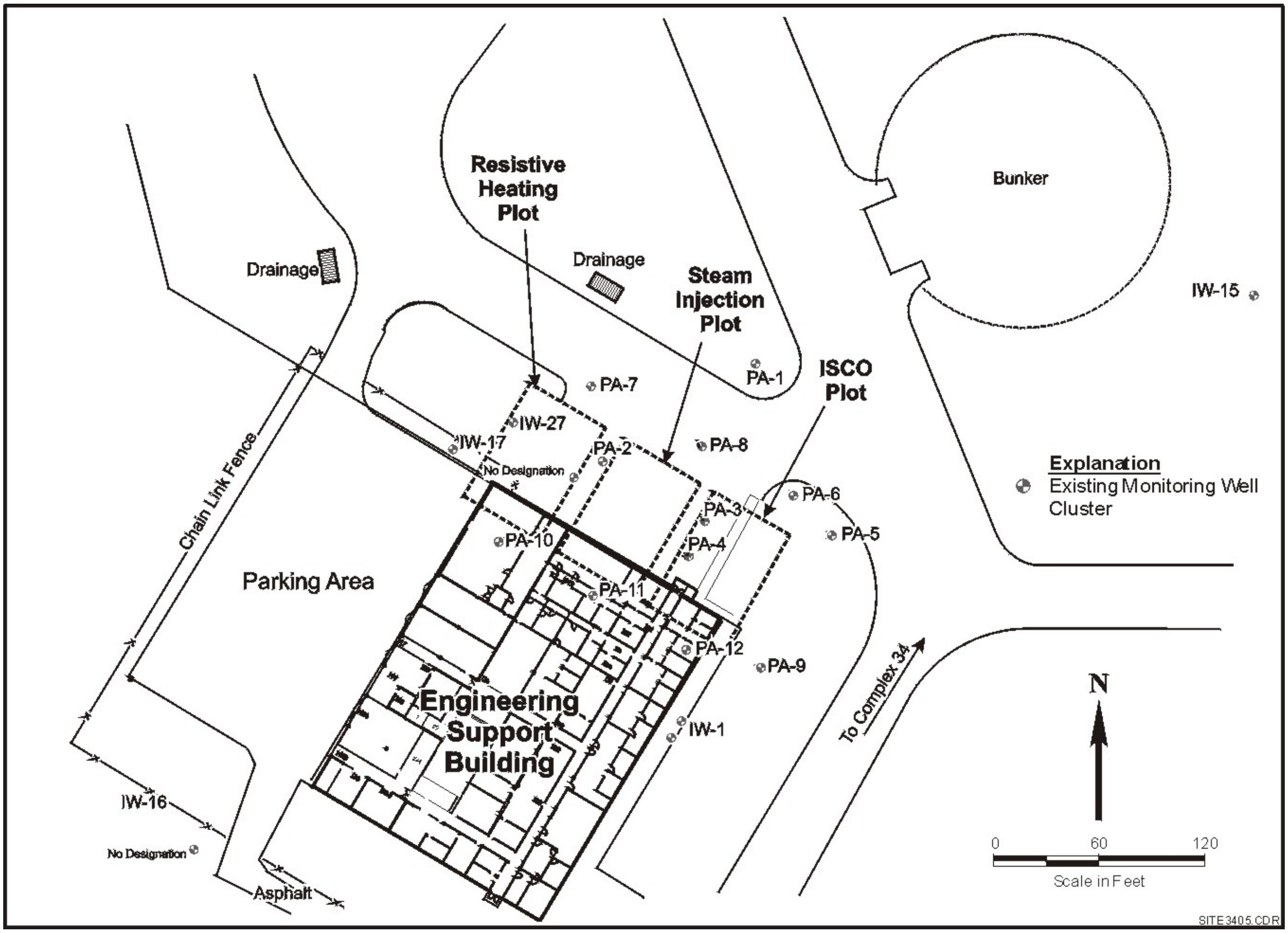


Figure 1-3. Location Map of Launch Complex 34 Site

Engineering Support Building and inside the building. Some of the solvents ran off to the surface or discharged into drainage pits. The site was abandoned in 1968; since then, much of the site has been overgrown by vegetation, although several on-site buildings remain operational.

Preliminary site characterization efforts suggested that approximately 20,600 kg (Battelle, 1999a) to 40,000 kg (Eddy-Dilek et al., 1998) of solvent could be present in the subsurface near the Engineering Support Building. Figure 1-4 is a map of the Launch Complex 34 site that shows the target DNAPL source area for the EZVI technology demonstration, located inside the Engineering Support Building. Figure 1-5 is a photograph looking south toward the EZVI plot inside the Engineering Support Building.

1.4 The EZVI Technology

EZVI can be used to enhance the dehalogenation of chlorinated DNAPL in source zones by creating intimate contact between the DNAPL and the nanoscale iron particles. The EZVI is composed of surfactant, biodegradable oil, water, and nanoscale zero-valent iron particles, which form emulsion particles (or micelles) that contain the iron particles in water surrounded by an oil-liquid membrane. Figure 1-6 is a schematic drawing of an EZVI micelle, and Figure 1-7 is a photograph of iron particles visible inside an emulsion drop. Because the exterior oil membrane of an emulsion particle has similar hydrophobic properties as the DNAPL, the emulsion is miscible with the DNAPL (i.e., the phases can mix).

Laboratory experiments conducted at UCF for NASA have demonstrated that DNAPL compounds (e.g., TCE) diffuse through the oil membrane of the emulsion particle and undergo reductive dechlorination facilitated by the zero-valent iron particles in the interior aqueous phase. The final byproducts from the dehalogenation reaction (i.e., nonchlorinated hydrocarbons) then can diffuse out of the emulsion into the surrounding aqueous phase. The main dehalogenation reaction pathways occurring at the iron surface require excess electrons, which are produced from the corrosion of the zero-valent iron in water as follows:

$$\mathrm{Fe}^0 \rightarrow \mathrm{Fe}^{2+} + 2e^- \qquad (1)$$

$$\mathrm{Fe}^{2+}_{(\mathrm{surface})} \rightarrow \mathrm{Fe}^{3+}_{(\mathrm{aqueous})} + e^- \qquad (2)$$

Hydrogen gas also is produced, as well as OH^-, which results in an increase in the pH of the surrounding water according to the following reaction:

$$2H_2O + 2\,e^- \rightarrow H_{2(\mathrm{gas})} + 2OH^- \qquad (3)$$

Some portion of the chlorinated ethenes is degraded by a stepwise dehalogenation reaction according to:

$$\mathrm{RCl}^- + \mathrm{H}^+ + 2e^- \rightarrow \mathrm{RH} + \mathrm{Cl}^- \qquad (4)$$

In the dehalogenation step, reaction (4), the “R” represents the molecular group to which the chlorine atom is attached. In the case of TCE, R would be the $CHClCl^-$ fragment. For the total dehalogenation of TCE, reaction (4) must occur three times, with the end product being ethene. The degradation of TCE also occurs via a β-elimination reaction where TCE is converted to chloroacetylene followed by a dehalogenation reaction to acetylene. The acetylene degrades to ethene and then to ethane. Figure 1-8 illustrates the degradation pathways for TCE using zero-valent iron. The predominant pathway for degradation of chlorinated ethenes is reported to be the β-elimination pathway (Roberts et al., 1996). Laboratory studies conducted at UCF have shown that complete dehalogenation occurs within the EZVI micelles (UCF, 2000).

Before the EZVI demonstration was started, concerns were raised about the potential difficulties associated with the injection and subsurface distribution of the emulsion. Concerns also were raised about the effectiveness of the recirculation system designed to establish steady state flow conditions in the test plot, and the possibility of contaminant dilution or drawing in contaminated water from outside the plot boundaries. The installation and operation of the EZVI technology is described in Section 3.

1.5 Technology Evaluation Report Structure

The EZVI technology evaluation report starts with an introduction to the project organization, the DNAPL problem, the technology demonstrated, and the demonstration site (Section 1). The rest of the report is organized as follows:

- Site Characterization (Section 2)
- Technology Operation (Section 3)
- Performance Assessment Methodology (Section 4)
- Performance Assessment Results and Conclusions (Section 5)
- Quality Assurance (Section 6)
- Economic Analysis (Section 7)
- Technology Applications Analysis (Section 8)
- References (Section 9).

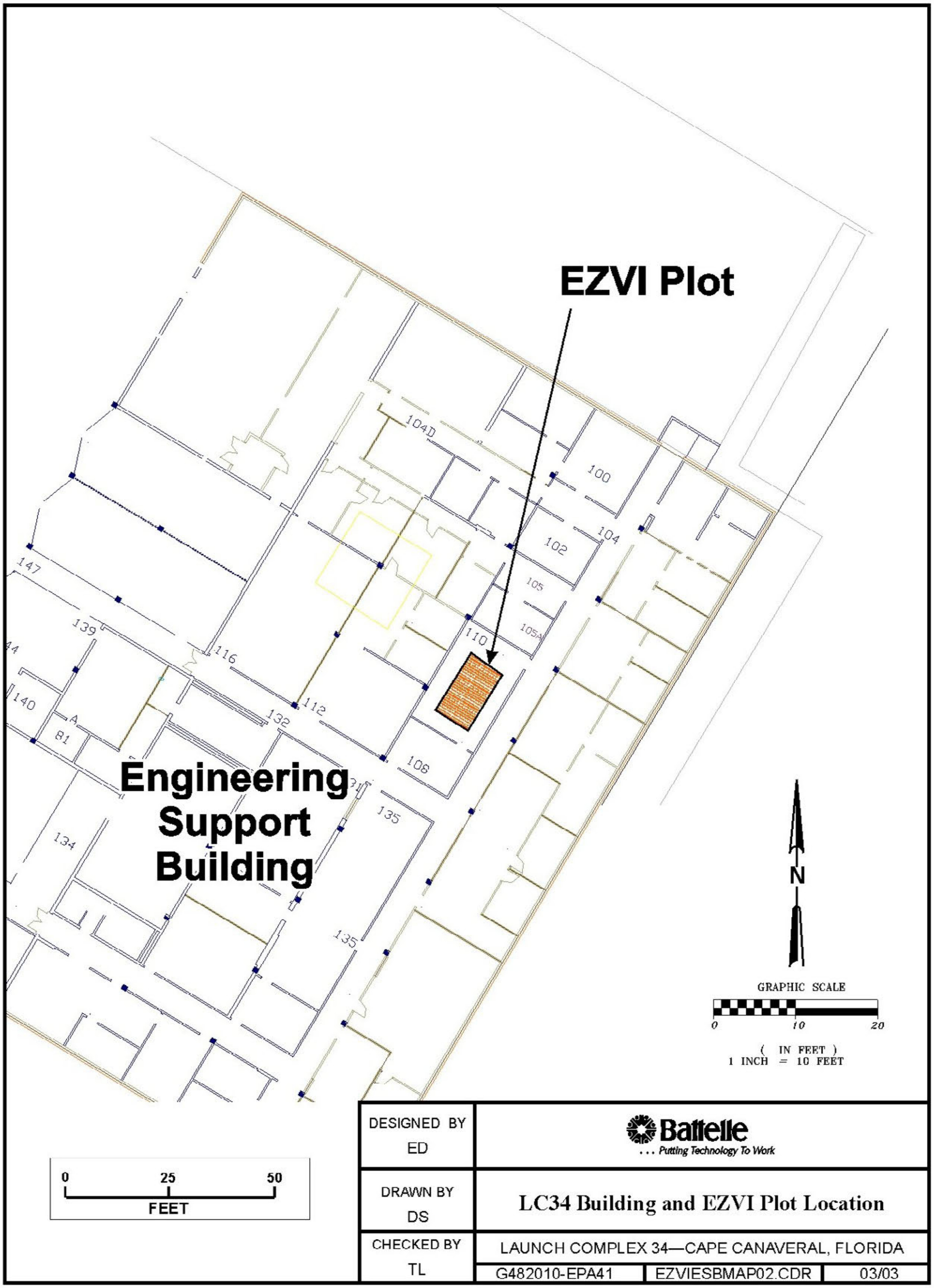


Figure 1-4. Demonstration Site Location

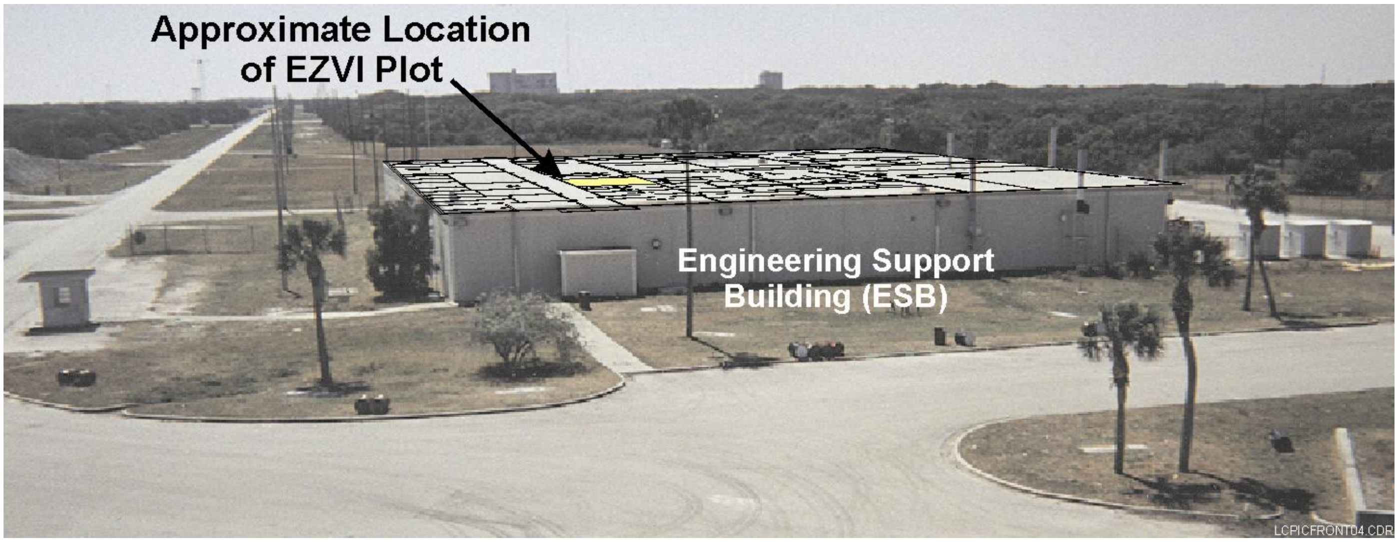


Figure 1-5. View Looking South toward Launch Complex 34, the Engineering Support Building and Relative Location of EZVI Plot

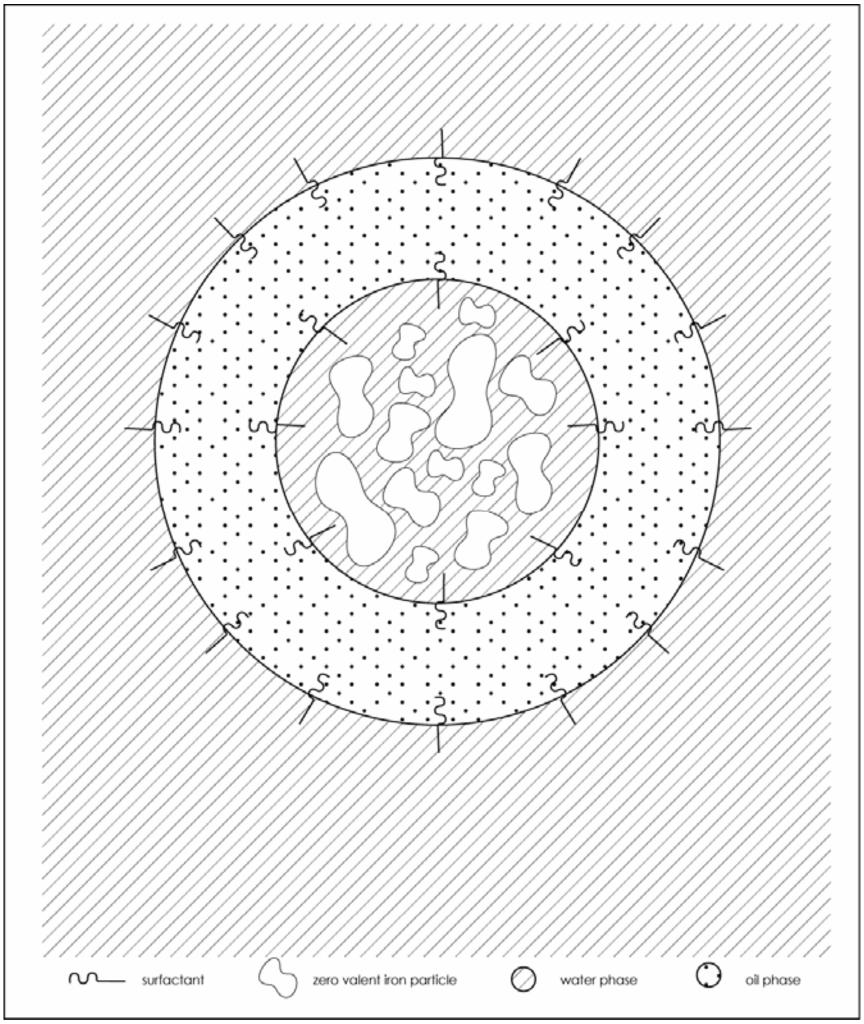


Figure 1-6. Schematic of a Micelle Structure of the Emulsified Zero-Valent Iron (from GeoSyntec, 2002)

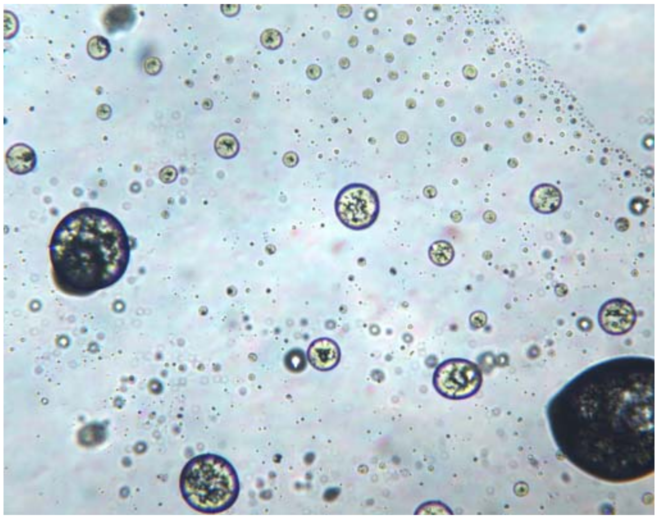


Figure 1-7. Picture of Iron Particles Trapped Inside a Drop of Water-Oil Emulsion

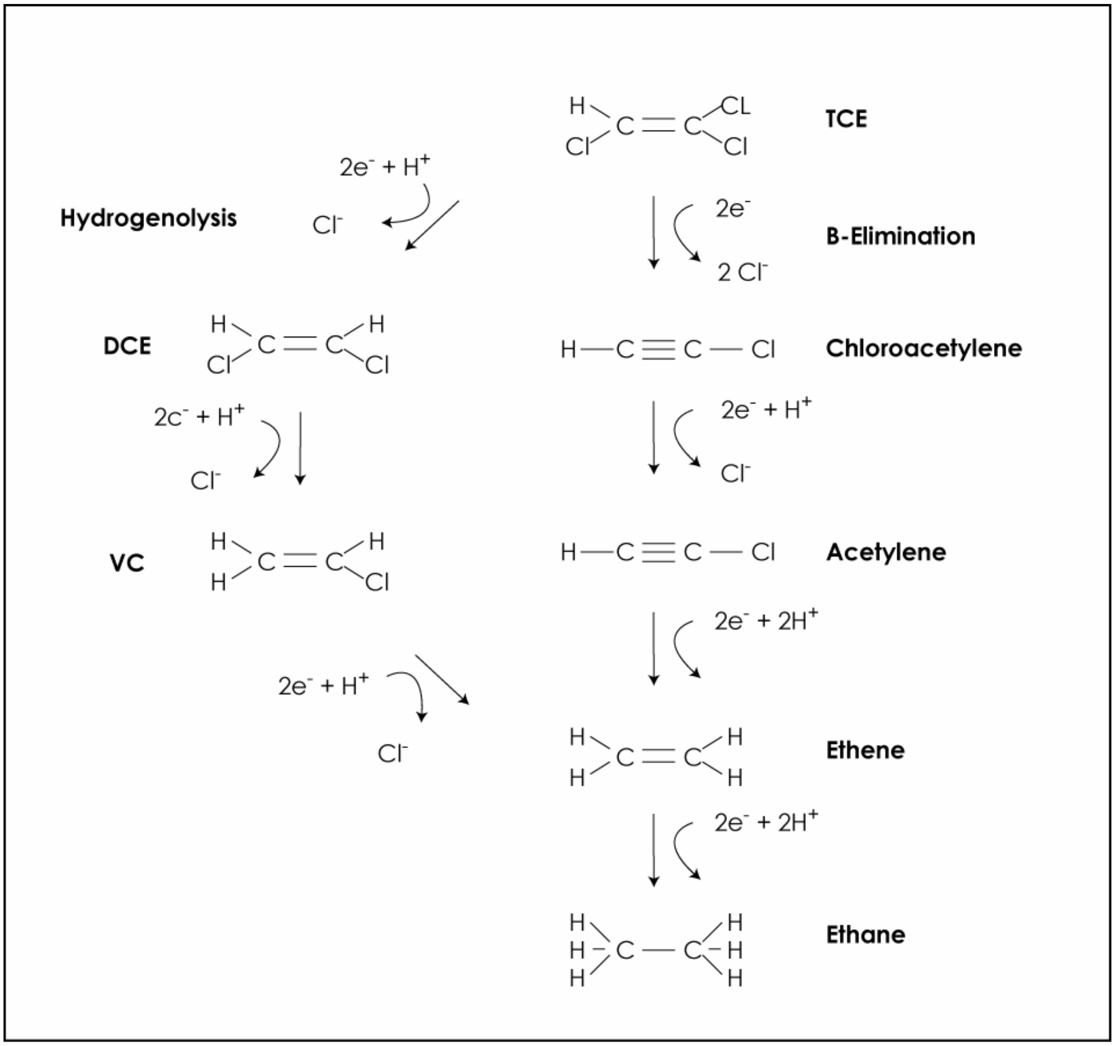


Figure 1-8. Degradation Pathways for TCE with Zero-Valent Iron (Source: GeoSyntec, 2002)

Supporting data and other information are presented in the appendices to the report. The appendices are organized as follows:

- Performance Assessment Methods (Appendix A)
- Hydrogeologic Measurements (Appendix B)
- CVOC Measurements (Appendix C)
- Inorganic and Other Aquifer Parameters (Appendix D)
- Quality Assurance/Quality Control Information (Appendix E)
- Economic Analysis Information (Appendix F)

2. Site Characterization

This section provides a summary of the hydrogeology and chemistry of the site based on the data compilation report (Battelle, 1999a), the additional site characterization report (Battelle, 1999b), and the pre-demonstration characterization report (Battelle, 1999c).

2.1 Hydrogeology of the Site

Several aquifers are present at the Launch Complex 34 area (Figure 2-1), reflecting a barrier island complex overlying coastal sediments. A surficial aquifer and a semi-confined aquifer comprise the major aquifers in the Launch Complex 34 area. The surficial aquifer extends from the water table to approximately 45 ft below ground surface (bgs) in the Launch Complex 34 area. A clay semi-confining unit (i.e., the Lower Clay Unit) separates the surficial aquifer from the underlying semi-confined aquifer. Details of the surficial aquifer are provided in Section 2.1.1. The underlying semi-confined aquifer is further described in Section 2.1.2.

2.1.1 The Surficial Aquifer at Launch Complex 34

Figures 2-2 and 2-3 are geologic cross sections, one along the northwest-southeast (NW-SE) direction across the middle of the test plot area and the other along the southwest-northeast (SW-NE) direction across the middle of the EZVI plot. As seen in these figures, the surficial aquifer is subclassified as having an Upper Sand Unit, a Middle Fine-Grained Unit, and a Lower Sand Unit. The Upper Sand Unit extends from ground surface to approximately 20 to 26 ft bgs and consists of unconsolidated, gray fine sand and shell fragments (see Table 2-1). The Middle Fine-Grained Unit is a layer of gray, fine-grained silty/clayey sand that exists between about 26 and 36 ft bgs. In general, this unit contains soil that is finer-grained than the Upper Sand Unit and Lower Sand Unit, and varies in thickness from about 10 to 15 ft. The Middle Fine-Grained Unit is thicker in the northern

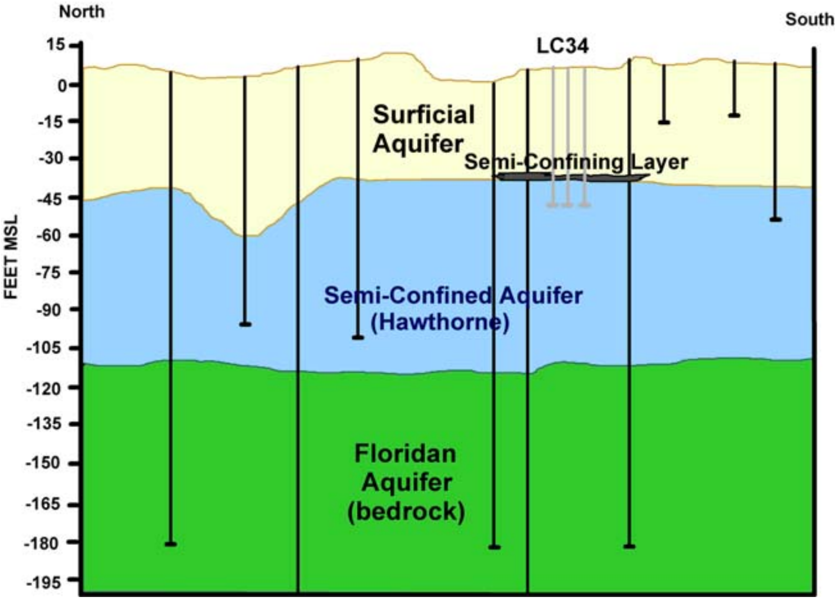


Figure 2-1. Regional Hydrogeologic Cross Section through the Kennedy Space Center Area (after Schmalzer and Hinkle, 1990)

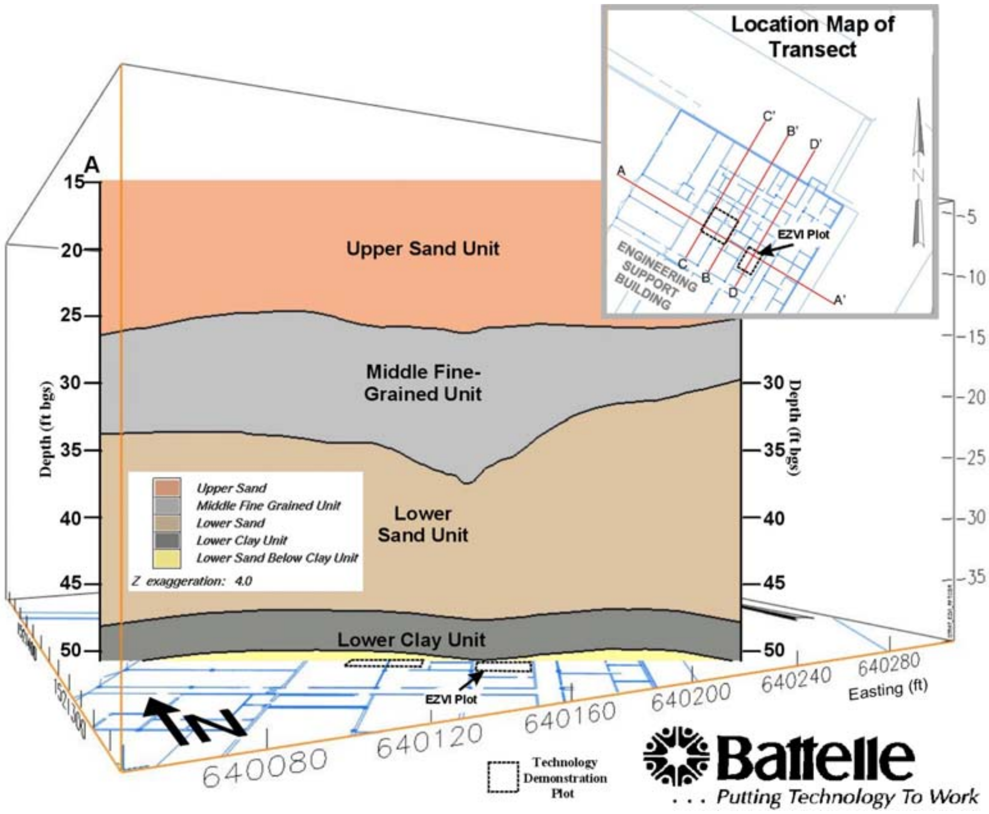


Figure 2-2. NW-SE Geologic Cross Section through the EZVI Plot

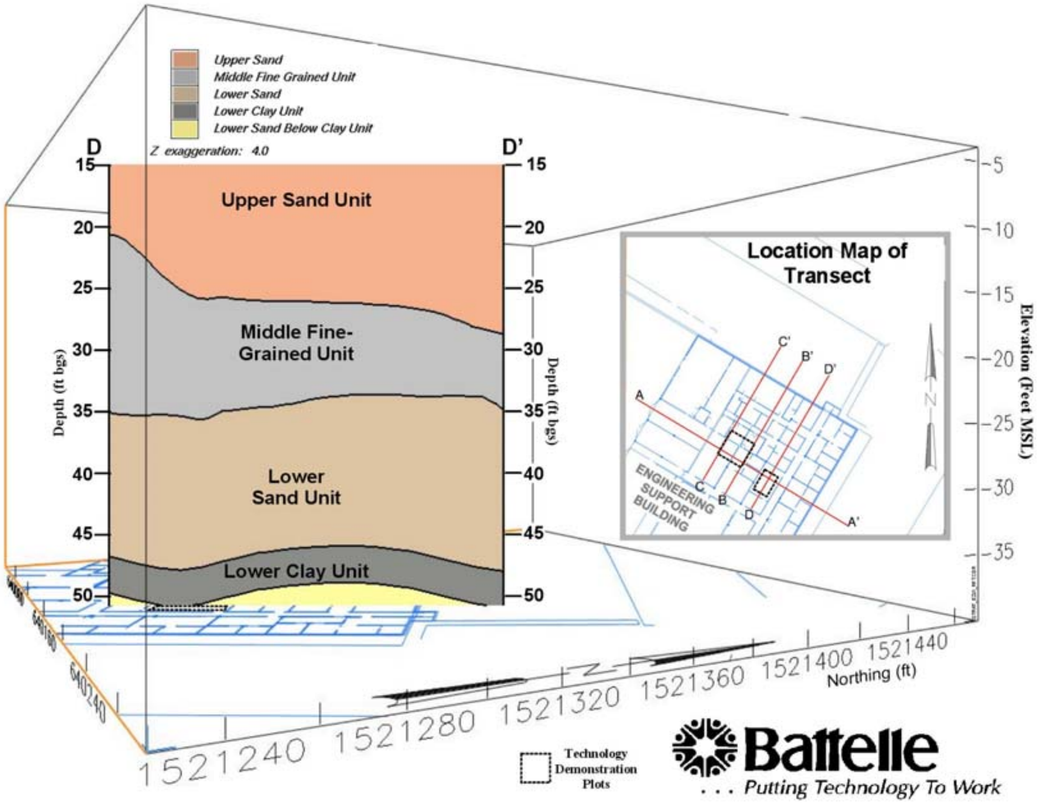


Figure 2-3. SW-NE Geologic Cross Section through the EZVI Plot

Table 2-1. Local Hydrostratigraphy at the Launch Complex 34 Site

Hydrostratigraphic Unit		Thickness (ft)	Sediment Description	Aquifer Unit Description
Surficial Aquifer	Upper Sand Unit	20-26	Gray fine sand and shell fragments	Unconfined, direct recharge from surface
	Middle Fine-Grained Unit	10-15	Gray, fine-grained silty/clayey sand	Low-permeability, semi-confining layer
	Lower Sand Unit	15-20	Gray fine to medium-sized sand and shell fragments	Semi-confined
Lower Clay Unit (Semi-Confining Unit)		1.5-3	Greenish-gray sandy clay	Thin low-permeability semi-confining unit
Semi-Confined Aquifer		>40	Gray fine to medium-sized sand, clay, and shell fragments	Semi-confined, brackish

portions of the test area under the Engineering Support Building and appears to become thinner in the southern and western portions of the test area. Below the Middle Fine-Grained Unit is the Lower Sand Unit, which consists of gray fine to medium-sized sand and shell fragments. The unit contains isolated fine-grained lenses of silt and/or clay. The lithologies of thin, very coarse, shell zones were encountered in several units. These zones may be important as reservoirs for DNAPL.

A 1.5- to 3-ft-thick semi-confining layer exists at approximately 45 ft bgs in the Launch Complex 34 area. The layer consists of greenish-gray sandy clay. The semi-confining unit was encountered in all borings across the Launch Complex 34 site, and it appears to be a pervasive unit. However, the clay unit is fairly thin (around 1.5 ft thick) in some areas (Battelle, 2001). Site characterization data (Battelle, 1999a and 1999b; Eddy-Dilek et al., 1998) suggest that the surfaces of the Middle Fine-Grained Unit and the Lower Clay Unit are somewhat uneven.

Baseline water level surveys were performed in the surficial aquifer in May 1997, December 1997, June 1998, October 1998, and March 1999. Water table elevations in the surficial aquifer were between about 1 and 5 ft mean sea level (msl). In general, the surveys suggest that water levels form a radial pattern with highest elevations near the Engineering Support Building. Figure 2-4 shows a water-table map from June 1998. The gradient and flow directions vary over time at the site. Table 2-2 summarizes the hydraulic gradients and their directions near the Engineering Support Building. The horizontal gradient ranged from 0.00009 to 0.0007 ft/ft. The flow direction varied from north-northeast to south-southwest.

Baseline groundwater levels for the EZVI project were measured in March 2002 from all monitoring wells in the surficial aquifer. A relatively flat hydraulic gradient was observed within the localized area of the test plot (Figures 2-5 to 2-7) (Battelle, 2003). On a regional scale, mounding of water levels near the Engineering Support Building generates a radial gradient (Battelle, 1999c); the regional gradient across the test plot is relatively flat (see Figure 2-4). Probable discharge points for the aquifer include wetland areas, the Atlantic Ocean, and/or the Banana River. Water level measurements from deep wells screened in the Lower Sand Unit usually are slightly higher than the water levels from the Upper Sand Unit and/or the Middle Fine-Grained Unit, which indicates that the Middle Fine-Grained Unit serves as a potential hydraulic barrier between the Upper Sand Unit and the Lower Sand Unit.

The baseline slug-test results indicate that the Upper Sand Unit is more permeable than the underlying units (the Middle Fine-Grained Unit and Lower Sand Unit), with hydraulic conductivity ranging from 4.0 to 5.1 ft/day in the shallow wells at the site. The hydraulic conductivities ranged from 1.4 to 6.4 ft/day from the intermediate wells in the Middle Fine-Grained Unit. The hydraulic conductivities ranged from 1.3 to 2.3 ft/day from the deep wells in the Lower Sand Unit. Porosity averaged 0.26 in the Upper Sand Unit, 0.34 in the Middle Fine-Grained Unit, 0.29 in the Lower Sand Unit, and 0.44 in the Lower Clay Unit. The bulk density of the aquifer materials averaged 1.59 g/cm^3 (Battelle, 1999b). Other notable hydrologic influences at the site include drainage and recharge. Paved areas, vegetation, and topography affect drainage in the area. No streams exist in the site area. Engineered drainage at the site consists of ditches that lead to the Atlantic Ocean or swampy areas. The flow system may be influenced by local recharge events, resulting in the variation in gradients. Recharge to the surficial aquifer is from infiltration of precipitation through surface soils to the aquifer. Permeable soils exist from the ground surface to the water table and drainage is excellent. Water infiltrates directly to the water table.

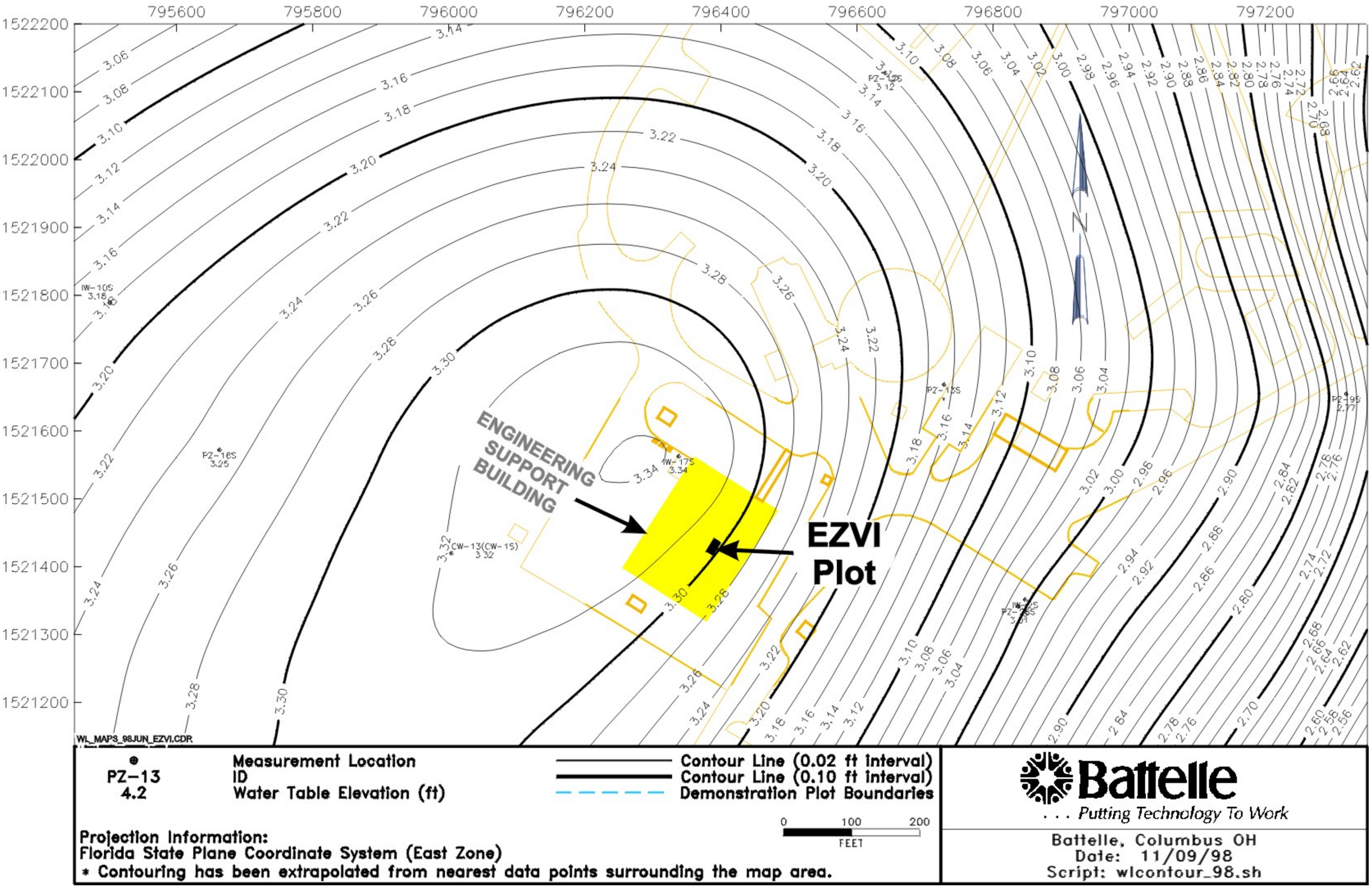


Figure 2-4. Water Table Elevation Map for Surficial Aquifer from June 1998

Table 2-2. Hydraulic Gradients and Directions in the Surficial and Semi-Confined Aquifers

Hydrostratigraphic Unit	Sampling Date	Gradient (ft/ft)	Direction
Surficial Aquifer	May 1997	0.00009	SW
	December 1997	0.0001	SSW
	June 1998	0.0006	WNW
	October 1998	0.0007	NNE
	March 1999	undefined	undefined
Semi-Confined Aquifer	December 1997	0.0008	S
	June 1998	0.0005	E
	October 1998	0.00005	SSW

2.1.2 The Semi-Confined Aquifer at Launch Complex 34

The semi-confined aquifer underlying the Lower Clay Unit was investigated as part of another technology demonstration at Launch Complex 34 (Battelle, 2001). The semi-confined aquifer (Caloosahatchee Marl formation or equivalent) is 40 to 50 ft thick or greater and is composed of silty to clayey sand and shells. Underlying the semi-confined aquifer is the Hawthorne formation, a clayey sand-confining layer. The limestone Floridan Aquifer underlies the Hawthorne formation and is a major source of drinking water for much of Florida. Table 2-3 summarizes the character and water-bearing properties of the hydrostratigraphic units in the area.

Water level surveys in the semi-confined aquifer were performed at various times from April 2001 to March 2002 (Battelle, 2003). Water table elevations were measured at approximately 1 to 5 ft msl, and formed a pattern similar to the pattern formed by surficial aquifer water levels. Water level elevations from wells in the deep aquifer were measured at approximately 1 to 5 ft msl, suggesting that the aquifer is confined in the Launch Complex 34 area. The gradient in the semi-confined aquifer is positioned in a similar direction to the surficial aquifer. The horizontal gradient is east to northeast. The vertical gradient changes from downward to upward depending on seasons, which suggests that the Lower Clay Unit is not a fully confined unit. Recharge to the aquifer may occur by downward leakage from overlying aquifers or from direct infiltration inland where the aquifer is unconfined. Schmalzer and Hinkle (1990) suggest that saltwater intrusion may occur in intermediate aquifers such as the semi-confined aquifer.

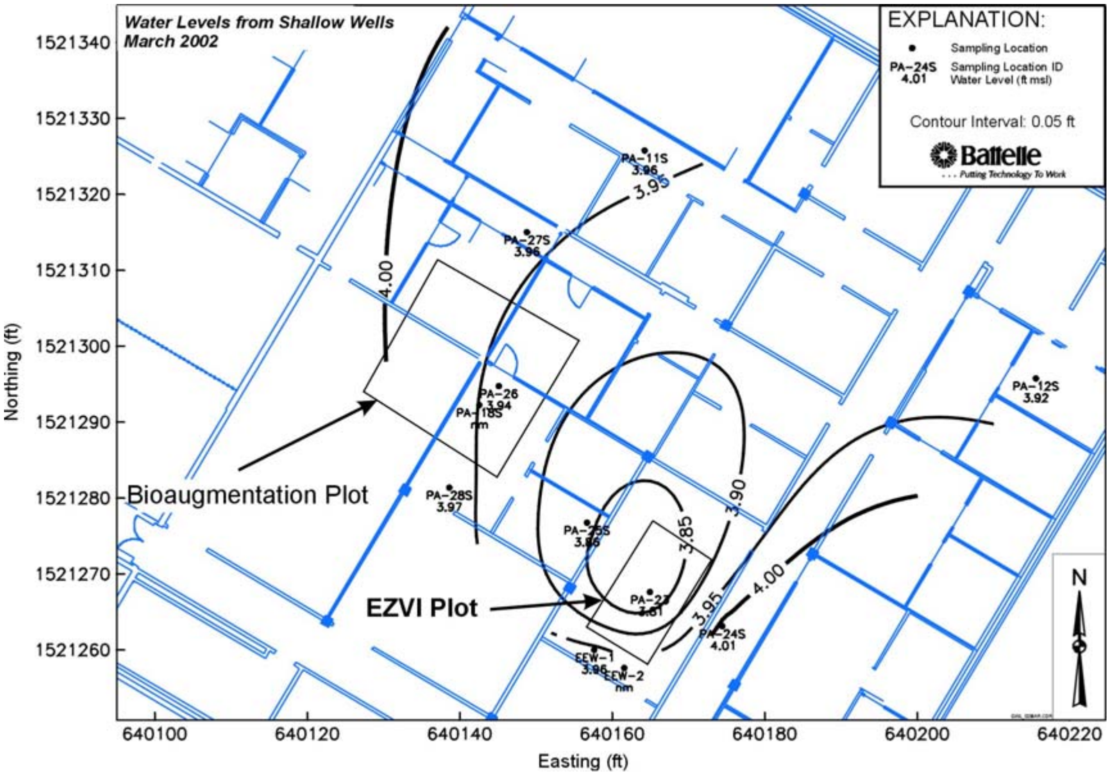


Figure 2-5. Pre-Demonstration Water Levels (as elevation msl) in Shallow Wells at Launch Complex 34 (March 2002)

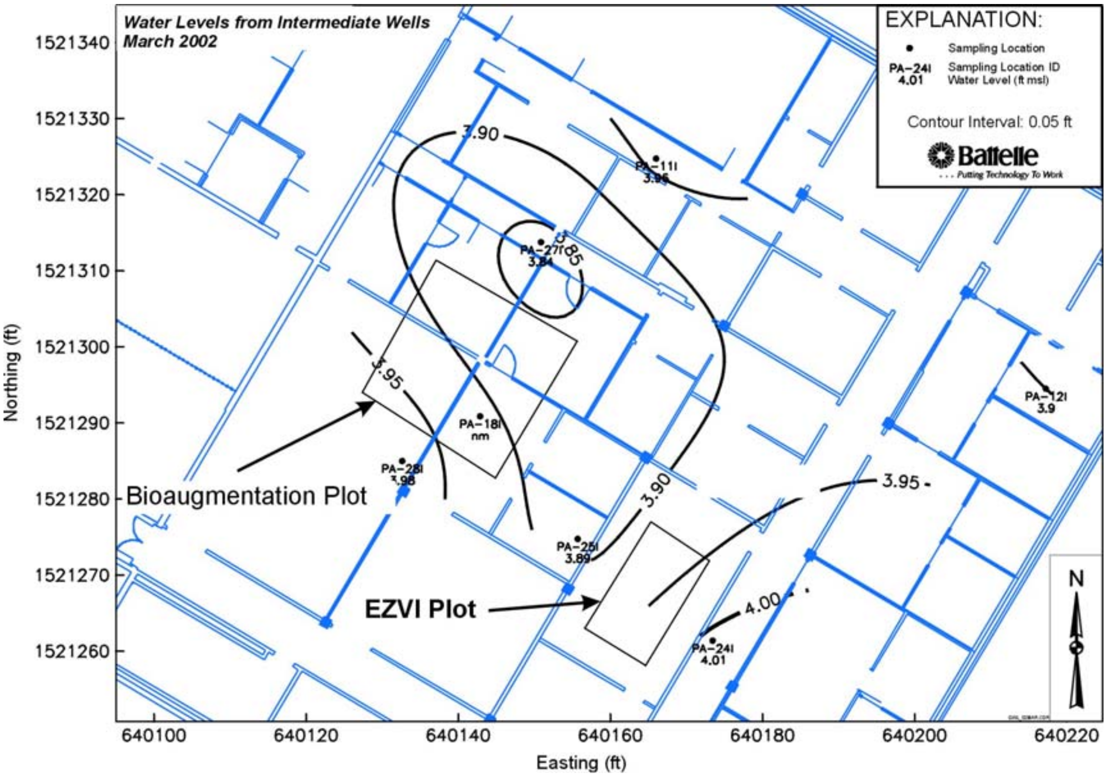


Figure 2-6. Pre-Demonstration Water Levels (as elevation msl) in Intermediate Wells at Launch Complex 34 (March 2002)

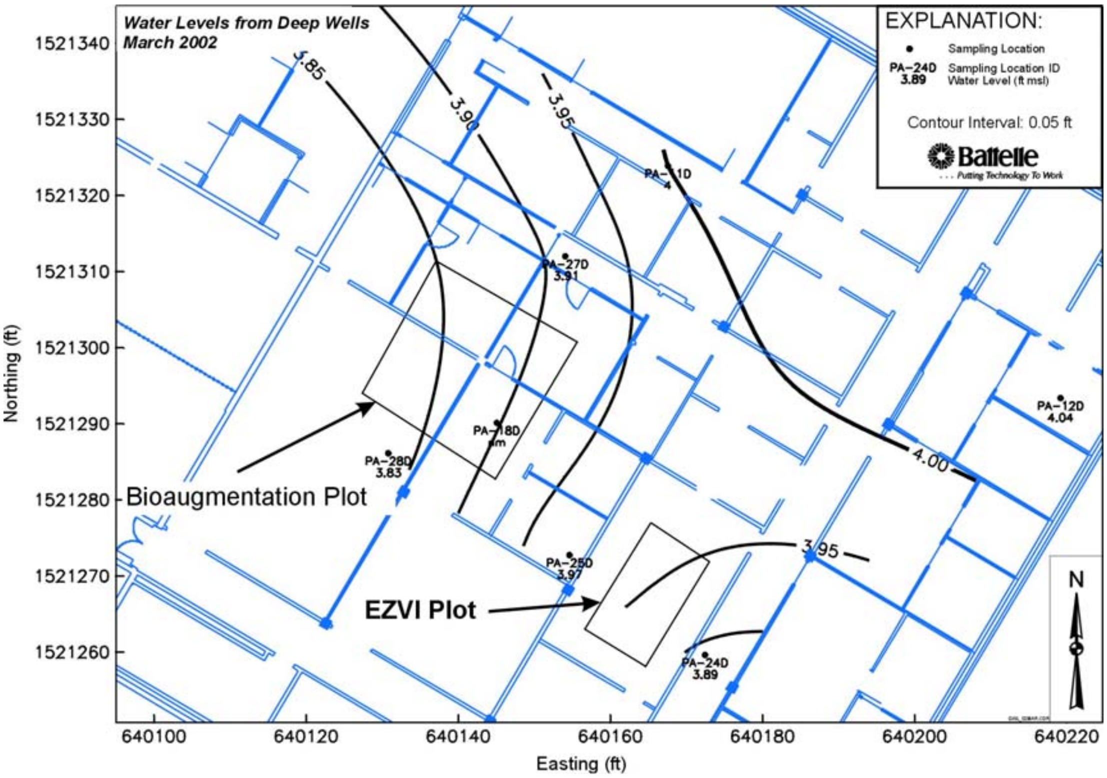


Figure 2-7. Pre-Demonstration Water Levels (as elevation msl) in Deep Wells at Launch Complex 34 (March 2002)

Table 2-3. Hydrostratigraphic Units of Brevard Country, Florida[a]

Geologic Age	Stratigraphic Unit		Approximate Thickness (ft)	General Lithologic Character	Water-Bearing Properties
Recent (0.1 MYA-present)	Pleistocene and Recent Deposits		0-110	Fine to medium sand, coquina and sandy shell marl.	Permeability low due to small grain size, yields small quantities of water to shallow wells, principal source of water for domestic uses not supplied by municipal water systems.
Pleistocene (1.8-0.1 MYA)					
Pliocene (1.8-5 MYA)	Upper Miocene and Pliocene Deposits (Caloosahatchee Marl)		20-90	Gray to greenish gray sandy shell marl, green clay, fine sand, and silty shell.	Permeability very low, acts as confining bed to artesian aquifer, produces small amount of water to wells tapping shell beds.
Miocene (5-24 MYA)	Hawthorne Formation		10-300	Light green to greenish gray sandy marl, streaks of greenish clay, phosphatic radiolarian clay, black and brown phosphorite, thin beds of phosphatic sandy limestone.	Permeability generally low, may yield small quantities of fresh water in recharge areas, generally permeated with water from the artesian zone. Contains relatively impermeable beds that prevent or retard upward movement of water from the underlying artesian aquifer. Basal permeable beds are considered part of the Floridan Aquifer.
Eocene (37-58 MYA)	Ocala Group	Crystal River Formation	0-100	White to cream, friable, porous coquina in a soft, chalky, marine limestone.	Floridan Aquifer: Permeability generally very high, yields large quantities of artesian water. Chemical quality of the water varies from one area to another and is the dominant factor controlling utilization. A large percentage of the groundwater used in Brevard County is from the artesian aquifer. The Crystal River Formation will produce large quantities of artesian water. The Inglis Formation is expected to yield more than the Williston Formation. Local dense, indurate zones in the lower part of the Avon Park Limestone restrict permeability but in general the formation will yield large quantities of water.
		Williston Formation	10-50	Light cream, soft, granular marine limestone, generally finer grained than the Inglis Formation, highly fossiliferous.	
		Inglis Formation	70+	Cream to creamy white, coarse granular limestone, contains abundant echinoid fragments.	
	Avon Park Limestone		285+	White to cream, purple tinted, soft, dense chalky limestone. Localized zones of altered to light brown or ashen gray, hard, porous, crystalline dolomite.	

(a) Source: Schmalzer and Hinkle (1990).
MYA = million years ago.

2.2 Surface Water Bodies at the Site

The major surface water body in the area is the Atlantic Ocean, located to the east of Launch Complex 34. To determine the effects of surface water bodies on the groundwater system, water levels were monitored in 12 piezometers for more than 50 hours for a tidal influence study during Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) activities (G&E Engineering, Inc., 1996). All the piezometers used in the study were screened in the surficial aquifer. No detectable effects from the tidal cycles were measured, suggesting that the surficial aquifer and the Atlantic Ocean are not well connected hydraulically. However, the Atlantic Ocean and the Banana River seem to act as hydraulic barriers or sinks, as groundwater likely flows toward these surface water bodies and discharges into them.

2.3 DNAPL Contamination in the EZVI Plot and Vicinity

Figure 2-8 shows representative pre-demonstration distributions of TCE in groundwater, the primary contaminant at Launch Complex 34, in the shallow wells. Pre-demonstration distributions of TCE in the intermediate and deep wells were not available due to the limited data set (i.e., only two wells per depth). The shallow, intermediate, and deep monitoring wells were installed during the site characterization to correspond with the hydrostratigraphic units: Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit (Battelle, 2002a), respectively. The targeted unit for the EZVI demonstration was the Upper Sand Unit. A pre-demonstration TCE concentration in groundwater greater than the solubility level of TCE (1,100,000 µg/L [1,100 mg/L]) was measured in monitoring well PA-23 in the center of the test plot (see Figure 2-8). Pre-demonstration TCE concentrations in groundwater measured in the shallow monitoring wells (EEW-1 and PA-24S) also were at or near the solubility level of TCE, suggesting that DNAPL was likely present in the EZVI plot and surrounding area. However, the TCE-DNAPL was not visually observed during the pre-demonstration monitoring. Substantial *cis*-1,2-DCE also was detected in the surficial aquifer, indicating some historical natural attenuation of TCE (see Figure 2-9).

Figures 2-10 to 2-11 show representative pre-demonstration horizontal distributions of TCE in soil from the Upper Sand Unit at 18 ft bgs and 22 ft bgs, respectively. TCE levels were highest in the western and southern portions of the test plot, and concentrations indicative of DNAPL extend beyond the plot boundaries. As seen in the vertical cross section in Figure 2-12, much of the TCE was present in the Upper Sand Unit and the Middle Fine-Grained Unit. Based on the results of the pre-demonstration soil sampling, the Upper Sand Unit was chosen as the targeted zone for the EZVI injection, specifically at the 18-ft depth.

The pre-demonstration soil sampling indicated that between 10 and 46 kg of TCE was present in the Upper Sand Unit of the EZVI plot before the demonstration. Approximately 3.8 kg of this TCE may occur as DNAPL, based on a threshold TCE concentration of about 300 mg/kg in the soil. This threshold figure is determined as the maximum TCE concentration in the dissolved and adsorbed phases in the Launch Complex 34 soil. This figure is a conservative estimate and takes into account the minor variability in the aquifer characteristics, such as porosity, bulk density, and organic carbon content. The native organic carbon content of the Launch Complex 34 soil is relatively low and the threshold TCE concentration is driven by the solubility of TCE in the porewater.

The threshold figure was calculated as follows:

$$C_{sat} = \frac{C_{water}\ (K_d \rho_b + n)}{\rho_b} \tag{2-1}$$

where C_{sat} = maximum TCE concentration in the dissolved and adsorbed phases (mg/kg)

C_{water} = TCE solubility (mg/L) = 1,100

ρ_b = bulk density of soil (g/cm^3) = 1.59

n = porosity (unitless) = 0.3

K_d = partitioning coefficient of TCE in soil [(mg/kg)/(mg/L)], equal to ($f_{oc} \cdot K_{oc}$)

f_{oc} = fraction organic carbon (unitless)

K_{oc} = organic carbon partition coefficient [(mg/kg)/(mg/L)].

At concentrations below the threshold value of 300 mg/kg, the TCE was considered to be present in the dissolved phase; at or above this threshold value, the TCE was considered to be TCE-DNAPL.

Figure 2-13 is a three-dimensional (3D) depiction of pre-demonstration concentrations of TCE as DNAPL in the soil of the Upper Sand Unit. Figure 2-13 was created by taking TCE concentrations above the threshold value of 300 mg/kg in the all three units (i.e., Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit) of the test plot (see Figure 2-12), and using the software program EarthVision® to create the 3D picture. The mass of TCE as DNAPL in Figure 2-13 is 3.8 kg in the Upper Sand Unit.

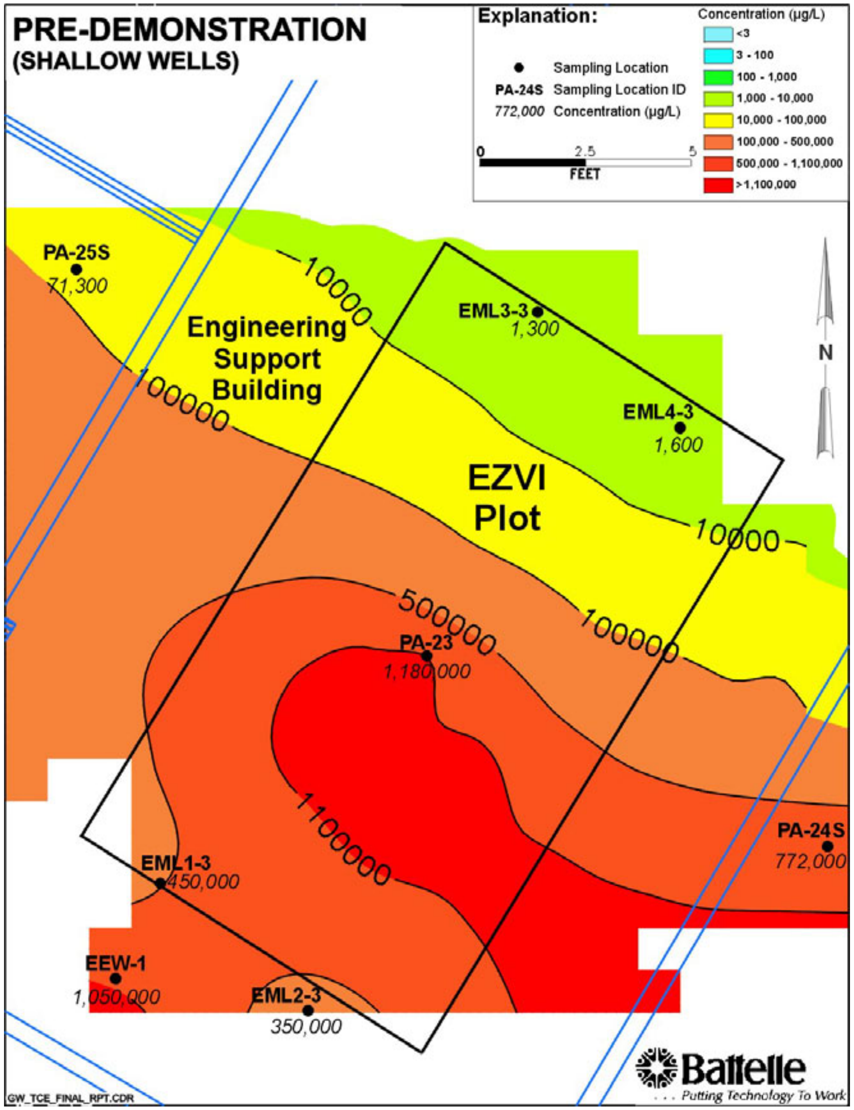


Figure 2-8. Pre-Demonstration Dissolved TCE Concentrations (µg/L) in Shallow Wells in the EZVI Plot (March 2002)

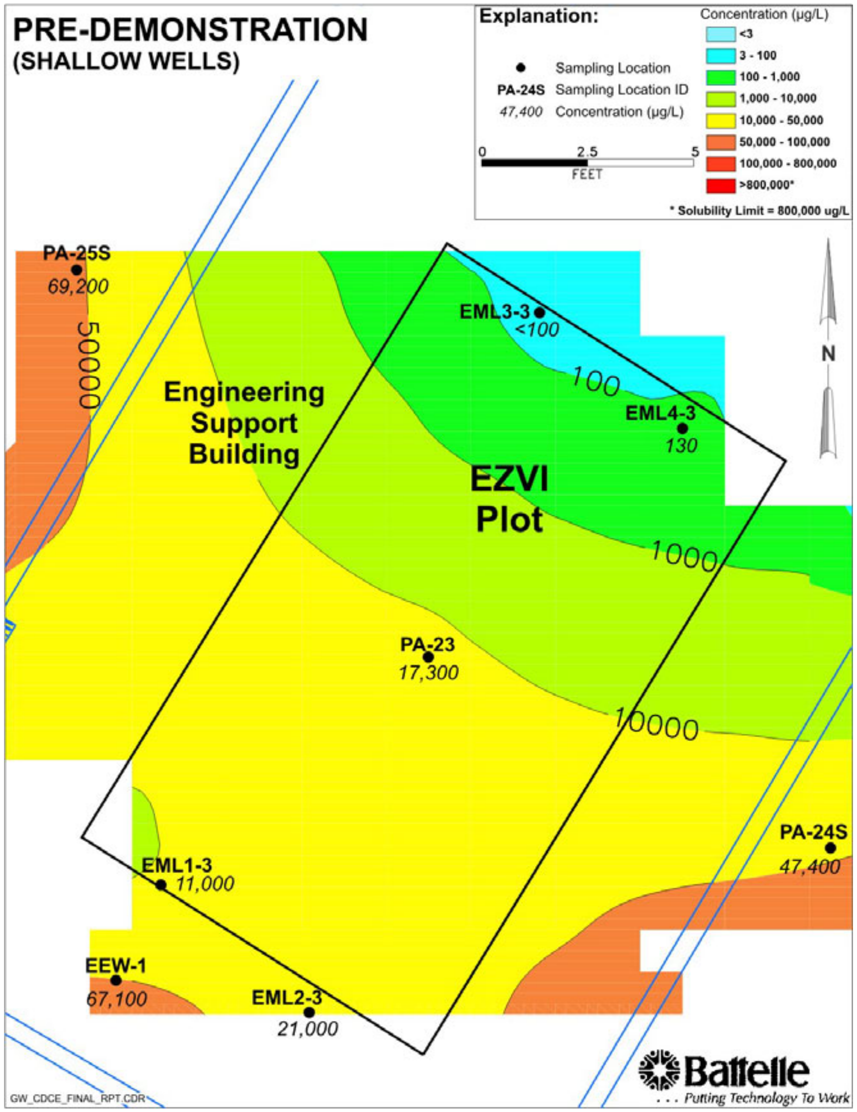


Figure 2-9. Pre-Demonstration Dissolved DCE Concentrations (µg/L) in Shallow Wells in the EZVI Plot (March 2002)

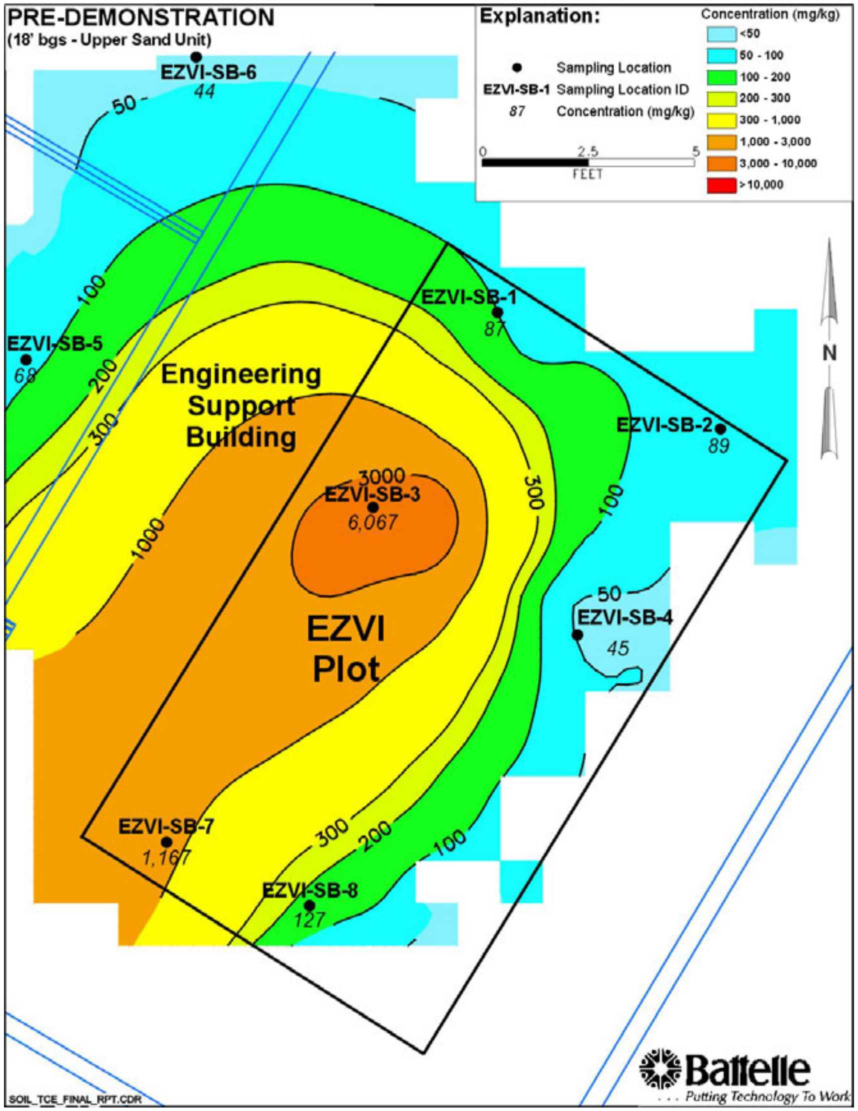


Figure 2-10. Pre-Demonstration TCE Concentrations (mg/kg) in Soil in the Upper Sand Unit approximately 18 ft bgs in the EZVI Plot and Vicinity (January 2002)

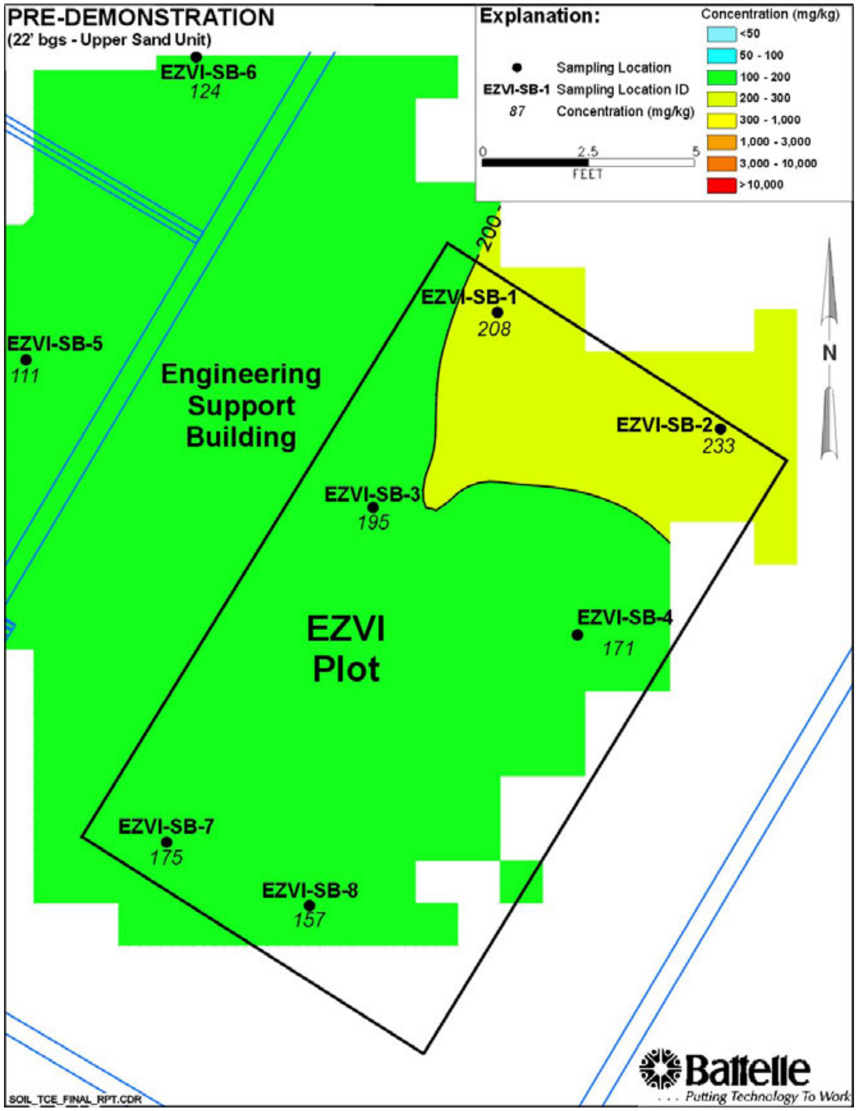


Figure 2-11. Pre-Demonstration TCE Concentrations (mg/kg) in Soil in the Upper Sand Unit approximately 22 ft bgs in the EZVI Plot and Vicinity (January 2002)

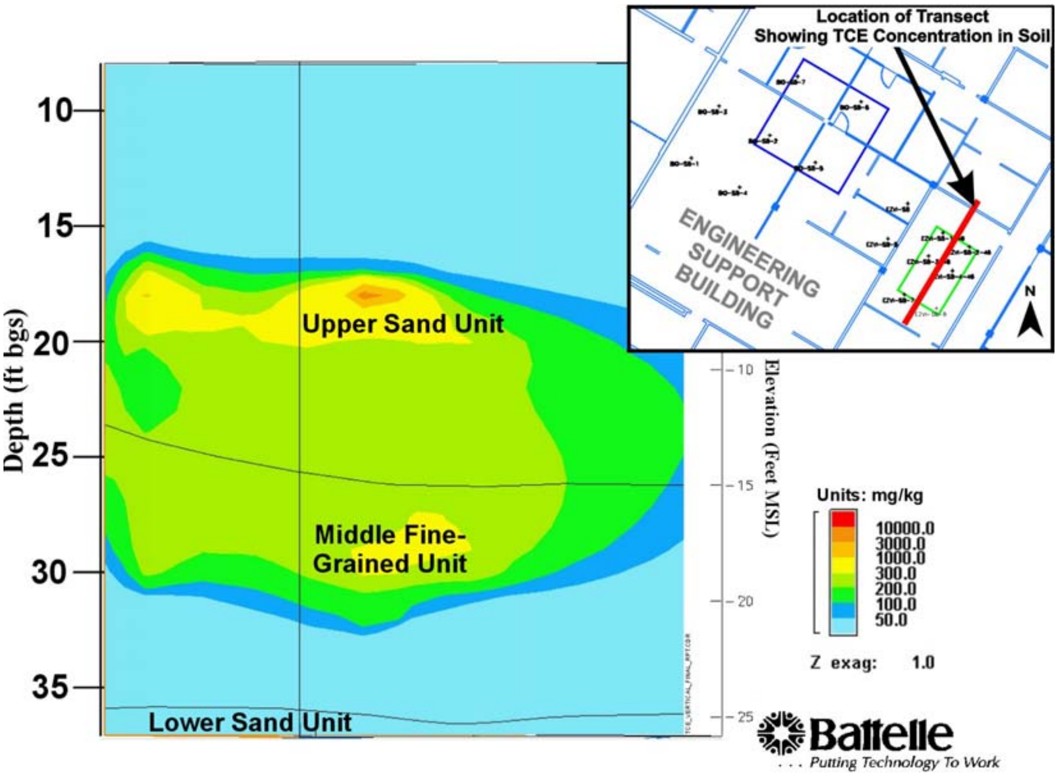


Figure 2-12. Vertical Cross Section through the EZVI Plot Showing Pre-Demonstration TCE Soil Concentrations (mg/kg) in the Subsurface

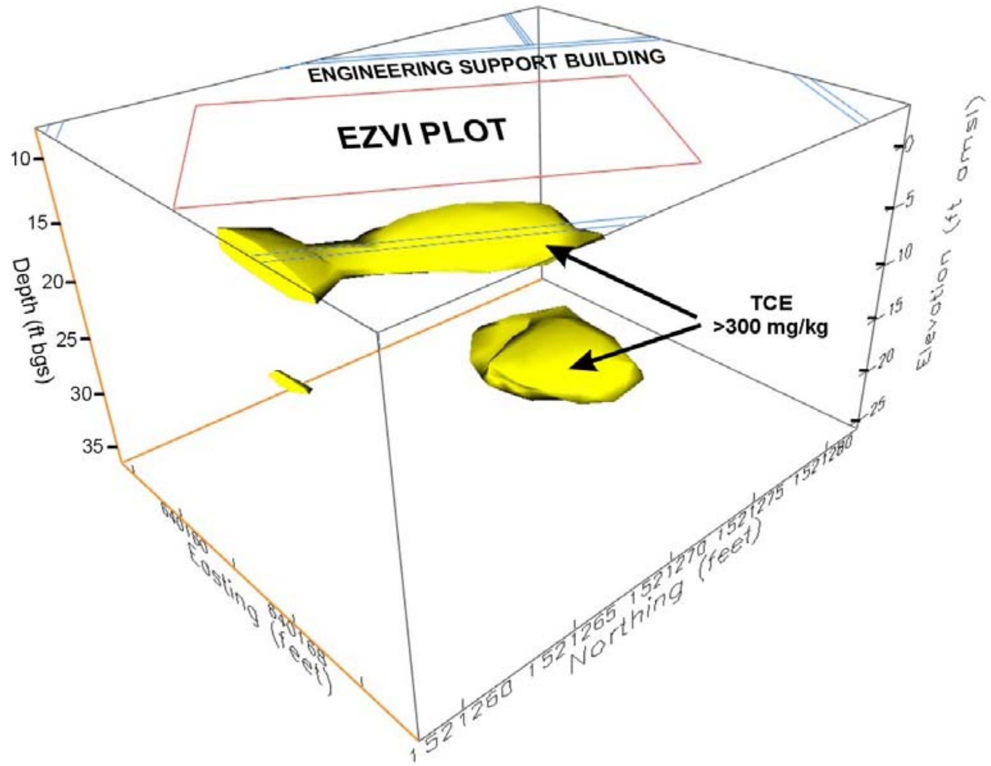


Figure 2-13. Pre-Demonstration TCE Concentrations (mg/kg) as DNAPL in Soil in the Upper Sand Unit at Launch Complex 34 (January/February 2002)

2.4 Aquifer Quality at the Site

Appendix A.3 lists the various aquifer parameters measured and the standard methods used to analyze them. Appendix D contains the results of the pre-demonstration groundwater analysis. Pre-demonstration groundwater field parameters were measured in several wells in the demonstration area in March 2002. The pH was relatively constant with depth, and ranged from 6.4 to 6.8. Prior to the EZVI application, dissolved oxygen (DO) levels were measured at 1 mg/L or less in all of the wells that were sampled, indicating that the aquifer was anaerobic. Oxidation-reduction potential (ORP) from all the sampled wells ranged from +15 to +148 millivolts (mV). The levels for total organic carbon (TOC) were relatively low and varied from 0.9 to 1.7% of dry soil weight, which indicates that microbes degrading TCE at the site used available TOC as a carbon source.

Inorganic groundwater parameters in the surficial aquifer were measured in March 2002 at the performance monitoring wells in the Upper Sand Unit to determine the pre-demonstration quality of the groundwater in the target area.

- Total dissolved solids (TDS) concentrations increased sharply with depth, suggesting that the water becomes more brackish with depth. The TDS levels ranged from 947 to 1,670 mg/L. Chloride concentrations ranged from 177 to 848 mg/L and increased sharply with depth, indicating some saltwater intrusion in the deeper layers. These high levels of chloride made it difficult to determine the extent to which additional chloride byproducts were formed after treatment.
- Alkalinity levels ranged from 222 to 475 mg/L, with no discernable trend with depth.
- Dissolved iron concentrations ranged from 1.1 to 27 mg/L in the groundwater, and decreased with depth. Total iron concentrations ranged from 1.2 to 22 mg/L in groundwater. Both dissolved and total iron concentrations in groundwater were highest in the Upper Sand Unit.
- Dissolved silica concentrations ranged from 20.4 to 54.6 mg/L, and increased with depth.
- Calcium concentrations ranged from 60 to 935 mg/L, with no discernible trend with depth. Magnesium concentrations ranged from 15 to 72 mg/L, and increased with increasing depth.
- Sodium concentrations were between 34 and 443 mg/L, and increased with depth. Potassium concentrations ranged from 17 to 299 mg/L, and decreased with depth.
- The changes in microbial characteristics of the aquifer were determined by comparing the biological oxygen demand (BOD) and dissolved methane gas concentrations in groundwater samples collected before and after the EZVI demonstration. BOD levels in the pre-demonstration groundwater samples ranged from <3 to 10 mg/L.

3. Technology Operation

This section describes the details of the EZVI technology demonstrated at Launch Complex 34.

3.1 EZVI Description

As discussed in Section 1.4, EZVI is composed of food-grade surfactant, biodegradable vegetable oil, water, and zero-valent iron particles, which form emulsion droplets (or micelles). The micelles contain the iron particles in water surrounded by an oil-liquid membrane (see Figures 1-6 and 1-7). The EZVI has a specific gravity of approximately 1.1 and exists in a nonaqueous phase that is stable in water. Because the exterior oil membrane of the emulsion particles has similar hydrophobic properties as the DNAPL, the emulsion is miscible with the DNAPL (i.e., the phases can mix). The DNAPL compounds (e.g., TCE) diffuse through the oil membrane of the emulsion particle and undergo reductive dechlorination facilitated by the zero-valent iron particles in the interior aqueous phase. Reductive dechlorination pathways are described in Section 1.4.

3.2 Regulatory Requirements

Prior to the design of the EZVI injection system, a petition for variance from Underground Injection Control (UIC) regulations was filed with the State of Florida Department of Environmental Protection (FDEP). Technically, the EZVI demonstration was considered a research project in a small area, and therefore was exempt from FDEP oversight. However, the variance was filed, and the project was reported to be consistent with good field practices involved with injecting materials prepared on the surface into the subsurface. Hydraulic control of groundwater in the EZVI plot area was achieved via recirculation of groundwater (taken up from upgradient extraction wells and reinjected into downgradient injection wells).

3.3 Application of EZVI Technology

The field application of the EZVI technology was conducted over six months from July 8, 2002 to January 6, 2003, and included frequent monitoring until January 2003. A long-term post-demonstration groundwater sampling event was conducted in March 2004. The detailed time line is summarized in Table 3-1.

The design report for the EZVI technology was prepared by GeoSyntec (2002) and includes location maps for injection and monitoring well locations; schematic diagrams of the EZVI delivery mechanism, groundwater recirculation system, hydraulic control recirculation system; and other design-related information. The treatment plot was located over an area of the DNAPL source zone at Launch Complex 34. This zone is contaminated primarily with TCE and to a lesser extent with tetrachloroethylene (PCE) and dichloroethylenes (including *cis*-1,2-DCE and *trans*-1,2-DCE).

Three other in situ remedial technology demonstrations previously were hosted at the Launch Complex 34 DNAPL source zone: in situ chemical oxidation (ISCO), resistive heating, and steam injection/extraction (SI/E). During the SI/E demonstration, it was noted that the injected heat and steam flowed along preferential pathways through the subsurface in the DNAPL source area. Therefore, it was decided that the EZVI technology would be applied at a location inside the Engineering Service Building and near the SI/E test plot (see Figure 1-3).

3.3.1 EZVI Injection Methods

In theory, delivering the EZVI emulsion into a DNAPL source area creates a multiphase environment (aqueous for groundwater, nonaqueous for DNAPL, nonaqueous for the emulsion, and solids from the aquifer formation), assuming that the emulsion is distributed relatively well in the subsurface. However, in practice, injecting EZVI into the subsurface is challenging due to the high viscosity and interfacial surface tension of the emulsion. Three commercially available injection techniques were evaluated for this project: high pressure injection, pneumatic injection, and pressure pulse enhanced injection. Each is described in detail below. Based on the results

Table 3-1. EZVI Demonstration Chronology

Dates	Activity	Comments
March 2001	Technology demonstration contract awarded to GeoSyntec and UCF.	
June 2001	Site characterization conducted by GeoSyntec.	
October 2001 to January 7, 2002	Design/modeling of the EZVI technology application performed.	
January 8, 2002	Final design report submitted to NASA.	
January 15-17 and 31, 2002	Pre-demonstration soil sampling conducted.	Cores SB-1 to SB-4; Core SB-5 (gap in January time due to sampling in bioaugmentation plot)
February 1-2 and 7, 2002	Pre-demonstration soil sampling continued.	Cores SB-6 and SB-7
February 22, 2002	First field emulsion injection test conducted (precision sampling-direction injection method) ☐ 44 gal of EZVI at 1,000 psi with piston pump (vibration mode); injected EZVI did not appear at the target depths, and short circuiting up borehole was observed.	Injection Technology: Pressure
March 20, 2002	Pre-demonstration soil sampling continued; groundwater monitoring.	Core SB-8
June 25 to July 17, 2002	Recirculation. Extraction rate at 0.5 gpm from each well for a total of 1 gpm. Pre-demonstration groundwater was collected by GeoSyntec.	
July 8-12, 2002	Field test and injection well installation in the plot: ☐ Injection well (6-inch diameter). ☐ Three observation wells located 2.4, 4, and 6.5 ft radial distance from injection well.	
July 15-16, 2002	Field injection test set up (pressure pulse technology).	Pressure pulse technology by Wavefront Environmental
July 17, 2002	**First Field Injection Test Conducted Using Pressure Pulse Technology** ***Deeper Depths (20 to 24 ft bgs) with Lower Pulse Pressure*** ☐ Started with 20 gal of EZVI at 60 psi pulse, then 10 gal of EZVI at 10 to 30 psi pulse (45 minutes). ☐ 240 gal of water for 35 min. ☐ Searching for EZVI from observation wells (OWs) (at 2.4, 4, and 6.5 ft from the injection well) using a bailer, no evidence of EZVI. ☐ Drilling at 2 ft and 4 ft radial distance from the injection well (IW), no evidence of EZVI. ☐ Drilling at 1 ft away from the IW; evidence of EZVI at 20 to 24 ft bgs (see Figure 3-3). ***Shallow Depths (14 to 17 ft bgs) with Higher Pulse Pressure*** ☐ Upper packer was set at 13.5 ft bgs. ☐ Evidence of short circuiting from observation of the upper packer. ☐ Injected 20 gal of EZVI with the pulse rate: 60 to 100 psi and frequency of 1 pulse/sec, followed by 350 gal of water. This higher pulsing damaged the pressure gauges and transducer. ☐ No evidence of EZVI from this injection at the OWs. ☐ Difficulties encountered during the extrusion of injection tool from the IW.	
August 1-7, 2002	**Second Field Injection Test Conducted Using Pressure Pulse Technology** ***Deeper Depths (20.5 to 24 ft bgs)*** ☐ 20 gal of EZVI and 250 gal of water with 100 psi pulse pressure. ☐ Cored soil samples at 1, 2, 4, and 6 ft from the IW. Evidence of EZVI was only from 1 ft-core sample at the depths of 20 to 24 ft bgs. ***Shallow Depths (17 to 21 ft bgs)*** ☐ Started with 100 gal of water at 60 psi with 2 pulses/sec, then the co-injection for 20 gal of EZVI and 150 gal of water followed by 110 gal of water. ☐ Cored at four locations, no evidence. ☐ Interfacial tension measurements from the OWs, which suggested the evidence of surfactant but no evidence of EZVI: o Background: 70 dynes/cm. o 2.5 ft-OW: 60 dynes/cm. o 4.5 ft-OW: 40 dynes/cm. ***Reinjection at Shallow Depths (17 to 21 ft bgs)*** ☐ 100 gal of water, followed by 32 gal of EZVI with 120 gal of water. ☐ Cored soil samples for the EZVI evidence at 23 and 22 inches from the IW. Smearing of EZVI observed at the core sleeve at the 22-inch core. ☐ Surface tension measured from the OWs and showed the evidence of surfactant but no EZVI.	

Table 3-1. EZVI Demonstration Schedule (continued)

Dates	Activity	Comments
August 8-13, 2002	**EZVI Injection Conducted** (see Table 3-2 and Figure 3-3).	
August 20-21, 2002	Groundwater sampling conducted during the monitoring.	
August 24-29, 2002	Groundwater extracted from PA-23 at 0.3 gpm.	
September 13-25, 2002	Groundwater extracted from PA-23 at 0.3 gpm.	
October 8-9, 2002	Simplified post-demonstration soil sampling.	Cores SB-203, -204, -207 to -210
November, 2002	Post-demonstration characterization (soil and groundwater).	Cores SB-301 to -304; -307 to -308
December 12, 2002 to January 6, 2003	Groundwater recirculation from the injection wells to extraction wells at 0.5 gpm per well for total of 1 gpm. Final round of groundwater samples collected (January 6) by GeoSyntec.	
March 8, 2004	Groundwater sampling conducted in select monitoring wells to collect long-term post-demonstration observational data.	PA-23, PA-24S, PA-25S, EIW-1, EEW-1

of field tests, one injection technique was selected for use during the demonstration.

3.3.1.1 Direct Injection

The first injection technology evaluated was direct injection with high pressure. A direct-push drilling rig (Precision Sampling) was used to advance a drilling rod to a desired depth, and then the outer casing of the driving rod was lifted in order to expose a screen to the formation. The emulsion then was injected downward through the rod and sideways through the screen.

The initial plans for EZVI injection were involved with the injection at multiple locations and multiple depths in the treatment zone of the EZVI plot using a direct-push drill rig equipped with a “top-to-bottom” injection tool and an injection pump. The vertical and horizontal spacing of the injection points were to be determined by the limited space of the plot.

A direct-push hydraulic drill rig was used to deliver the EZVI into the subsurface over three discrete adjacent 2-ft intervals. The EZVI was injected over a 6-ft interval to simplify monitoring of the subsurface distribution of EZVI.

During the field test, the hydraulic rig advanced a custom top-down injection slide tool assembly attached to a direct-push, hollow 1.5-inch-outside diameter (O.D.) drive rod. The injection tip was comprised of a customized Geoprobe® open interval, 360-degree-circumference, hole-perforated drive stem sealed within the drive rods. The assembled slide tool was advanced to the top of the injection interval using a standard drive cap. An injection pull cap was connected to the top probe rod and the tool string was withdrawn 4 to 6 inches to expose the injection ports in the drive-point. The upper portion of the probe rod, which is pulled back to expose the injection ports seals off the zones above the injection ports, was intended to function as a packer and minimize short-circuiting of the emulsion. The injection tip was advanced to approximately 2 ft below the water table and the first injection of EZVI was initiated. The EZVI emulsion was injected using a GS2000 grout pump (reciprocating-type piston pump) capable of providing operating pressures up to 1,500 pounds per square inch (psi). The EZVI emulsion was gravity fed to the pump from a hopper and pumped through high pressure hose to the hollow drill stem and down to the injection tip. After the target volume of EZVI had been pumped at the first injection depth, the injection tip was advanced 2 ft and the injection process was repeated (GeoSyntec, 2003).

Before the EZVI emulsion was injected at the third depth it became obvious that the emulsion was short-circuiting up the drill stem and evidenced both at the ground surface and over the interface of water table and unsaturated interval. The injection was repeated at two different locations with varying injection pressures but the EZVI emulsion continued to travel vertically up the injection tool rather than out into the aquifer formation.

It was determined that the direct injection method was not suitable for the demonstration of EZVI injection.

3.3.1.2 Liquid Atomization Injection

The second injection technology evaluated was the Liquid Atomization Injection (LAI) pneumatic injection technique by ARS Technologies. This technique is more effective at injecting gases or “aerosols” into the subsurface. The technique involves using nitrogen gas to atomize low-kinetic-energy, high-viscosity fluids into high-energy aerosols, and then using a multiphase injection system to distribute the material into the subsurface.

An aboveground field test was conducted using LAI to evaluate whether the EZVI remained intact after being atomized and sprayed from a nozzle. The emulsion was introduced into a high-flow, high-velocity gas stream at relatively low pressures (<100 psi) and sprayed out of an injection nozzle outside of the Engineering Support Building. Microscopic analysis of the atomized EZVI indicated that the emulsion structure had been destroyed (i.e., it had separated out into iron particulate and oil droplets). Although the LAI technique is very innovative and promising, it was determined that it was not suitable for the injection of EZVI.

3.3.1.3 Pressure Pulse Technology

The third injection technology evaluated was pressure pulse technology (PPT) by Wavefront Environmental. This technology involves injecting fluid while simultaneously applying large-amplitude pulses of pressure to porous media at the water table or variable depths. These pressure pulses cause instantaneous dilation of the pore throats in the porous media, and thus increase fluid flow and minimize the “fingering” effect that occurs when a fluid is injected into a saturated media.

PPT uses a process of periodic (e.g., one pulse per second) large-impulse hydraulic excitations to introduce hydraulic strain energy into the formation. Applied to geologic formations exhibiting elastic properties, this energy opens perforations, increases pressure, and generally enhances the ability to move fluids. High-amplitude wave pulses are generated by blasts of air delivered by a proprietary pneumatic system. The air is used to drive down a piston in the wellhead assembly that transmits the pressure pulse to the fluid contained in the injection tool and well. Pulse rate and amplitude are calculated based on-site parameters. A porosity-pressure pulse propagates at between 5 and 300 m/s (15 to 900 ft/s) depending on the fluid viscosity, permeability, and the scale of the pulse. Mechanical energy capture causes a buildup of pressure in the reservoir, deforming the material elastically outward.

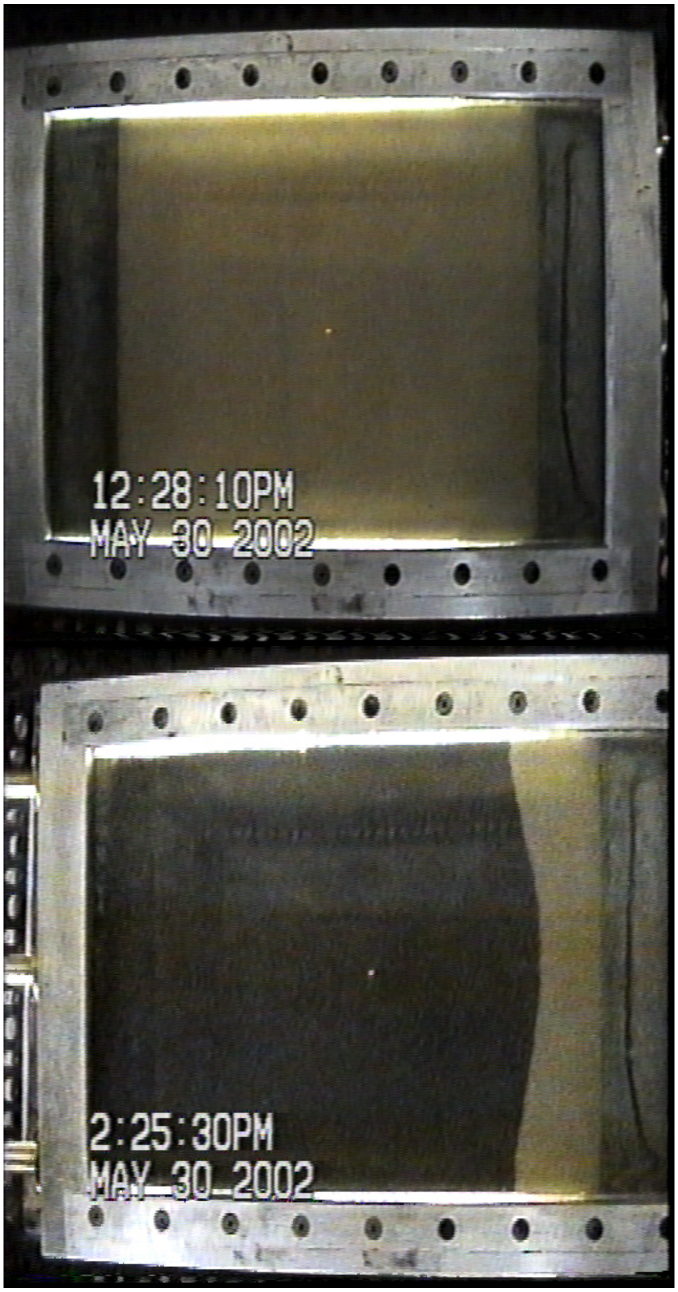


Figure 3-1. EZVI Experiments Using Pressure Pulse Technology, before (above) and after (below)

Before any field injection tests were conducted using PPT, laboratory tests were conducted by Wavefront to insure that the technology would be able to move the EZVI without destroying the emulsion structure. A batch of EZVI was produced and shipped to Wavefront, where a set of injection tests were conducted in a two-dimensional (2D) sandbox set up in their laboratory. Figure 3-1 shows the advancement of EZVI through a media of saturated and compacted sand. PPT appeared to be able to move the EZVI through the sand matrix with minimal fingering at relatively low pressures (~30 psi). A second test was conducted to investigate the potential for the PPT to move the DNAPL before the advancing EZVI front. For this test, a free-phase TCE-DNAPL was placed in the 2D sand matrix, and EZVI was pumped through the matrix while applying PPT. The location and motion of the TCE could be monitored because of its distinct color and the corrosive effects it had on the walls of the cell. Based on these laboratory tests, it appeared that PPT was effective at moving the EZVI to the DNAPL source zone without displacing the DNAPL.

After the successful laboratory experiments, a field test for the EZVI injection system and for the flow properties of the emulsion in undisturbed geologic media was conducted at an uncontaminated area outside the Engineering Support Building.

The injection components consist of a well-head assembly that contains the piston that is used to transmit the pressure pulse to the fluids being injected (Figure 3-2). The well-head assembly isolates the well casing so that the pressure pulses are transmitted to the fluid contained in the well. The downhole injection assembly comprises a set of packers, positioned approximately 4 ft apart with a screened interval between. The lower packer assembly is removable to allow injection into the lower portion of the well screen. The injection tool was threaded onto lengths of steel riser pipe and the whole system was lowered into the well to the desired injection depth and held in place by the well-head assembly. A minimum volume of fluid had to be contained in the well casing in order to maximize the effects of the pressure pulse on that fluid. It was determined that a minimum 3-inch O.D. was needed for the EZVI injection wells.

Figure 3-2. Field Injection Test Setup with PPT Injection Technique

The first field injection test using a PPT injection apparatus was conducted to apply EZVI into the aquifer formation in a 3-inch injection well (Figure 3-2). After several injection attempts, soil coring samples were collected a few inches from the injection wells. It appeared from the soil samples that the EZVI emulsion was not distributed. After a thorough field investigation of the injection assembly, it was determined that the packers inside the casing were not sealing tight and were causing a poor distribution.

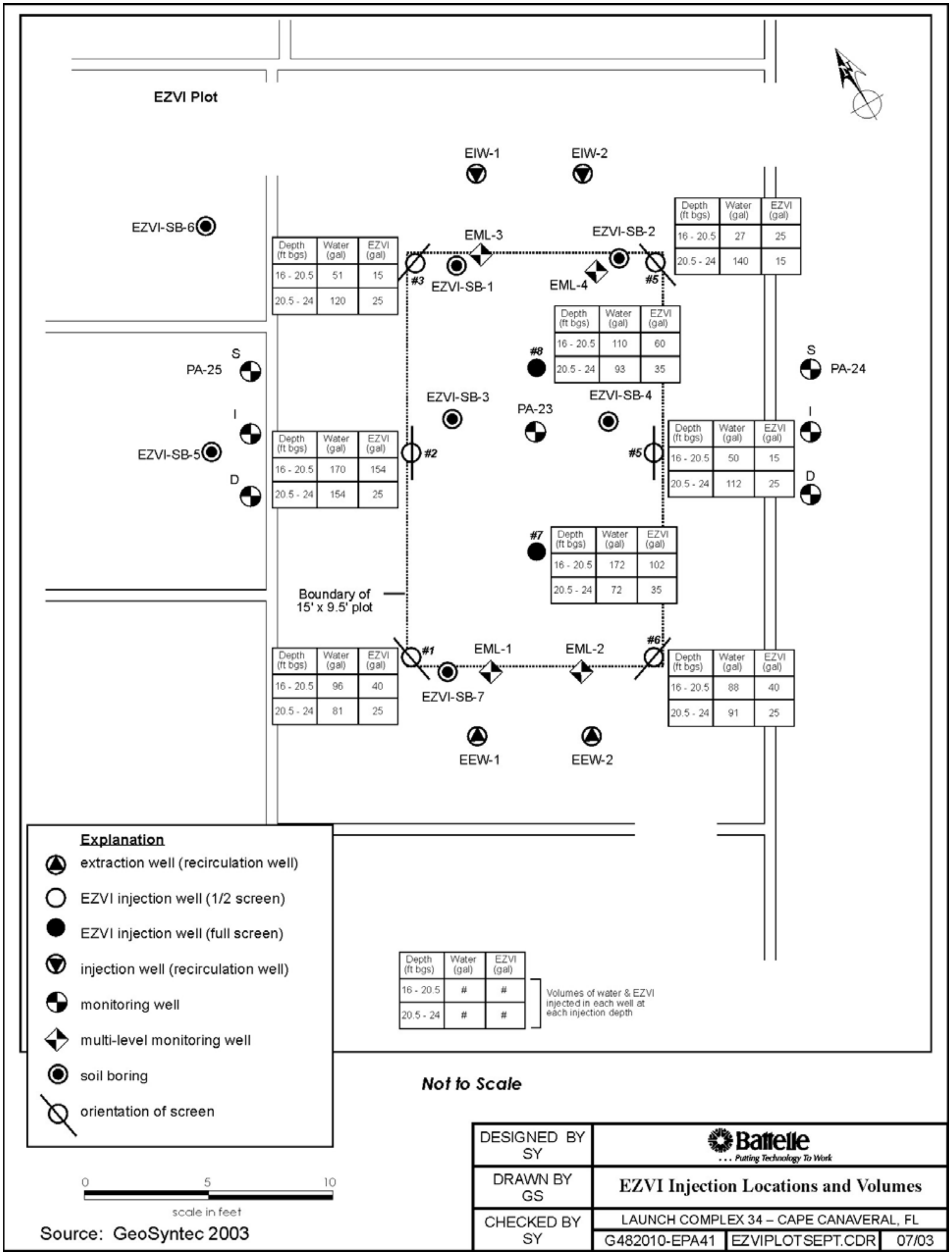
The second field test was attempted at another injection well with a proper set of packers. With a few trials of injection by PPT and soil sample verification, the application of EZVI was successful with the modified packer design. After the successful field test, the injection assembly for the PPT method was directly employed in the EZVI application in the EZVI plot.

3.3.2 EZVI Injection Field Operations

One of the main goals of the technology demonstration was to determine the best method of introducing the EZVI into the contaminated zone. From an evaluation of three injection techniques, Wavefront's PPT was selected for the EZVI technology demonstration.

The total amount of EZVI to be injected was a function of the estimated mass of TCE-DNAPL in the treatment zone and the estimated mass of the EZVI required per unit mass of TCE based on stoichiometric calculations and laboratory experiments. The TCE-DNAPL mass in the treatment zone was difficult to estimate due to its heterogeneous distribution in the subsurface. The estimated TCE-DNAPL mass in the EZVI plot was calculated using TCE results in soil from the pre-demonstration coring (see Section 5.1) using a threshold TCE soil concentration of 300 mg/kg to determine the presence of DNAPL. Stoichiometric calculations suggested that 8 kg of EZVI is required per kg of TCE. Using a safety factor of 2 and using an average concentration of 2,000 mg of TCE per kg of soil, it was estimated that the required volume of EZVI would range from 608 gal (2,300 L) to 845 gal (3,200 L) per each injection round, and that multiple injections may be necessary depending on the injection scenario.

After the treatment zone size for the EZVI plot was determined based on the vendor's project budget, Battelle performed pre-demonstration characterization to estimate the mass of TCE by soil coring. The target volume for treatment was approximately 1,425 ft^3 (a 15 ft × 9.5 ft rectangle treating the lower 10 ft of the Upper Sand Unit). The target treatment zone for the EZVI demonstration was between 16 and 24 ft bgs. An assumption was made for the radius of influence to pump and pulse EZVI at the distance of 4.5 ft from the injection well. A series of eight 3-inch-diameter Schedule 80 polyvinyl chloride (PVC) injection wells with 10-ft screens were installed in the EZVI plot, six along the edges and two in the center of the EZVI plot. The injection wells were screened from 14 to 24 ft bgs. The wells installed on the edges of the EZVI plot were screened only on 180° of the well circumference and oriented so that the screened interval was pointing into the plot. This was done to minimize the amount of EZVI that would be injected outside of the EZVI plot. Figure 3-3 shows the location of the EZVI injection wells and the assumed injection radius used in the design of the EZVI injection network.



Depth (ft bgs)	Water (gal)	EZVI (gal)
16 - 20.5	51	15
20.5 - 24	120	25

Depth (ft bgs)	Water (gal)	EZVI (gal)
16 - 20.5	27	25
20.5 - 24	140	15

Depth (ft bgs)	Water (gal)	EZVI (gal)
16 - 20.5	110	60
20.5 - 24	93	35

Depth (ft bgs)	Water (gal)	EZVI (gal)
16 - 20.5	170	154
20.5 - 24	154	25

Depth (ft bgs)	Water (gal)	EZVI (gal)
16 - 20.5	50	15
20.5 - 24	112	25

Depth (ft bgs)	Water (gal)	EZVI (gal)
16 - 20.5	172	102
20.5 - 24	72	35

Depth (ft bgs)	Water (gal)	EZVI (gal)
16 - 20.5	96	40
20.5 - 24	81	25

Depth (ft bgs)	Water (gal)	EZVI (gal)
16 - 20.5	88	40
20.5 - 24	91	25

Depth (ft bgs)	Water (gal)	EZVI (gal)
16 - 20.5	#	#
20.5 - 24	#	#

Figure 3-3. Location Map and Injection Volume for EZVI Injection

Table 3-2. EZVI Demonstration Schedule

Injection Well ID	Depth (ft bgs)	Date	Water Volume Added Before EZVI Injection (gal)	Water Volume Added with EZVI Injection (gal)	Water Volume Added After EZVI Injection (gal)	Total Volume of Water (gal)	Volume of EZVI (gal)	Comments
Injection #1	20.5 to 24	09-Aug-02	30	38	13	81	25	
	16-20.5	13-Aug-02	20	54	22	96	40	
Injection #2	20.5 to 24	09-Aug-02	25	129		154	25	
	16-20.5	12-Aug-02	20	150	0	170	154	EZVI injection stopped – Injection Well #8 has water and EZVI flowing out of it
Injection #3	20.5 to 24	08-Aug-02				120	25	
	16-20.5	12-Aug-02	36	5	10	51	15	
Injection #4	20.5 to 24	08-Aug-02				140	25	
	16-20.5	13-Aug-02					15	
Injection #5	20.5 to 24	09-Aug-02				112	25	
	16-20.5	13-Aug-02	20	22	8	50	15	
Injection #6	20.5 to 24	10-Aug-02	23	58	10	91	25	
	16-20.5	13-Aug-02	20	40	28	88	40	
Injection #7	20.5 to 24	10-Aug-02				72	35	
	16-20.5	12-Aug-02	20	49	20	89	60	
	16-20.5	13-Aug-02				83	42	Second injection at this depth
Injection #8	20.5 to 24	10-Aug-02	30	50	13	93	35	
	16-20.5	12-Aug-02	20	75	15	110	60	
	16-20.5	13-Aug-02						Attempt second injection of EZVI but Injection Well #2 starts to have EZVI and water flowing out as soon as injection starts

Before injecting the EZVI emulsion into the test plot, a second injection test with the PPT system was conducted outside Engineering Services Building. This test was conducted from August 1-7, 2002 (see Table 3-1.) The second field injection test demonstrated that the bottom packer was not properly working as designed: the lower packer inflation line was breaking when the packer was inflated. After the vendor fixed the bottom packer, 20 gal of EZVI was injected, followed by 250 gal of fresh water in order to chase EZVI at an injection pressure of 100 psi. Gauges confirmed that the injection was working and that pressure was maintained on the packers, injection pulses, and wellhead. After the EZVI injection, several soil cores were collected at distances of 1, 2, 4, and 6 ft from the injection well. Only one soil core sample saturated with EZVI was observed at 1 ft from the injection well at depths of 20 to 24 ft bgs. Given that co-injection with water appeared able to carry the EZVI emulsion into the formation, it was determined that fluidizing the subsurface prior to the EZVI injection was necessary. A rough calculation suggested that the injection of 20 gal of EZVI filled more than 100% of the void space in the radius around the injection well at depths of 20 to 24 ft bgs. As a result of the oversaturated pore space, the EZVI was forced to move through preferential flows and channels towards the surface. Therefore, the injection technique was modified by first injecting water in the aquifer before and after the injection of EZVI. This modified injection technique was able to successfully overcome the difficulties of injecting a high-viscosity emulsion into subsurface.

During the EZVI application in the treatment plot, the co-injection ratio of EZVI and water was maintained between 1:2 to 1:4 at various depths as summarized in Table 3-2. The total volume of EZVI injected was approximately 661 gal and the total volume of water injected into the injection wells was 1,627 gal (Table 3-2). Approximately 2,300 gal of water and EZVI were injected into the EZVI plot. The details of the injection information are summarized in Figure 3-3 and Table 3-2.

3.4 Groundwater Control System

A groundwater control system was designed and installed to maintain the hydraulic groundwater control in the EZVI plot. The groundwater control system consists of (1) two injection wells (EIW-1 and EIW-2) upgradient and two extraction wells (EEW-1 and EEW-2) downgradient of the EZVI plot, (2) an aboveground treatment system (see Figure 3-4) to treat VOCs prior to reinjection, (3) the associated process piping, and (4) additional monitoring wells on the edges of the plot (EML-1 to -4), outside the plot (PA-24S/I/D and PA-25S/I/D), and inside the plot (PA-23).

The groundwater control system was used to maintain flow and hydraulic residence time in the EZVI plot. The technology vendor designed the specifics of the flow control based on Visual MODFLOW™ (GeoSyntec, 2002). The results indicated that a flowrate of 1 gallon per minute (gpm) was sufficient to maintain flow in the system. Extra care was taken to prevent any potential air from entering into the treatment system. Flowrate, pressure, and the extracted groundwater chemistry were monitored by the vendor.

The groundwater control system was operated during three separate periods: (1) pre-demonstration (June 25 to July 17, 2002) from EEW-1 and EEW-2, (2) during the demonstration (August 24 to 29 and September 13 to 25, 2002) from PA-23, and (3) post-demonstration (December 16, 2002 to January 6, 2003) from EEW-1 and EEW-2. Although the optimal flowrate indicated by the modeling results was 1 gpm, the recirculation system could be controlled with much lower flow. The technology vendor frequently calibrated and daily recorded the logs of the average groundwater extraction flowrates using a pressure transducer from various sample ports. The water level was measured and recorded several times a day with a data logger (GeoSyntec, 2003). During every site visit (every other week), the following activities were performed to maintain the groundwater control system:

- Monitoring of the pressure drop across granulated activated carbon (GAC) tank filter cartridges
- Collection of water samples from the effluent sampling port of the GAC tanks
- Flowrate and pressure measurements
- Water level measurements
- Site inspection and engineering control
- Replacement of GAC tanks and filter cartridges when necessary
- Routine maintenance of the extraction pump.

Before the demonstration, the average flowrate was maintained at 0.5 gpm from both EEW wells (EEW-1 and EEW-2) downgradient from the EZVI plot. The flowrate was kept at average of 0.3 gpm from PA-23 prior to and during the demonstration. Approximately 7,000 gal was extracted from PA-23. Of those 7,000 gal, approximately 2,300 gal of water extracted from PA-23 were then co-injected with EZVI into the EZVI plot. The remaining water was reinjected into the injection wells (EIW-1 and EIW-2), which are approximately 20 ft upgradient of the plot, after the EZVI injection. This reinjection scheme would likely induce an inward gradient into the plot.

Figure 3-4. Aboveground Water Treatment System (A Series of Two Carbon Tanks and a Backup Tank)

In the post-demonstration period, the extraction rate averaged between 0.4 and 0.7 gpm to induce the remaining unspent EZVI into action.

In summary, the groundwater control system was operated to maintain groundwater flow through the EZVI plot with minimal hydraulic disturbance.

3.5 Waste Handling and Disposal

Spent GAC was characterized and disposed of by the manufacturer of the GAC units. Solid waste generated during the demonstration such as gloves and sampling tubes were contained in open-top 55-gal drums specified (UN1A2/Y1.4/100) by the U.S. Department of Transportation and required by the site owner (NASA). Liquid samples were contained in closed-top 55-gal drums specified (UN1A1/Y1.4/100) and stored on site in a locked, fenced storage area until disposal by the site owner. If DNAPL was present in the extracted groundwater, the DNAPL was stored in liquid waste disposal drums with the liquid samples.

4. Performance Assessment Methodology

Battelle, in conjunction with the U.S. EPA SITE Program, conducted an independent performance assessment of the EZVI demonstration at Launch Complex 34 (see Figure 4-1). The objectives and methodology for the performance assessment were outlined in a QAPP prepared before the field demonstration and reviewed by all project stakeholders (Battelle, 2002a). The objectives of the performance assessment were to:

- Estimate the change in total TCE and DNAPL mass in the test plot and the change in TCE flux in groundwater due to the EZVI treatment;
- Evaluate changes in aquifer quality due to the EZVI treatment;
- Evaluate the fate of TCE due to the EZVI treatment;
- Verify EZVI technology operating requirements and costs.

Table 4-1 summarizes the measurements and sampling locations associated with each performance objective.

Figure 4-1. Soil Sampling for Performance Assessment at Launch Complex 34

The performance assessment was based on results obtained from sampling activities in the targeted hydrostratigraphic unit for the EZVI injection, which was the Upper Sand Unit. Results from samples collected in other units (Middle Fine-Grained Unit, Lower Sand Unit) were used to evaluate the technology's effect, if any, on vertical contaminant migration.

4.1 Estimating Changes in TCE-DNAPL Mass and TCE Flux

The primary objective of the performance assessment was to estimate the changes in total TCE and DNAPL mass in the target unit (i.e., the Upper Sand Unit), as well as the change in TCE flux in groundwater, due to the EZVI treatment. Total TCE includes both dissolved-phase and free-phase TCE present in the aquifer soil matrix. DNAPL refers to free-phase TCE only and is defined by the threshold TCE concentration of 300 mg/kg as calculated in Section 2.3. Soil sampling in the EZVI plot was used for estimating changes in TCE-DNAPL mass before and after the demonstration. The method used to estimate TCE mass flux in groundwater was the measurement of mass changes due to TCE dissolution in groundwater from the multichamber wells located in upgradient and downgradient sides of the EZVI plot, before and after the demonstration.

4.1.1 Changes in TCE-DNAPL Mass

At the outset of the demonstration, a total TCE removal target of 50% in the Upper Sand Unit was chosen for the EZVI demonstration, as determined by 80% confidence levels by kriging. Previous soil coring, sampling, and analysis at Launch Complex 34 (Battelle, 1999b; Eddy-Dilek et al., 1998) indicated that soil sampling was a viable technique for identifying the boundaries of the DNAPL source zone and estimating the TCE and DNAPL mass. The advantage of soil sampling (see Figure 4-2) was that relatively intensive horizontal and vertical coverage of any test plot, as well as of the

Table 4-1. Summary of Performance Assessment Objectives and Associated Measurements

Objective	Measurements	Frequency	Sampling Locations(a)
		Primary Objective	
Estimate change in total TCE and DNAPL mass in soil, and change in TCE flux in groundwater	CVOCs(b) in soil	Before and after treatment	Six horizontal locations in the Upper Sand Unit. Extract and analyze every 2-ft depth.
	CVOCs(b) and dissolved hydrocarbon gases(c) in groundwater	Before, during, and after treatment	Extraction wells (EEW-1 and EEW-2); test plot well PA-23.
		Secondary Objectives	
Evaluate changes in aquifer quality	CVOCs(b), inorganics(d), TOC, BOD, field parameters(e) in groundwater	Before, during, and after treatment	Center well PA-23 and perimeter well clusters PA-24 and PA-25.
	TOC in soil	Before and after treatment	Three multiple depths of two locations inside the plot.
	Hydraulic conductivity of the aquifer	Before and after treatment	Center well PA-23.
Evaluate the fate of TCE	CVOCs(b) in soil	Before and after treatment	Extend the six locations from the Upper Sand Unit vertically into the Middle Fine-Grained Unit and Lower Sand Unit. Extract and analyze every 2-ft depth.
	CVOCs(b), inorganics(d), field parameters, dissolved hydrocarbon gases(c) in groundwater	Before, during, and after treatment	Perimeter well clusters PA-24 and PA-25; injection well EIW-1 and extraction well EEW-2.
	Chloride in groundwater	Before and after treatment	Four locations in the plot at five discrete depths using a Waterloo Profiler®.
	Hydraulic gradient in the aquifer	Before, during, and after treatment	Water level measurements taken in the test plot well (PA-23), perimeter well clusters (PA-24 and PA-25), and distant wells.
Verify operating requirements and costs of the EZVI technology	Field observations, tracking materials consumption and costs	Before, during, and after treatment	Field observations by vendor and Battelle; materials and consumption costs reported by vendor to Battelle.

(a) Figures 4-3 and 4-4 show soil core sampling locations and groundwater monitoring well locations within the EZVI plot.
(b) CVOCs of interest are TCE, *cis*-1,2-DCE, *trans*-1,2-DCE, and VC.
(c) Dissolved hydrocarbon gases are methane, ethane, and ethane.
(d) Inorganics include cations (Ca, Mg, total and dissolved Fe, Mn, Na, K), anions (chloride, bromide, sulfate, phosphate, and nitrate/nitrite), alkalinity, dissolved silica, and TDS.
(e) Field parameters are pH, DO, ORP, conductivity, and temperature.

dissolved-phase TCE and DNAPL distribution, could be achieved with a reasonable number of soil samples and without DNAPL access being limited to preferential flowpaths in the aquifer. Soil sampling was conducted before (pre-demonstration event) and after (post-demonstration event) the EZVI application (see Figures 4-3 and 4-4). An additional soil sampling event was held approximately six weeks after EZVI was injected at the target depths in the plot, but prior to post-demonstration monitoring. The purpose of this intermediate soil sampling event was to verify that the EZVI had been distributed into the subsurface area under the test plot, and also to determine if an additional EZVI injection would be necessary to treat any remaining contaminant before beginning the post-demonstration characterization. An additional EZVI injection was determined to be unnecessary based on the preliminary results of the intermediate soil sampling event. The results of all three soil sampling events are presented in Section 5.1.

Figure 4-2. Soil Sample Collection (tan color indicates the native soil color; the gray to blackish band indicates evidence of the injected EZVI)

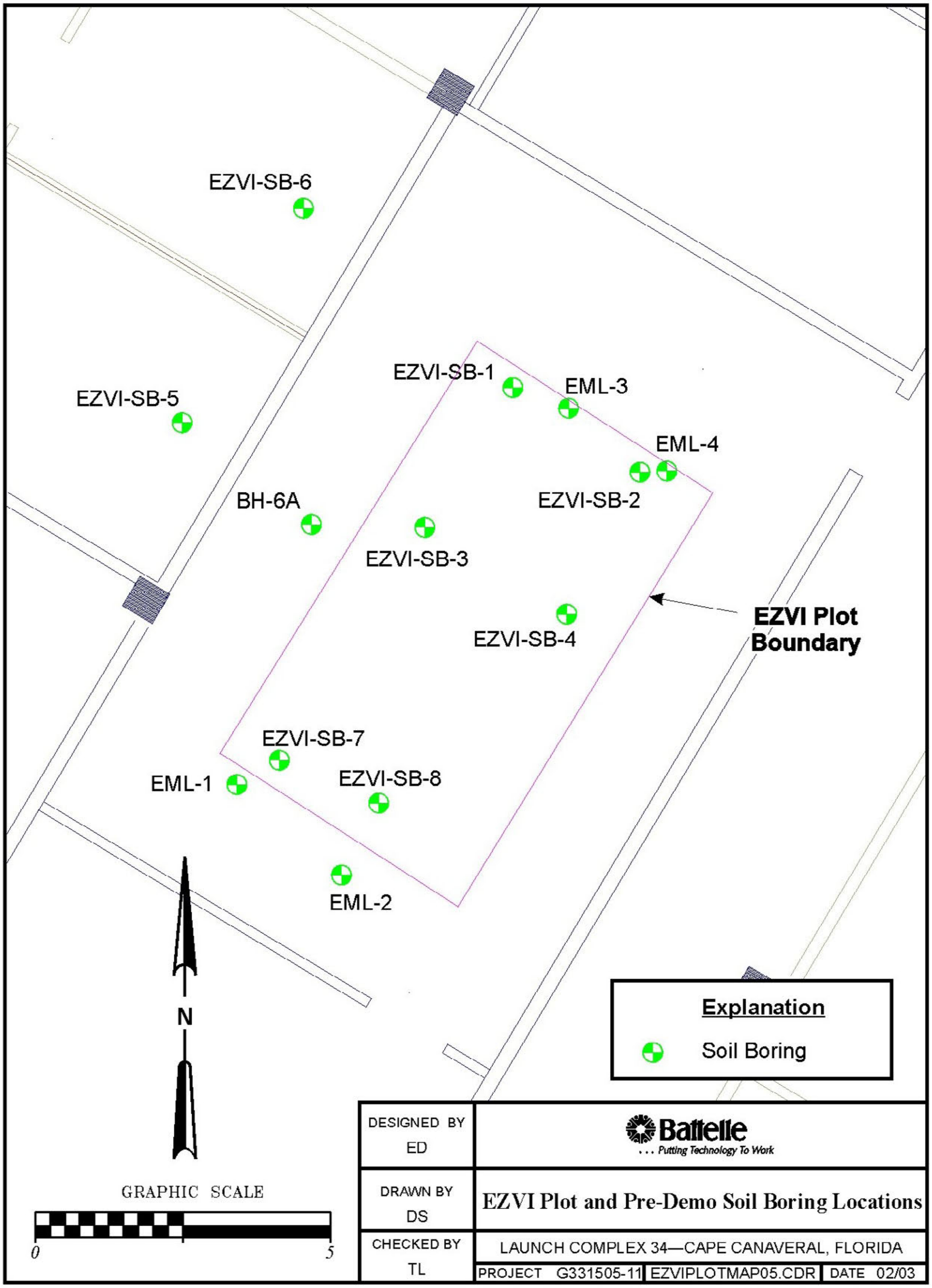


Figure 4-3. Pre-Demonstration Soil Boring Locations (SB-1 through SB-4; SB-7; SB-8) in the EZVI Plot (January/February 2002)

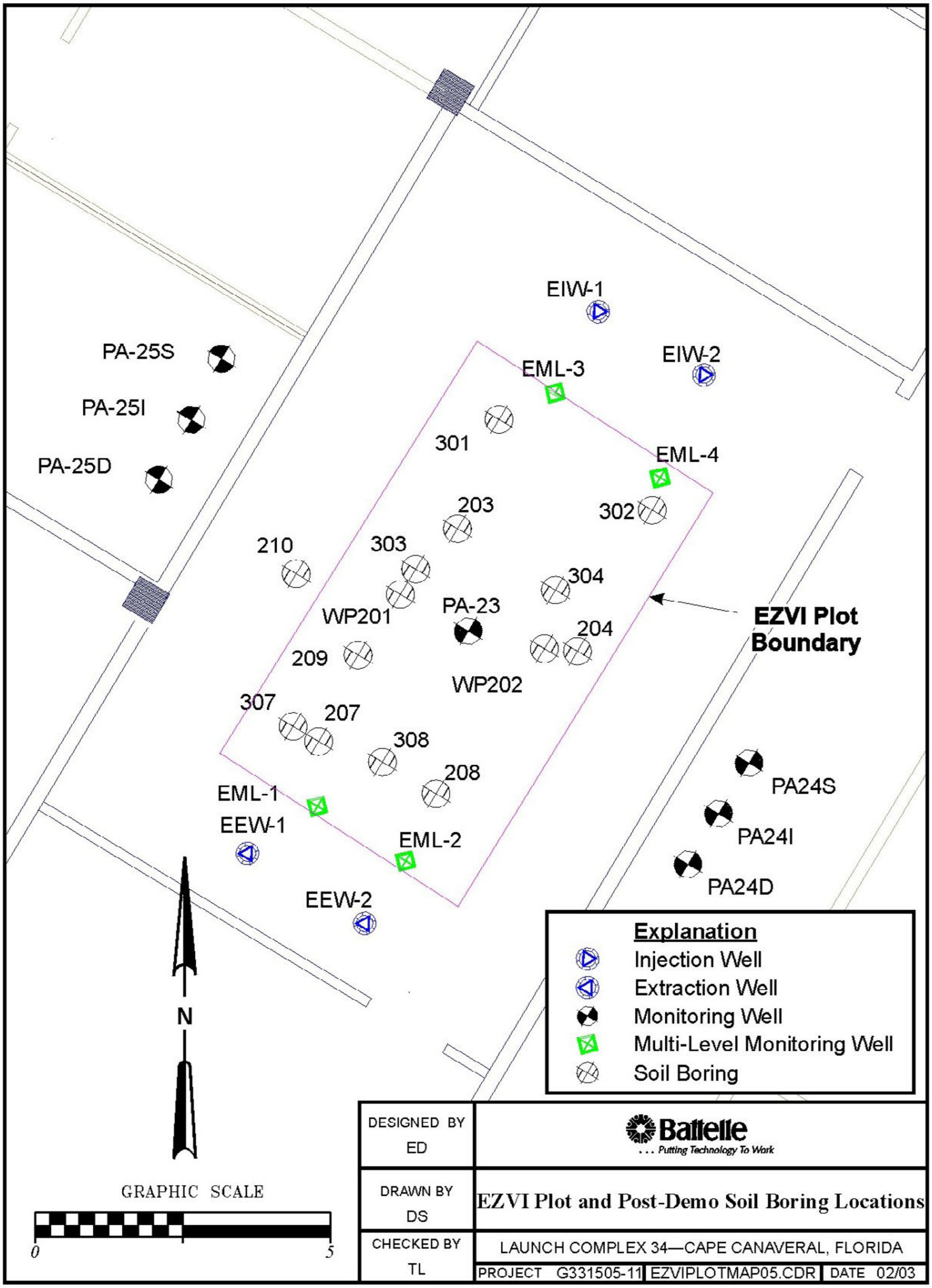


Figure 4-4. Post-Demonstration Soil Boring Locations (SB-201 through SB-204; SB-207; SB-208; and SB-301 to SB-304; SB-307; SB-308) in the EZVI Plot (October 2002; November 2002)

Although the primary focus of the performance assessment was on TCE, the soil samples also were analyzed for *cis*-1,2-DCE and VC to determine if these degradation products were accumulating in the aquifer after treatment due to reductive dechlorination in anaerobic conditions.

Geostatistical methods were used to determine the number of soil coring locations and number of soil samples required. A minimum sample size for each characterization event (i.e., pre- and post-demonstration) was selected at 50 in the Upper Sand Unit based on the sample requirements for the kriging analysis, which was the highest number of samples that would be practical to collect for the smaller size of the test plot (15 × 9.5 ft) and still produce an 80% confidence interval.

The number of boreholes (6) chosen for the plot was limited by the small size of the test plot (15 x 9.5 ft). Initially, a systematic unaligned sampling scheme (Battelle, 1999c) was designed for the plot. However, the small size of the plot and some physical obstructions limited the actual spatial locations that could be sampled. Many possible borehole locations were obstructed by the EZVI injection points in the test plot, and also by the requirement that grouted boreholes produce minimal interference with the hydraulic aspects of EZVI injection and extraction. To compensate for these limiting factors, a systematic aligned sampling scheme was used whereby the plot was divided into a 3 × 2 grid, and the soil core sample locations were placed as close as possible to the center of each grid cell. The resulting sampling configuration provided good horizontal and vertical coverage of the test plot within the level of resources available. Figure 4-3 contains the pre-demonstration soil coring locations (soil cores SB-1 through SB-4; SB-7 and SB-8).

For each soil boring collected during the pre- and post-demonstration, the entire soil column from ground surface to the Lower Clay Unit (approximately 45 ft bgs) was sampled and analyzed in 2-ft sections. However, only the soil samples collected from the Upper Sand Unit were considered in evaluating the EZVI technology. Seven soil borings (SB-201 to -204; SB-207 to -209) were collected and analyzed for CVOCs during the intermediate soil sampling event that was held shortly after EZVI injection. Sample SB-209 was collected from outside the western edge of the plot. Six soil borings (SB-301 to SB-304; SB-307 and SB-308) were collected during the post-demonstration characterization, as shown in Figure 4-4. Each soil sampling event, therefore, consisted of nearly 50 soil samples collected for the purposes of evaluating the EZVI technology (5 to 6 borings with approximately ten 2-ft intervals per boring in the Upper Sand Unit, plus duplicates).

Soil coring, sampling, and extraction methods are described in Appendix A.2 and summarized in this section. Figure 4-5 shows the indoor rig used for soil coring inside the Engineering Support Building. A direct Vibra-Push™ rig with a 2-inch-diameter, 4-ft-long sample barrel was used for coring. As soon as the sample barrel was retrieved, the 2-ft section of core was split vertically and approximately one-quarter of the core (approximately 125 g of wet soil) was deposited into a predetermined volume (250 mL) of methanol for extraction in the field. The methanol extract was transferred into 20-mL volatile organic analysis (VOA) vials, which were shipped to a

Figure 4-5. Indoor Vibra-Push™ Rig (LD Geoprobe® Series) Used in the EZVI Plot Inside the Engineering Support Building

certified off-site laboratory for analysis. The sampling and extraction technique used at this site provided better coverage of a heterogeneously distributed contaminant distribution as compared to the more conventional method of collecting and analyzing small soil samples at discrete depths, because the entire vertical depth of the soil column at the coring location could be analyzed. Preliminary site characterization had shown that the vertical variability of the TCE distribution was greater than the horizontal variability, and this sampling and extraction method allowed continuous vertical coverage of the soil column (GeoSyntec, 2002). The efficiency of TCE recovery by this method (modified U.S. EPA Method 5035; see Appendix A.2) was evaluated through a series of tests conducted for the demonstration (Battelle, 2003). In these tests, a surrogate compound (1,1,1-trichloroethane [1,1,1-TCA]) was spiked into soil cores from the Launch Complex 34 aquifer, extracted, and analyzed. Replicate extractions and analysis of the spiked surrogate indicated a CVOC recovery efficiency between 84 and 113% (with an average recovery of 92%), which was considered sufficiently accurate for the demonstration.

Two data evaluation methods were used for estimating the change in TCE-DNAPL mass in the EZVI plot: linear interpolation by contouring, and kriging. The spatial variability or spread of the TCE distribution in a DNAPL source zone typically is high, the reason being that small pockets of residual solvent may be distributed unevenly across the source region. The two methods address this spatial variability in different ways, and therefore the resulting mass removal estimates differ slightly. Because it is impractical to collect a sample from every single point in the EZVI plot and obtain a true TCE mass estimate for the plot, both methods address the practical difficulty of estimating the TCE concentrations at unsampled points by interpolating (estimating) between sampled points. The objective of both methods is to use the information from a limited sample set to make an inference about the entire population (the entire plot or a stratigraphic unit).

4.1.2 Linear Interpolation by Contouring

Linear interpolation by contouring is the most straightforward and intuitive method for estimating TCE concentration or mass in the entire plot, based on a limited number of sampled points. TCE concentrations are assumed to be linearly distributed between sampled points. A software program, such as EarthVision™, has an advantage over manual calculations in that it is easier to conduct the linear interpolation in three dimensions. In contouring, the only way to address the spatial variability of the TCE distribution is to collect as large a number of samples as is practical so that good coverage of the plot is obtained; the higher the sampling density, the smaller the distances over which the data need to be interpolated.

For linear interpolation by contouring, input parameters must be adjusted to accommodate various references such as geology and sample size. Nearly 200 soil samples were collected from the 17 coring locations in the plot during each event (pre-demonstration, intermediate, and post-demonstration), which was the highest number practical within the resources of this project. The number and distribution of these sampling points were determined to obtain good representative coverage of the plot.

Linear interpolation by contouring using EarthVision™ software uses the same methodology that is used for drawing water level contour maps based on water level measurements at discrete locations in a region. The only difference with this software is that the TCE concentrations are mapped in three dimensions to generate iso-concentration shells (i.e., volumes of soil that fall within a specified concentration range). The average TCE concentration of each shell is multiplied by the volume of the shell (as estimated by the volumetric package in the software) and the bulk density of the soil (1.59 g/cm^3) to estimate a TCE mass for each shell. The TCE mass in each region of interest (Upper Sand Unit, Middle-Fine-Grained Unit, or Lower Sand Unit) is obtained by adding up the portion of the shells contained in that region. The DNAPL mass is obtained by adding up the masses in only those shells that have TCE concentrations above 300 mg/kg. Contouring provides a single mass estimate for the region of interest.

4.1.3 Kriging

Kriging is a geostatistical interpolation method that takes into consideration the spatial correlations among the TCE data in making inferences about the TCE concentrations at unsampled points. Spatial correlation analysis determines the extent to which TCE concentrations at various points in the plot are similar or different. Generally, the degree to which TCE concentrations are similar or different is a function of distance and direction. Based on these correlations, kriging determines how the TCE concentrations at sampled points can be optimally weighted to infer the TCE concentrations/masses at unsampled points in the plot or the TCE mass in an entire region of interest (entire plot or stratigraphic unit). Kriging accounts for the uncertainty in each point estimate by calculating a standard error for the estimate. Therefore a range of TCE mass estimates is obtained instead of a single estimate; this range is defined by an average and a standard error or by a confidence interval. The confidence or level of significance required by the project objectives determines the width of this range. A level of significance of 0.2 (or 80% confidence) was determined as necessary at the beginning of the demonstration (Battelle, 2002a).

4.1.4 Interpreting the Results of the Two Mass Removal Estimation Methods

The two data evaluation methods address the spatial variability of the TCE distribution in different ways and, therefore, the resulting mass removal estimates differ slightly between the two methods.

In both contouring and kriging, TCE mass removal is accounted for on an absolute basis; higher mass removal in a few high-TCE concentration portions of the plot can offset low mass removal in other portions of the plot, to infer a high level of mass removal. Kriging most likely provides a more informed inference of the TCE mass removal than contouring because it takes into account the spatial correlations in the TCE distribution and the uncertainties (error) associated with the estimates. The results in Section 5.1 show that contouring was able to overcome the spatial variability to a considerable extent and provide mass estimates that were generally in agreement with the ranges provided by kriging.

4.1.5 TCE Flux Measurements in Groundwater

In addition to estimating the changes in TCE-DNAPL mass, another primary objective of the performance assessment was to evaluate any changes in TCE flux in groundwater after the EZVI injection. Groundwater samples were collected by the vendor from the multilevel samplers and the performance monitoring well network in the plot. The change in TCE flux is a measure of the reduction in activity of the DNAPL source (i.e., the strength of the DNAPL contribution to plume formation) brought about by the technology.

4.2 Evaluating Changes in Aquifer Quality

A secondary objective of the performance assessment was to evaluate any short-term changes in aquifer quality due to the treatment. EZVI affects the contaminant and, to a lesser extent, the native aquifer characteristics. Pre- and post-demonstration measurements conducted to evaluate the short-term impacts of the technology application on the aquifer included:

- CVOC measurements in the groundwater inside the EZVI plot
- Field parameter measurements (pH, DO, ORP, temperature, and conductivity) in the groundwater
- Inorganic measurements (common cations and anions) in the groundwater
- TDS and 5-day BOD
- TOC measurements in the soil
- Hydraulic conductivity of the aquifer.

These measurements were conducted in the monitoring well within the plot and in the extraction wells and perimeter wells surrounding the plot.

4.3 Evaluating the Fate of the TCE-DNAPL

Another secondary objective of the performance assessment was to evaluate the fate of TCE removed from the plot by the EZVI treatment. Possible pathways (or processes) for TCE removal include dehalogenation (destruction of TCE) and migration from the EZVI plot (to outside the plot). Dehalogenation will be determined by the presence of TCE degradation products, including chloride. The amount of chloride generated during EZVI treatment was evaluated by collecting groundwater samples with a Waterloo Profiler® inside the plot (see Figure 4-6), as well as from the performance monitoring wells. These pathways were evaluated by the following measurements:

- Chloride in groundwater (mineralization of CVOCs leads to formation of chloride) and other inorganic constituents in groundwater
- Alkalinity in groundwater (oxidation of CVOCs and native organic matter leads to formation of CO_2 which, in a closed system, forms carbonate)
- Hydraulic gradients (injection of the emulsion creates gradients indicative of groundwater movement)
- Dissolved and total iron concentrations in the EZVI plot and surrounding wells
- Changes in dehalogenated byproducts (*cis*-1,2-DCE, VC, and ethenes)
- Impact on natural attenuation products (nitrate, sulfate) via the aerobic process.

Figure 4-6. Collecting and Processing Groundwater Samples Using the Waterloo Profiler®

4.4 Verifying Operating Requirements and Costs

The final secondary objective of the performance assessment was to verify the vendor's operating requirements and cost for the technology application. The costs were evaluated, reported, and presented using the methodology outlined in the Federal Remediation Technologies Roundtable report (FRTR, 1998). The vendor prepared a detailed report describing the operating requirements and costs of the EZVI application (GeoSyntec, 2003). An operating summary based on this report is provided in Section 3.3.2. Site characterization costs were estimated by Battelle.

5. Performance Assessment Results and Conclusions

The results of the performance assessment methodology outlined in Section 4 are described in this section.

5.1 Changes in TCE-DNAPL Mass in the Plot

Section 4.1 describes the methodology used to estimate the masses of total TCE and TCE-DNAPL removed from the plot due to the EZVI treatment at Launch Complex 34. Intensive soil sampling was the primary tool for estimating total TCE and DNAPL mass removal. Total TCE refers to both dissolved-phase and TCE-DNAPL. DNAPL refers to that portion of total TCE in a soil sample that exceeds the threshold concentration of 300 mg/kg (see Section 2.3). TCE concentrations for pre- and post-demonstration characterization from six soil cores (approximately 50 soil samples each) of the EZVI plot were tabulated and graphed to *qualitatively* identify changes in TCE-DNAPL mass distribution and determine the efficiency of the EZVI treatment in different parts of the plot (Section 5.1.1). In addition, TCE-DNAPL mass removal was *quantified* by three methods:

- Contouring (Section 5.1.2)
- Kriging (Section 5.1.3)
- Groundwater Mass Flux (Section 5.1.4).

The quantitative techniques for estimating TCE-DNAPL mass removal due to the EZVI treatment are described in Section 4.1; the results are described in Sections 5.1.2 through 5.1.5.

5.1.1 Qualitative Evaluation of Changes in TCE-DNAPL Distribution

Figure 5-1 charts the pre-demonstration, intermediate, and post-demonstration TCE concentrations at six paired locations in the EZVI plot (see Figures 4-3 and 4-4); detailed TCE results in soil samples are tabulated in Appendix C. The thick horizontal line in the chart indicates the depth at which the Middle Fine-Grained Unit was encountered. Soil samples were collected from the groundwater table (approximately 6 ft bgs) down to the Lower Sand Unit; however, this discussion of sampling results will focus primarily on concentrations in the Upper Sand Unit because the EZVI treatment focused on that specific geographical stratigraphic unit.

At several locations in the plot at that target depth, TCE concentrations were considerably lower after the EZVI injection. Cells highlighted in gray on Figure 5-1 indicate depths where EZVI was visually observed in the soil samples during sample collection. Note that the TCE concentrations were considerably lower at the depths where EZVI was visually observed. The highest pre-demonstration contamination was detected in soil core SB-3 (6,067 mg/kg at 18 ft bgs). Similarly, the highest post-demonstration TCE concentration was detected in soil core SB-303 (4,502 mg/kg at 24 ft bgs).

Figures 5-2 and 5-3 show representative pre-demonstration and post-demonstration distributions of TCE in soil at two selected depths (18 and 22 ft bgs) in the Upper Sand Unit of the EZVI plot and surrounding aquifer. These figures illustrate the areal and vertical extent of the initial contaminant distribution, and the subsequent changes in TCE concentrations. The yellow to red colors indicate the presence of free-phase TCE-DNAPL (based on the TCE-DNAPL threshold of 300 mg/kg). In general, the southern and western portions of the plot (SB-3 and SB-7) had the highest pre-demonstration TCE concentrations in and near the EZVI plot. Post-demonstration coring indicated that the injection of EZVI decreased TCE distribution at multiple depths in the plot (16 to 20.5 ft bgs, and 20.5 to 24 ft bgs).

Figure 5-4 depicts 3D distributions of TCE-DNAPL identified from the pre- and post-demonstration characterization in the EZVI plot, and based on the 300 mg/kg threshold. Suspected TCE-DNAPL prior to the application of EZVI in the Upper Sand Unit appeared at the depths of approximately 16 to 24 ft as well. After the application of the EZVI injection at strategic depths (between 16 and 24 ft bgs), a relatively well-distributed mass of TCE-DNAPL appeared to decrease to relatively smaller residual pocketfuls in and around the EZVI plot.

Top Depth	Bottom Depth	Pre-Demo SB-1	Post-Demo SB-301	Pre-Demo SB-3	Intermediate SB-203	Post-Demo SB-303	Pre-Demo SB-7	Intermediate SB-207	Post-Demo SB-307
6	8	ND	0	ND	1	0	ND	1	0
8	10	1	1	0	NA	0	0	NA	NA
10	12	1	1	0	1	1	0		2
12	14	3	4	1		1	2	ND	1
14	16	6	1	7	13	4	70	ND	0
16	18	87	1	6,067	1	1	1,167	0	NA
18	20	282	12	209	1,023	451	207	[1] 54	23
20	22	208	8	195	[1] 798	7	175	ND	NA
22	24	230	0	253	495	4,502	202	268	19
24	26	283	NA	272	2	17	222	177	149
26	28	263	119	252	1	45	268	252	175

Top Depth	Bottom Depth	Pre-Demo SB-2	Post-Demo SB-302	Pre-Demo SB-4	Intermediate SB-204	Post-Demo SB-304	Pre-Demo SB-8	Intermediate SB-208	Post-Demo SB-308
6	8	ND	0	ND	ND	0	ND	ND	ND
8	10	ND	NA	0	NA	0	3	ND	0
10	12	ND	1	0	0	0	2	ND	1
12	14	1	1	6	1	0	2	ND	0
14	16	10	11	6	1	ND	21	ND	NA
16	18	89	5	45	1	ND	127	ND	0
18	20	182	57	161	6	2	136	ND	NA
20	22	233	NA	171	3	1	157	NA	177
22	24	262	18	249	35	0	162	143	130
24	26	259	7	289	183	0	212	NA	125
26	28	270	8	255	27	28	237	269	NA

Summary chart for TCE results is divided into two groups (the western soil boring group: SB-1/-3/-7; the eastern soil boring group: SB-2/-4/-8).
NA: Not available due to no recovery or no sample collection at the sample depth.
ND: The sample was detected below the detection limit.
Solid horizontal line indicates the lithologic unit change from the Upper Sand Unit to the Middle Fine-Grained Unit.
Pre-Demo: January 2002.
Intermediate: October 2002.
Post-Demo: November 2002.

Figure 5-1. Distribution of TCE Concentrations (mg/kg) During Pre-Demonstration and Post-Demonstration Characterization in the EZVI Plot Soil

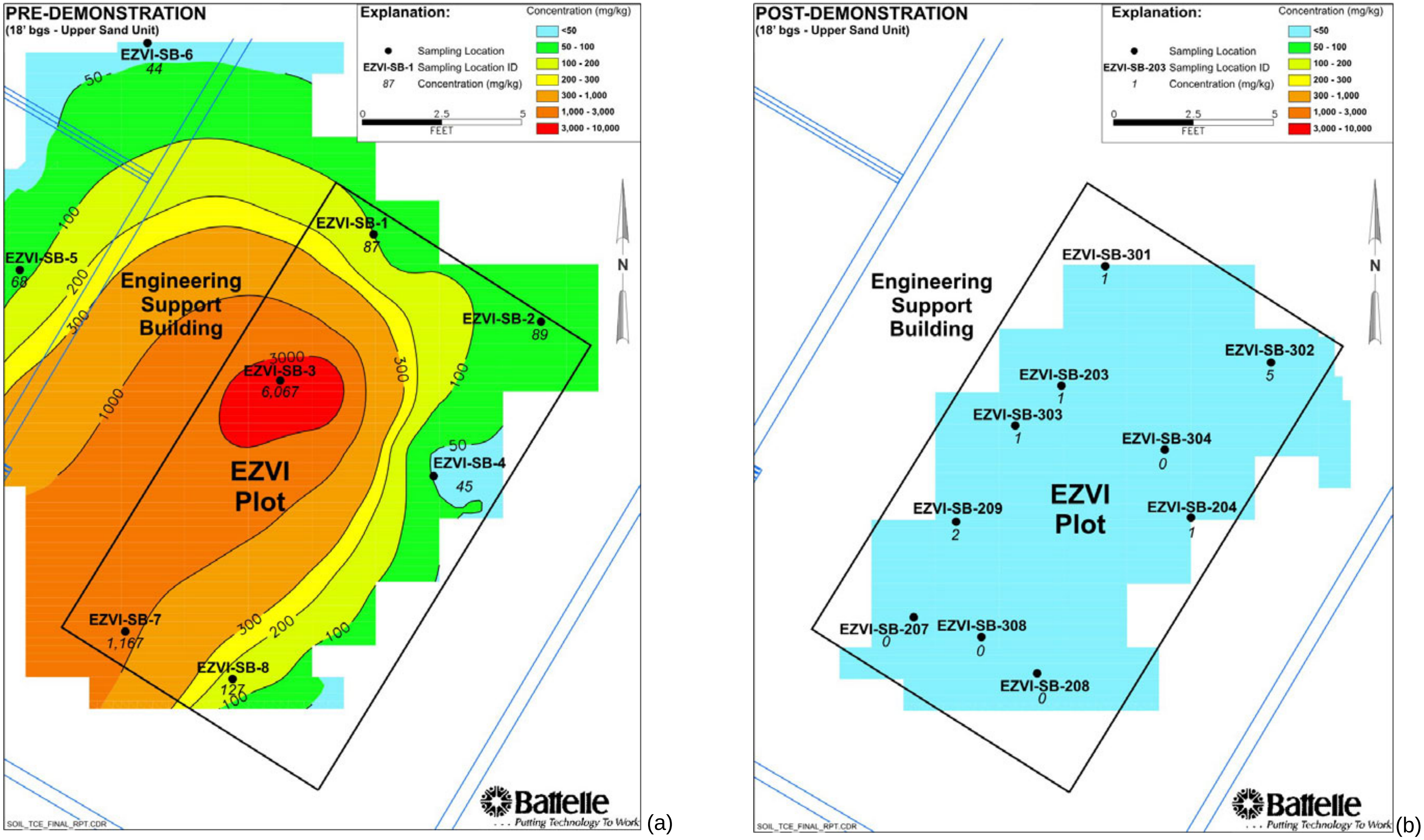


Figure 5-2. Representative (a) Pre-Demonstration (January 2002) and (b) Post-Demonstration (October to November 2002) Horizontal Cross Sections of TCE (mg/kg) in soil at 18 ft bgs in the Upper Sand Unit Soil

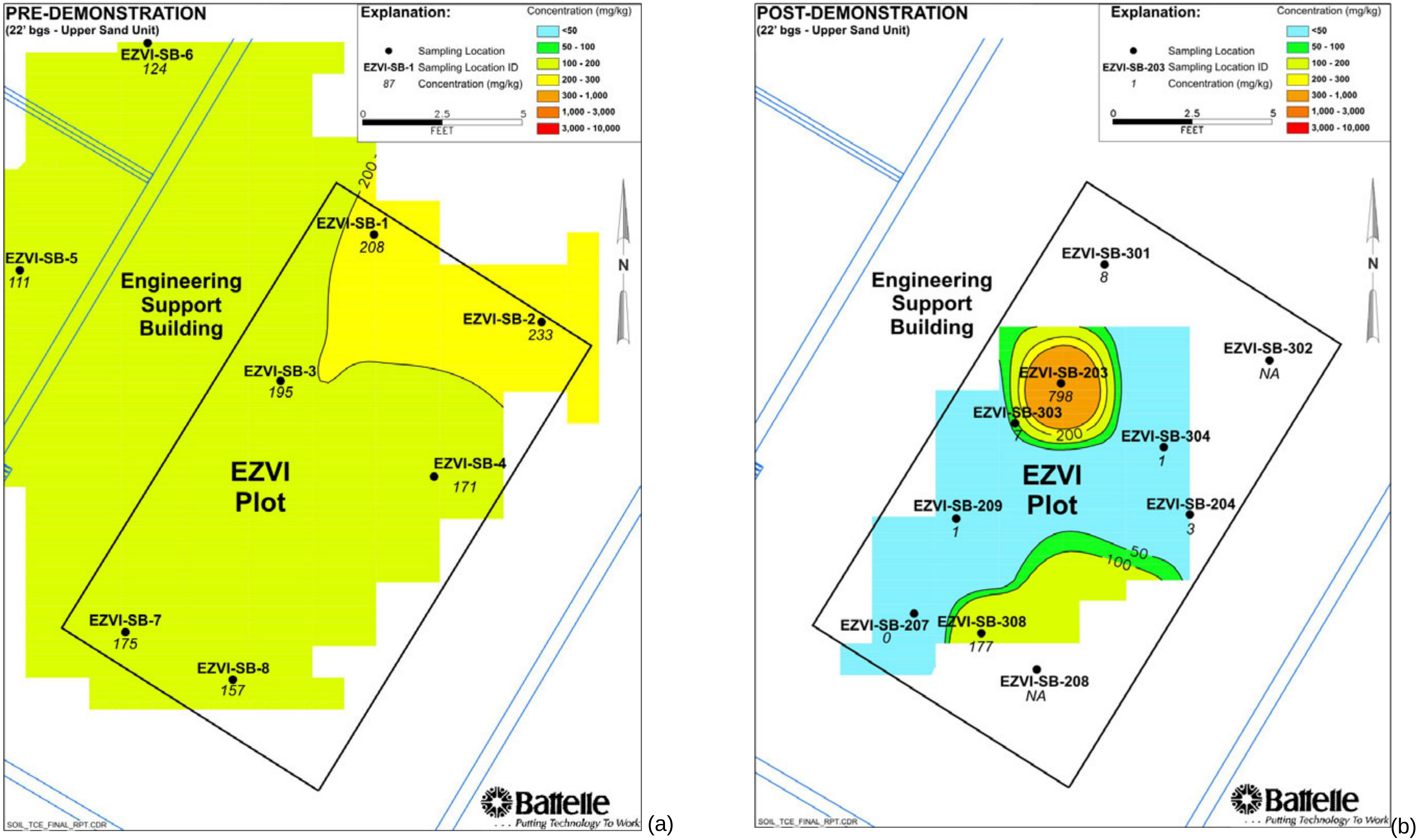


Figure 5-3. Representative (a) Pre-Demonstration (January 2002) and (b) Post-Demonstration (October to November 2002) Horizontal Cross Sections of TCE (mg/kg) in soil at 22 ft bgs in the Upper Sand Unit

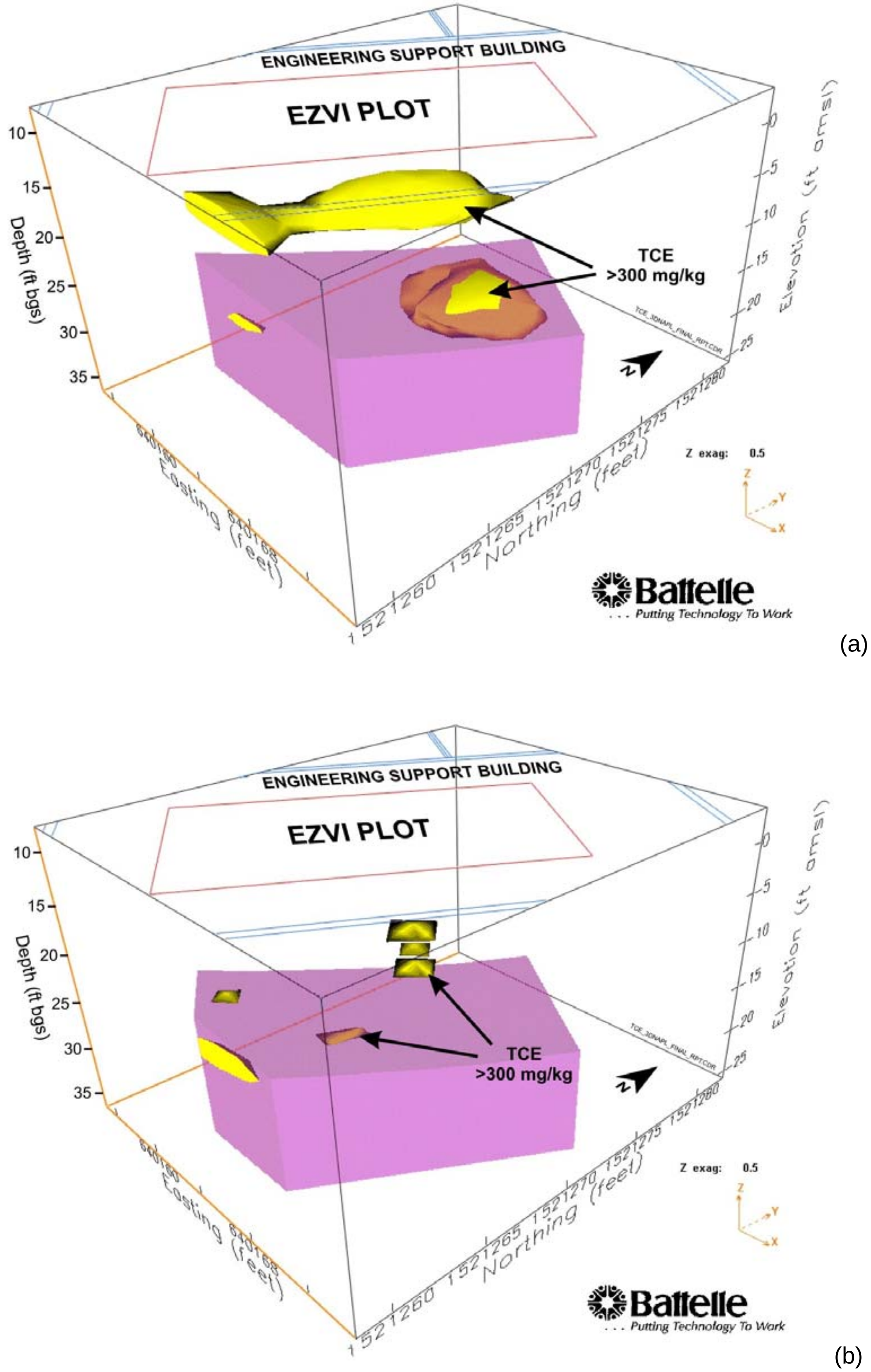


Figure 5-4. 3D Distribution of DNAPL in the EZVI Plot Based on (a) Pre-Demonstration (January 2002) and (b) Post-Demonstration (October to November 2002) Characterization (Purple block is an underlying lithologic unit of Middle Fine-Grained Unit)

One narrow pocket of significant DNAPL (4,502 mg/kg) was found in SB-303 at a depth of 22 to 24 ft bgs. Interestingly, EZVI also was observed at much shallower depths between 10 and 16 ft bgs where EZVI was not intentionally injected, but which reacted with TCE at the shallower depths (see Figure 5-1). This indicates that the EZVI was not evenly distributed laterally and ascended close to the groundwater table, suggesting that EZVI was likely pushed up during the injection.

In summary, a qualitative evaluation of the TCE-DNAPL changes indicates that the injection of EZVI treatment was able to achieve partial decrease of free-phase TCE-DNAPL in some parts of the plot. However, the efficiency of EZVI distribution may need to be improved in order to treat the remaining pockets of DNAPL.

5.1.2 TCE-DNAPL Mass Estimation by Linear Interpolation

Section 4.1.2 describes the use of linear interpolation or contouring to estimate pre- and post-demonstration TCE-DNAPL masses and calculate TCE-DNAPL mass changes within the plot. In this method, EarthVision™, a 3D contouring software, is used to group the TCE concentration distribution in the EZVI plot into 3D shells (or bands) of equal concentration. The concentration in each shell is multiplied by the volume of the shell and the bulk density of the soil to arrive at the TCE mass in that shell. The masses in the individual shells are summed to arrive at a total TCE mass for the entire plot. This process is conducted separately for the pre- and post-demonstration TCE distributions in the test plot. The pre-demonstration TCE-DNAPL mass in the entire plot then can be compared with the post-demonstration mass in the entire plot to estimate the change in TCE-DNAPL mass in the plot. During the post-demonstration characterization, however, one soil sample contained a much higher level of TCE (at 4,502 mg/kg from soil core SB-303 at the depth of 24 ft bgs). This TCE level prompted a concern by the project team on the uncertainties from limited field sampling. After a thorough QA review process eliminated the possibility of errors due to either field sampling or laboratory procedures, it was determined that two sets of scenarios for TCE distribution in soil would be evaluated: TCE mass estimates with and without the highest post-demonstration TCE data point (4,502 mg/kg).

Table 5-1 presents the estimated masses of total TCE and TCE-DNAPL in the EZVI plot and the three individual stratigraphic units. Although the target depth for the EZVI treatment was the Upper Sand Unit, the evaluation was performed in the entire surficial aquifer in order to examine the potential impact of vertical migration from the injection in the Upper Sand Unit. Under pre-demonstration conditions, soil sampling indicated the presence of 17.8 kg of total TCE (dissolved and free phase) in the Upper Sand Unit, approximately 3.8 kg of which was estimated to be TCE-DNAPL. Following the demonstration, soil sampling indicated that 2.6 kg of total TCE remained in the plot, approximately 0.6 kg of which was estimated to be TCE-DNAPL. Therefore, the overall mass removal indicated by contouring was 86% of total TCE and 84% of DNAPL. Without the possible post-demonstration outlier, 1.8 kg of total TCE is estimated to remain in the plot; approximately 0.2 kg of this remaining TCE is DNAPL.

The EZVI treatment is estimated to have removed 86% of total TCE and 84% of TCE-DNAPL in the target treatment zone (i.e., the Upper Sand Unit). The mass reduction percentage was not estimated in the other two stratigraphic units because EZVI was not applied in those lower stratigraphic units. It was only verified that no mass increases were observed in the lower stratigraphic units that could be attributed to DNAPL migration from the treated Upper Sand Unit.

5.1.3 TCE Mass Estimation by Kriging

Section 4.1.3 describes the use of kriging to estimate the pre- and post-demonstration TCE masses in the aquifer.

Table 5-1. Estimated Total TCE and TCE-DNAPL Mass Reduction by Linear Interpolation

	Pre-Demonstration		**Post-Demonstration**		**Change in Mass (%)**	
Stratigraphic Unit	**Total TCE Mass (kg)**	**TCE-DNAPL Mass (kg)**	**Total TCE Mass (kg)**	**TCE-DNAPL Mass (kg)**	**Total TCE**	**TCE-DNAPL**
Upper Sand Unit	17.8	3.8	2.6	0.6	86	84
Upper Sand Unit (without outlier)[(a)]	17.8	3.8	1.8	0.2	90	95
Middle Fine-Grained Unit[(b)]	11.8	1.5	6.9	0.5	N/A	N/A
Lower Sand Unit[(b)]	0.12	0.0	0.10	0.0	N/A	N/A

(a) The highest data point in the post-demonstration TCE data was dropped as a possible outlier.

(b) The last two rows are shaded because any EZVI treatment of the Middle Fine-Grained Unit and Lower Sand Unit was incidental and these two units were not targeted during the injection.

N/A = not applicable.

Although linear interpolation estimates TCE concentrations of unsampled points based on the TCE measurements of discrete sampling point, kriging takes into account the spatial variability and uncertainty of the TCE distribution when estimating TCE concentrations (or masses) at unsampled points. As a result, kriging analysis results provide a range of probable values. Thus, kriging is a good way of obtaining a global estimate for the parameters of interest (such as pre- and post-demonstration TCE masses), when the parameter is heterogeneously distributed.

Appendix A contains a description of the kriging model and results for the TCE distribution in the EZVI plot as well as the statistics summary of the data distribution. Mass estimation by kriging was conducted to evaluate the EZVI technology performance in the heterogeneously distributed TCE contamination source in the Upper Sand Unit. The estimation also was conducted for two sets of scenarios (with and without the highest TCE level from soil samples).

Table 5-2 summarizes the total TCE mass estimates calculated from kriging. The table summarizes an average and range (lower bound and maximum bound) for total TCE only for each stratigraphic unit. Limiting the evaluation to TCE-DNAPL was difficult due to the number of usable data points to those with TCE concentrations greater than 300 mg/kg. Thus, kriging was conducted on total TCE values only to avoid using too few data points for the mass estimates of TCE-DNAPL.

In general, the pre- and post-demonstration total TCE mass ranges estimated from kriging match the total TCE calculated from contouring, which suggests that contouring was able to capture much of the variability of the TCE distribution in the plot despite the relatively small sample size. Kriging results show that the estimated decrease in TCE mass in the plot after the EZVI treatment is between 22 and 100% (58% on average) for the entire data set from the Upper Sand Unit. For the data set without the post-demonstration outlier, the TCE mass reduction is averaged at 73% with the range between 53 and 93%. As described in Appendix A.1, the variability of the data was much greater for the entire data set than for the individual stratigraphic units. As a result, the estimated TCE-DNAPL reduction for the entire plot was quite different from the arithmetic sum of the TCE mass in the individual units. The TCE mass reduction efficiencies in the Middle Fine-Grained Unit and Lower Sand Unit were not quantified because the EZVI treatment was not applied in those stratigraphic units.

In this demonstration of in situ dehalogenation of TCE-DNAPL by EZVI, the range of TCE mass estimation by kriging after the treatment overlaps the TCE mass range before the treatment. The overlapping may be attributed to an insufficient number of soil samples collected before and after the demonstration. This overlap creates some uncertainty in the estimates, as evidenced by the wide range of estimates (22 to 100%) for the change in TCE mass.

5.1.4 Groundwater Mass Flux

Mass flux is a measure of the TCE that dissolves from the source zone and crosses a defined vertical cross-sectional plane in the aquifer. In order to estimate mass flux, defined spatial transects and flow velocity are required. Two transects (upgradient and downgradient) at right angles to the flowpath were selected for the cross-sectional planes. The upgradient transect is composed of the plane determined from five discrete sampling locations of each multilevel sample chamber (EML-3 and EML-4). Similarly, five discrete depths of the downgradient multilevel sampler chambers (EML-1 and EML-2) were used. Groundwater samples were collected *before* (June 2002) and *after* (January 2003) the EZVI treatment in the plot when the recirculation system was operating. Collected groundwater samples were analyzed for CVOCs and ethene (nonchlorinated). Then, analytical results in groundwater (µg/L) from each sampling point

Table 5-2. Estimated Total TCE Mass Reduction by Kriging

	Pre-Demonstration Total TCE Mass			Post-Demonstration Total TCE Mass			Change in Mass		
Stratigraphic Unit	**Average (kg)**	**Lower Bound (kg)**	**Upper Bound (kg)**	**Average (kg)**	**Lower Bound (kg)**	**Upper Bound (kg)**	**Average (%)**	**Lower Bound (%)**	**Upper Bound (%)**
Upper Sand Unit	28	10	46	11.7	2.5	21	58	22	100
Upper Sand Unit (without outlier)(a)	28	10	46	7.5	4.6	10.5	73	53	93
Middle Fine-Grained Unit(b)	6.6	6	8	5.9	5	7	N/A	N/A	N/A
Lower Sand Unit(b)	0.2	0.05	0.4	0.1	0.06	2	N/A	N/A	N/A
Total (Entire Plot)	35.2	16.5	54.5	17.8	8.5	27.1	N/A	N/A	N/A

(a) The highest data point in the post-demonstration TCE data was dropped as a possible outlier.

(b) The last two rows are shaded because any EZVI treatment of the Middle Fine-Grained Unit and Lower Sand Unit was incidental and these two units were not targeted during the injection.

N/A = not applicable.

were converted to a mass discharge in each grid (1-ft wide, 3-ft tall, and 1-ft deep) in molar-based concentrations. The flow velocity used for the mass flux estimation was 0.75 ft/day.

Mass flux estimation was summarized for the extraction and injection transects of the recirculation pathway *before* and *after* the treatment (see Table 5-3). Approximately 1,826 mmoles/day of TCE flux before the treatment decreased to 810 mmoles/day of TCE flux after the treatment in the extraction transect. Note that 56% of reduction in dissolved TCE flux was achieved. Approximately 1,909 mmoles/day of total ethenes were present in the extraction transect before the treatment. The discharge of the ethene mass decreased to 1,461 mmoles/day after the treatment. Mass flux of *cis*-1,2-DCE, VC, and ethene show overall increases in the extraction transect after the treatment.

For the injection transect, the flux change in TCE mass discharge was minimal, as expected, because less EZVI was applied. The TCE mass discharge rate decreased, from 14 mmoles/day before the treatment to 11 mmoles/day after the treatment (21%). However, the total mass discharge rate for total ethenes increased significantly, from 16 mmoles/day before the treatment to 127 mmoles/day after the treatment, which is an increase of 694%. This may suggest that the EZVI injected through wells #3 and #5 (see Figure 3-3) migrated upgradient of the plot and caused both redistribution and degradation of TCE around the plot.

5.1.5 Summary of Changes in the TCE-DNAPL Mass and Mass Flux in the Plot

In summary, the evaluation of TCE concentrations in soil indicates the following:

- In the horizontal plane, the highest pre-demonstration DNAPL contamination was in the western half of the EZVI plot.
- In the vertical plane, the highest pre-demonstration TCE-DNAPL contamination was at the target depths for the injection (between 16 and 26 ft bgs).
- A statistical evaluation for mass estimation by linear interpolation based on TCE in soil shows that the EZVI treatment reduced the original TCE mass by approximately 86%.
- A statistical evaluation for mass estimation by kriging of TCE concentrations in soil from pre- and post-demonstration characterization shows that the EZVI treatment removed between 22 and 100% with the average reduction of 58%. The reduction efficiency estimated by kriging is in a wide range because, unlike contouring, kriging takes into account the uncertainties associated with the pre-demonstration and post-demonstration mass estimates. This range was based on a confidence level of 80%.

5.2 Evaluating Changes in Aquifer Quality

This section describes the changes in aquifer characteristics created by the EZVI application at Launch Complex 34. Aquifer parameters were measured by monitoring conducted before, during, and after the demonstration. Changes in aquifer characteristics were determined by comparing the changes between the pre-demonstration and post-demonstration sampling events. The affected aquifer characteristics are grouped into four subsections:

- Changes in CVOC levels (see Appendix C for detailed results)

Table 5-3. Total Mass Discharge of CVOCs in Groundwater Before and After the Demonstration

	Total Mass Discharge Mass Flux (mmoles/day)				
Transect	**TCE**	***cis*-1.2-DCE**	**VC**	**Ethene**	**Total Ethenes**
		Pre-Demonstration			
EML-1 and EML-2	1,826	83	0	0	1,909
(Extraction Transect)	95.7%	4.3%	0	0	100%
EML-3 and EML-4	14	2	0	0	16
(Injection Transect)	88.2%	11.8%	0.0%	0.0%	100%
		Post-Demonstration			
EML-1 and EML-2	810	438	143	69	1,461
(Extraction Transect)	55.5%	30.0%	9.8%	4.7%	100%
EML-3 and EML-4	11	35	13	69	127
(Injection Transect)	8.7%	27.3%	10.1%	53.9%	100%

The percentage represents a portion of total ethenes as a specified compound.

- Changes in aquifer geochemistry (see Appendix D for detailed results)
- Changes in the hydraulic properties of the aquifer (see Appendix B for detailed results)
- Changes in the aquifer biology.

Table 5-4 lists selected CVOC concentrations in groundwater at the EZVI plot, and Table 5-5 lists levels of various groundwater parameters that indicate aquifer quality and the impact of the EZVI treatment. The tables summarize the levels from pre-demonstration and post-demonstration sampling events. Other important organic and inorganic aquifer parameters are discussed in this subsection.

5.2.1 Changes in CVOC Levels in Groundwater

CVOC levels in groundwater were monitored from wells screened in the Upper Sand Unit, Medium Fine-Grained Unit, and the Lower Sand Unit. A greater number of monitoring wells (i.e., performance assessment and multilevel wells) were screened in the Upper Sand Unit because the EZVI injection was targeted to that zone. General observations are made about CVOC concentrations in groundwater sampled from the intermediate and deep wells, but trends are difficult to identify with the limited data set available.

CVOC levels in groundwater were measured in several shallow wells screened in the Upper Sand Unit, including the performance assessment wells inside the plot (PA-23) and around the perimeter of the plot (PA-24S and PA-25S), in the multilevel wells along the plot edges (EML-1 through EML-4), and in extraction well EEW-1. Table 5-4 shows the changes in TCE, *cis*-1,2-DCE, and VC concentrations in the monitoring wells screened in the Upper Sand Unit. Figures 5-5, 5-6, and 5-7 show dissolved TCE, *cis*-1,2-DCE, and VC concentrations in the shallow wells, respectively, in the EZVI plot and perimeter. Table C-1 of Appendix C tabulates the levels of TCE, *cis*-1,2-DCE and VC in the groundwater in all of the monitoring wells for the EZVI demonstration.

Before the demonstration, concentrations of TCE above or close to the solubility of TCE (1,100,000 µg/L) were detected in PA-23 in the center of the plot and in extraction well EEW-1 just outside the southern edge of the plot. Immediately after the demonstration, TCE concentrations in several of the shallow wells in and around the plot (i.e., PA-23, EEW-1, EML-1, EML-2, and PA-24S) decreased significantly. TCE concentrations in PA-23 decreased from 1,180,000 µg/L to less than 9,000 µg/L after the demonstration. TCE concentrations in EEW-1 decreased from 1,050,000 µg/L to 471,000 µg/L after the demonstration.

Figure 5-5 indicates that the EZVI injection had a positive impact on the concentrations of dissolved TCE in the demonstration plot (i.e., TCE concentrations decreased), and that the impact extended beyond the plot boundary. Some redistribution of TCE due to the injections may have occurred as indicated by a decrease in one perimeter well (PA-24S) and an increase in another perimeter well (PA-25S).

A tenfold increase in *cis*-1,2-DCE was evident in PA-23, from 16,900 µg/L to 169,000 µg/L (see Figure 5-6). A corresponding increase in VC concentrations also was evident in PA-23, where concentrations of VC increased from less than 1,000 µg/L to 21,600 µg/L (see Figure 5-7). The groundwater standard for VC is 1 µg/L, and was exceeded in the majority of the wells both before and after the demonstration.

Table 5-4. CVOCs in Groundwater in the EZVI Plot Before and After the Demonstration

	TCE (µg/L)		*cis*-1,2-DCE (µg/L)		Vinyl Chloride (µg/L)	
Well ID	Pre-Demonstration	Post-Demonstration	Pre-Demonstration	Post-Demonstration	Pre-Demonstration	Post-Demonstration
PA-23	1,180,000	8,790	16,900	169,000	<1,000	21,600
EEW-1	1,050,000	471,000	67,100	80,100	<1,000	6,980
EML-1	450,000	76,000	11,000	96,000	<500	29,000
EML-2	350,000	23,000	21,000	130,000	<500	20,000
EML-3	1,300	74,000	<100	41,000	<100	500
EML-4	1,600	24,000	130	42,000	<20	1,500
PA-24S	772,000	12,100	47,400	31,700	<1,000	1,580
PA-25S	71,300	129,000	69,200	42,800	<1,000	75J

J = Estimated value; below reporting limit.
Pre-demonstration: March 2002; Post-Demonstration: November 2002

Table 5-5. Groundwater Parameters in the EZVI Plot Before and After the Demonstration

Groundwater Parameter (mg/L)	Applicable Groundwater Standard[(a)] (mg/L)	Aquifer Depth[(b)]	Pre-Demonstration (mg/L)[(c)]	Post-Demonstration (mg/L)[(c)]
pH	Not applicable	Shallow	6.4 to 6.6	6.4 to 7.1
		Intermediate	6.8	7.1 to 7.2
		Deep	6.8	6.9 to 7.0
ORP (mV)	Not applicable	Shallow	+15 to +148	–17 to +106
		Intermediate	+33 to +83	+11 to +55
		Deep	+15 to +71	+3 to +40
DO	Not applicable	Shallow	0.3 to 1.0	0.0
		Intermediate	0.6 to 0.9	0.0
		Deep	0.9 to 1.0	0.0
Conductivity (mS/cm)	Not applicable	Shallow	0.15 to 0.22	0.12 to 0.24
		Intermediate	0.21 to 0.22	0.19 to 0.28
		Deep	0.16 to 0.33	0.28 to 0.30
Calcium	Not applicable	Shallow	138 to 184	72 to 240
		Intermediate	66 to 935	49 to 59
		Deep	60 to 104	59 to 87
Magnesium	Not applicable	Shallow	15 to 27	17 to 58
		Intermediate	65	59 to 66
		Deep	53 to 72	59 to 66
Alkalinity as $CaCO_3$	Not applicable	Shallow	320 to 475	208 to 669
		Intermediate	342 to 363	341 to 391
		Deep	222 to 320	267 to 316
Chloride	250	Shallow	177 to 244	128 to **294**
		Intermediate	**359** to **463**	**277** to **581**
		Deep	**353** to **848**	**572** to **722**
Manganese	0.05	Shallow	**0.099** to **0.21**	0.019 to **0.65**
		Intermediate	0.046 to **0.15**	0.026 to **0.057**
		Deep	0.039 to **0.089**	0.024 to 0.035
Dissolved Iron	0.3	Shallow	**7.2** to **27**	**3.0** to **16**
		Intermediate	**2.7** to **5.5**	**1.8** to **2.6**
		Deep	**1.1** to **2.4**	**0.9** to **3.1**
Total Iron	0.3	Shallow	**7.3** to **22**	**2.5** to **17**
		Intermediate	**1.5** to **6.0**	**1.8** to **2.6**
		Deep	**1.2** to **3.1**	**1.0** to **4.2**
Dissolved Silica	Not applicable	Shallow	20.4 to 32.1	44.1 to 92.2
		Intermediate	38.4 to 54.6	65.8 to 87.1
		Deep	37.8 to 53.5	61.2 to 76.4
TDS	500	Shallow	**947** to **1,230**	**663** to **1,470**
		Intermediate	**1,120** to **1,290**	**1,040** to **1,460**
		Deep	**1,100** to **1,670**	**1,450** to **1,600**
BOD	Not applicable	Shallow	<3.0 to 7.0	5.0 to 148
		Intermediate	6.0 to 10.0	<3.0 to 5.0
		Deep	<6.0 to 6.0	<3.0 to 4.0
TOC	Not applicable	Shallow	55 to 154	21 to 85
		Intermediate	54 to 87	19 to 28
		Deep	18 to 66	19 to 21
Potassium	Not applicable	Shallow	116 to 299	87 to 170
		Intermediate	52 to 56	27 to 29
		Deep	17 to 50	20 to 46
Sodium	160	Shallow	34 to 99	62 to 73
		Intermediate	**232** to **280**	**195** to **312**
		Deep	**174** to **443**	**257** to **374**
Phosphate	Not applicable	Shallow	<3.0	<0.5
		Intermediate	<6.0	<0.5
		Deep	<3.0	<0.5

Table 5-5. Groundwater Parameters in the EZVI Plot Before and After the Demonstration (continued)

Groundwater Parameter (mg/L)	Applicable Groundwater Standard[(a)] (mg/L)	Aquifer Depth[(b)]	Pre-Demonstration (mg/L)[(c)]	Post-Demonstration (mg/L)[(c)]
Bromide	Not applicable	Shallow	<2.0	0.41J to 3.8
		Intermediate	<4.0	0.36J to 1.1
		Deep	<2.0 to 22.9	1.4 to 5.5
Total Nitrate/Nitrite as N	10	Shallow	NA	<0.5 to 0.84
		Intermediate	NA	<0.5
		Deep	NA	<0.5
Sulfate	250	Shallow	90.7 to 164	1.4J to 118
		Intermediate	100 to 136	77.5 to 112
		Deep	58.0 to 89.6	61.6 to 73.9

(a) State of Florida drinking water standards for organic contaminants (TCE, *cis*-1,2-DCE, VC), inorganic contaminants (sodium, total nitrate/nitrite) and secondary drinking water standards (iron, manganese, chloride, sulfate, pH, TDS)

(b) Shallow well screens are located in the Upper Sand Unit; intermediate well screens are located in the Middle Fine-Grained Unit; and deep well screens are located in the Lower Sand Unit.

(c) All reported quantities are in mg/L, except for pH, which is in log units, ORP, which is in mV, and conductivity in mS/cm.

J = Estimated value but below reporting limit.

NA = Not analyzed.

Bold face denotes that the level exceeds Florida cleanup standards for groundwater.

The significant accumulation of *cis*-1,2-DCE and VC in groundwater suggests that multiple TCE degradation mechanisms may have been stimulated by the EZVI injection. Abiotic degradation of TCE by zero-valent iron primarily bypasses the formation of *cis*-1,2-DCE and VC and results in the direct formation of ethene (Roberts et al., 1996). On the other hand, biological degradation of TCE, as may be stimulated by the addition of an electron donor source (e.g., the vegetable oil portion of the EZVI), would result in significant generation of *cis*-1,2-DCE and VC. Other evidence of this type of anaerobic biodegradation is described in Section 5.2.2. The generation of ethene, *cis*-1,2-DCE, and VC in substantial quantities indicates that the EZVI causes TCE degradation through multiple pathways.

CVOC concentrations in groundwater sampled at intermediate depths in the Middle Fine-Grained Unit and deep depths in the Lower Sand Unit varied in the perimeter wells (i.e., wells PA-24I/D, PA-25I/D) during post-demonstration characterization (see Table C-1 in Appendix C). In well PA-24I, TCE concentrations decreased from 258,000 µg/L to 86,400 µg/L, whereas *cis*-1,2-DCE concentrations in the same well increased from 149,000 µg/L to 181,000 µg/L after the demonstration. In the Lower Sand Unit, TCE concentrations in well PA-24D increased from 469,000 µg/L to 656,000 µg/L, and *cis*-1,2-DCE levels also increased from 61,800 µg/L to 99,400 µg/L after the demonstration. Outside the western edge of the plot in well PA-25, TCE concentrations increased from 534,000 µg/L to 944,000 µg/L at intermediate depths (i.e., well PA-25I), whereas *cis*-1,2-DCE concentrations decreased from 116,000 µg/L to 90,900 µg/L. At deep depths, TCE concentrations increased from 2,800 µg/L in well PA-25D to 53,200 µg/L after the demonstration, and *cis*-1,2-DCE levels increased from 60,800 µg/L to 117,000 µg/L. The increase in TCE concentrations observed in groundwater sampled from the perimeter monitoring wells suggests that some unexpected redistribution of TCE may be occurring in the aquifer. The groundwater data set from the Middle Fine-Grained Unit and the Lower Sand Unit is too limited to determine if CVOCs migrated downward as a result of the EZVI injections. Soil data indicate that there is no increasing trend in the Lower Sand Unit.

Section C-5 in Appendix C contains the results of groundwater sampling conducted in the test plot after one year of EZVI injection. This long-term sampling showed that TCE, *cis*-1,2-DCE, and (eventually) vinyl chloride levels continued to decline sharply for several months.

5.2.2 Changes in Aquifer Geochemistry

Among the field parameter measurements (tabulated in Table 5-5 and Appendix D) conducted in the affected aquifer before, during, and after the demonstration, the following trends were observed:

- Groundwater *pH* in the shallow wells increased slightly, from 6.4 to 6.6 before the demonstration to 6.4 to 7.1 after the demonstration, and reached a peak of 7.2 during the demonstration (see Table D-1 in Appendix D). The same increasing trend was observed in the intermediate and deep wells. Much greater pH increase was expected because the corrosion of zero-valent iron in water

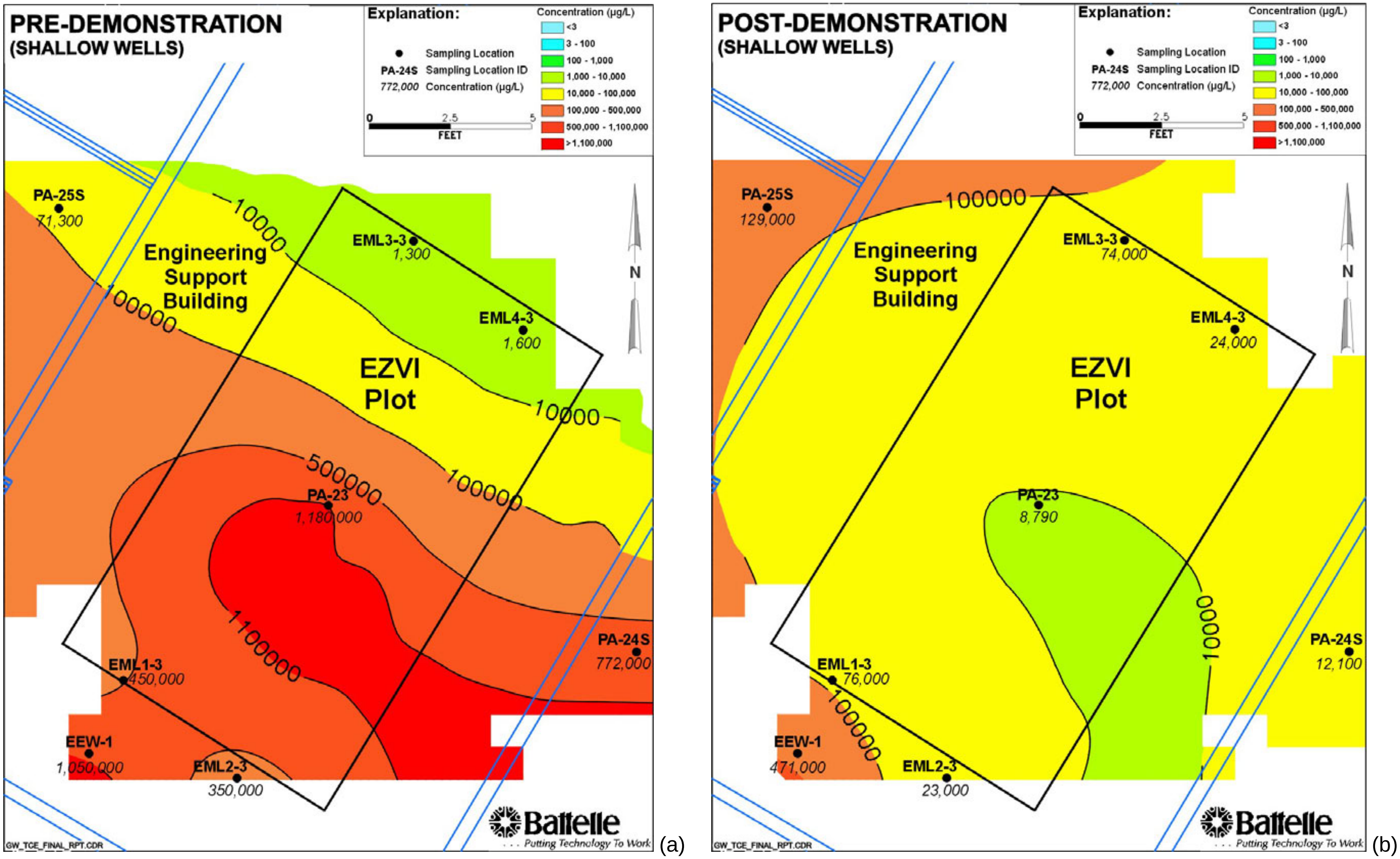


Figure 5-5. Dissolved TCE Concentrations (µg/L) during (a) Pre-Demonstration (March 2002) and (b) Post-Demonstration (November 2002) Sampling of Shallow Wells

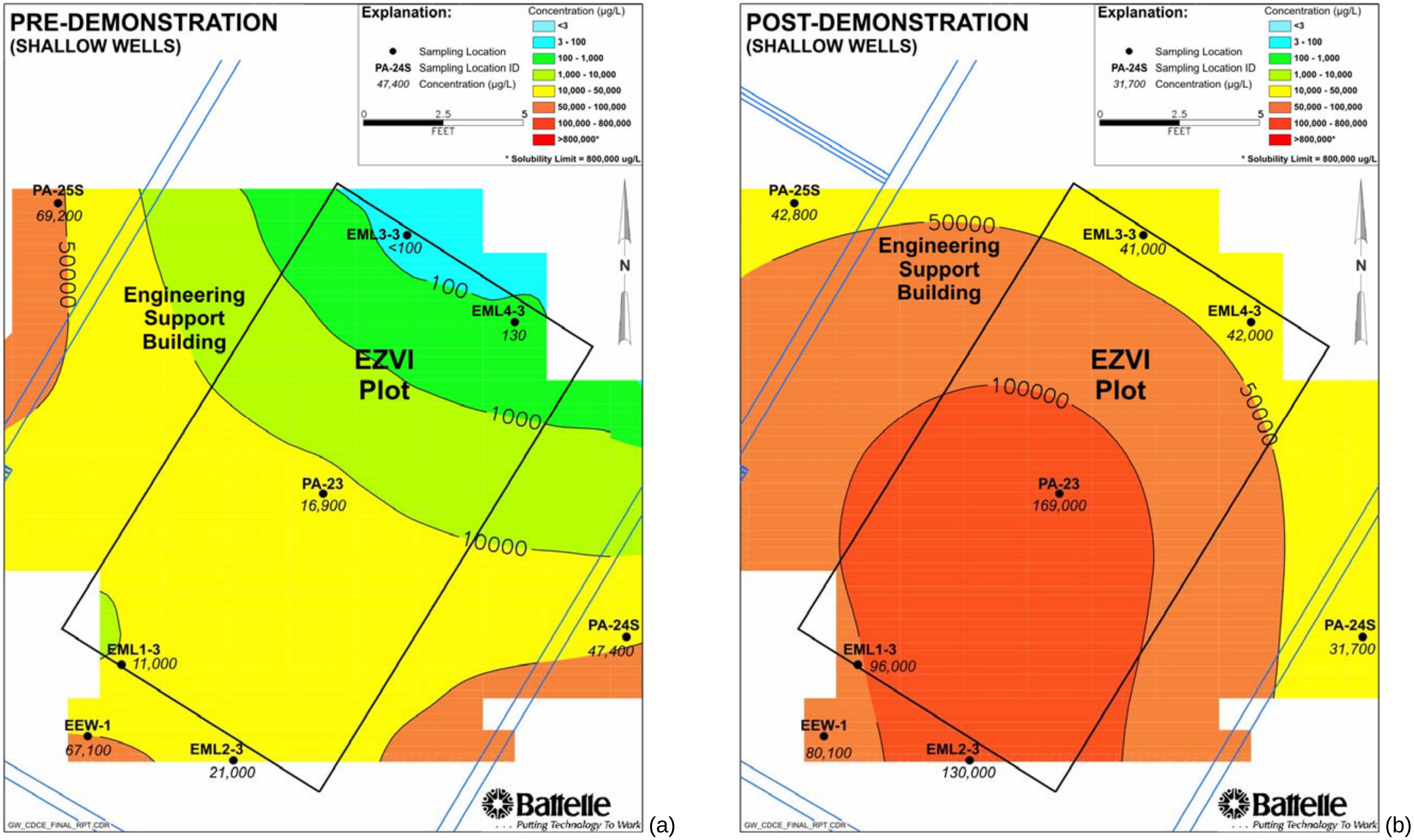


Figure 5-6. Dissolved *cis*-1,2-DCE Concentrations (µg/L) during (a) Pre-Demonstration (March 2002) and (b) Post-Demonstration (November 2002) Sampling of Shallow Wells

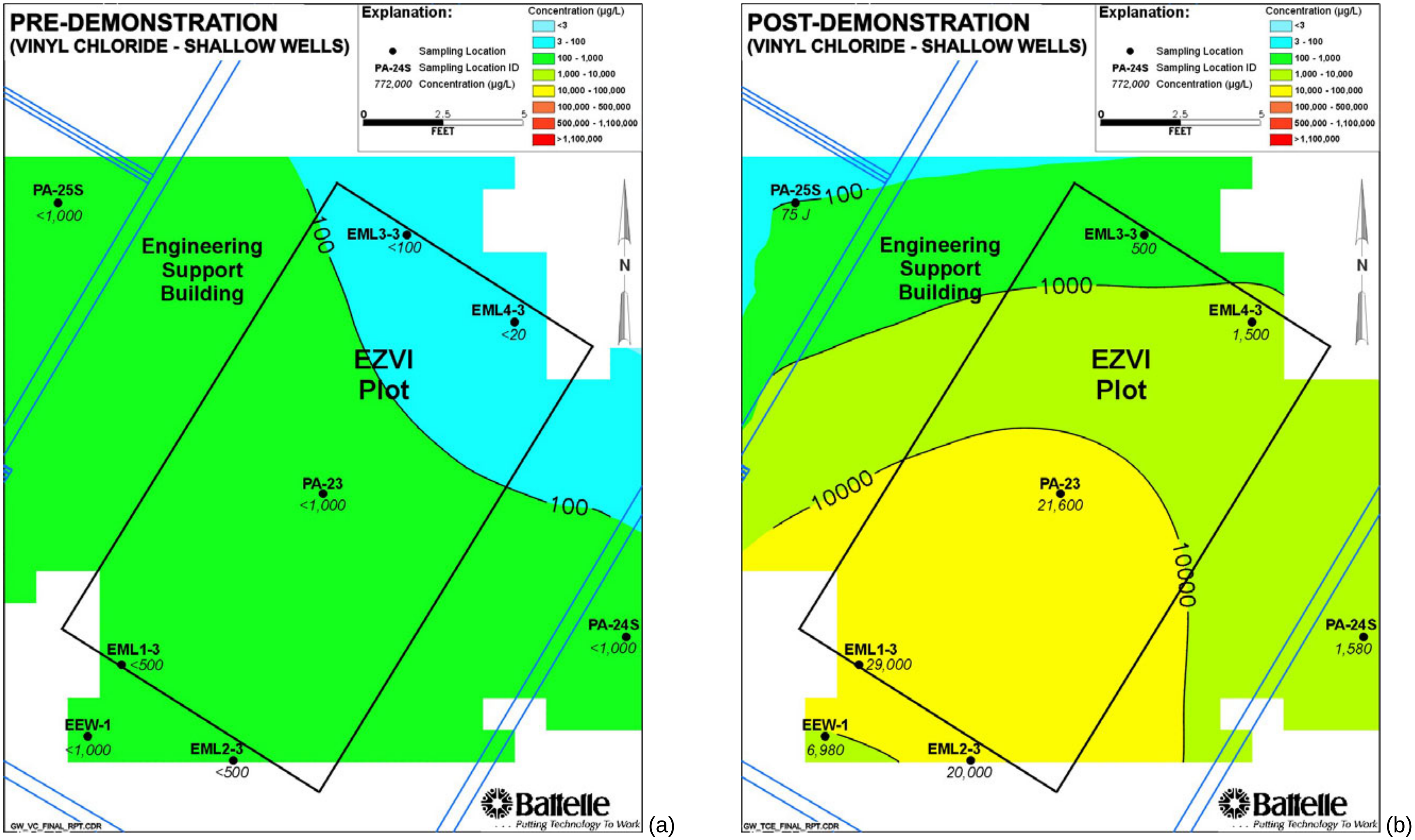


Figure 5-7. Dissolved Vinyl Chloride Concentrations (µg/L) during (a) Pre-Demonstration (March 2002) and (b) Post-Demonstration (November 2002) Sampling of Shallow Wells

produces excess electrons, which then react with water to produce hydrogen gas and OH^-.

At some sites where zero-valent iron has been used for groundwater treatment, pH increases of up to 10 or 11 have been reported (Battelle, 2002c). This indicates that the iron in the EZVI influences the aquifer environment, but does not create strongly reducing conditions.

- *ORP* decreased in the center of the test plot (i.e., well PA-23) from +31 mV before the demonstration to −143 mV during the demonstration (see Table D-1 in Appendix D). The drop in ORP is indicative of reducing conditions created in the plot immediately after the EZVI injection. The ORP in well PA-23 showed a net decrease to −17 mV during the post-demonstration characterization. The same trend was observed in all of the perimeter wells (i.e., PA-24S/I/D and PA-25S/I/D), indicating that the EZVI injection influenced the reduction potential of groundwater throughout the test plot aquifer, but did not generate strongly reducing conditions.
- *DO* decreased from a maximum of 1.0 mg/L before the demonstration to 0.0 mg/L after the demonstration. The decrease in DO is expected as both zero-valent iron and vegetable oil deplete dissolved oxygen in the groundwater. This decreasing trend in dissolved oxygen concentrations was observed in all wells regardless of location or depth (see Table D-1 in Appendix D). Due to the limitations of measuring DO with a flowthrough cell, groundwater with DO levels below 1.0 mg/L is considered anaerobic. All three hydrologic units of the shallow aquifer (i.e., the Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit) were anaerobic for the duration of the demonstration.
- *Conductivity* in the Upper Sand Unit increased from approximately 0.2 mS/cm before the demonstration to 1.8 mS/cm during the demonstration (see Table D-1 in Appendix D). The increase is attributed to a buildup of dissolved ions formed from the mineralization of organic matter and CVOCs. Conductivity does not appear to have increased as a result of adding iron particles to the subsurface because both dissolved and total iron concentrations in groundwater decreased after the technology demonstration.

Other groundwater measurements indicative of aquifer quality included inorganic ions, BOD, and TOC. The results of these measurements are as follows:

- *Dissolved iron* concentrations in well PA-23 in the center of the test plot decreased from 15.7 mg/L to 3.0 mg/L after the demonstration. Decreases also were observed in the shallow wells around the perimeter of the plot (i.e., PA-24S and PA-25S). Dissolved iron concentrations at intermediate and deep depths decreased during the demonstration and then rose during post demonstration characterization, but remained below pre-demonstration concentrations. The secondary drinking water limit for iron is 0.3 mg/L, which was exceeded before, during, and after the demonstration. Precipitation of ferric iron on soil was not visually seen (as tan color) during post-demonstration characterization, but a full microscopic analysis of the soil was not conducted to verify the presence of iron precipitates. The relatively high levels of dissolved iron before EZVI injection and their subsequent decrease are somewhat contrary to the expected trend.
- *Total iron* concentrations in all of the wells were very similar to dissolved iron concentrations, indicating that dissolved iron is the dominant form in groundwater. It suggests that nanoscale iron particles used in EZVI pass through 0.45 µm-size filter. The trends in total iron concentrations mimicked those of dissolved iron, with substantial decreases seen during the demonstration, and then slight increases in total iron concentrations during post-demonstration characterization. The secondary drinking water limit for iron is 0.3 mg/L, which was exceeded before, during, and after the demonstration in all wells.
- *Calcium, magnesium,* and *alkalinity* levels measured in the shallow center well (PA-23) of the test plot remained relatively steady or increased slightly. Evidence of microbial respiration was seen in the dramatic increases in dissolved methane gas, from 0.013 mg/L before the demonstration to 0.55 mg/L after the demonstration. Methane concentrations also increased in the perimeter wells at all depths and in the injection and extraction wells EIW-1 and EEW-1 (Table D-5 in Appendix D).
- *Chloride* levels were already relatively high in the aquifer before the demonstration (in PA-23, PA-24, and PA-25) and do not appear to have changed significantly after the EZVI treatment. The secondary MCL for chloride in drinking water is 250 mg/L, which was exceeded in several wells both before and after the demonstration.

  Chloride concentrations also were measured using a Waterloo Profiler® in two locations in the test plot at various depths. As seen in Table D-4 (in Appendix D) and illustrated in Figure 5-8, chloride concentrations, as measured in the Waterloo Profiler® samples, remained relatively steady with a slight increasing trend.

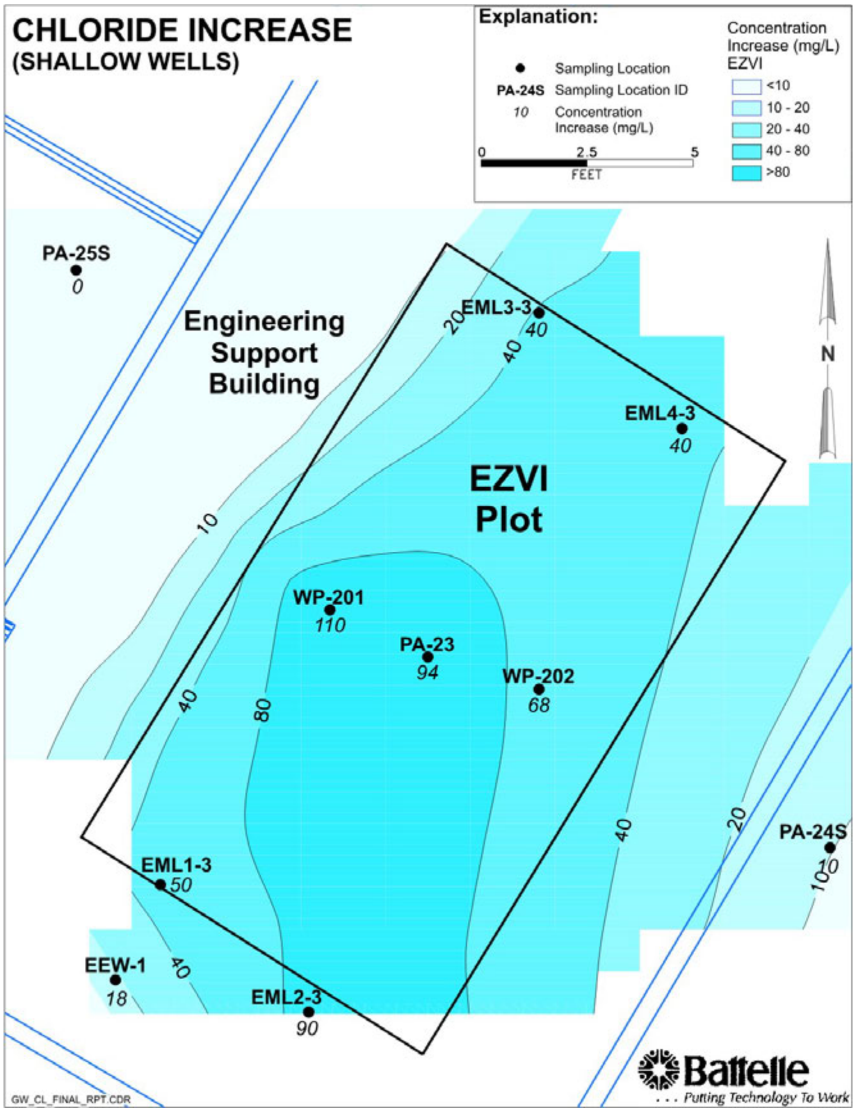


Figure 5-8. Chloride Increases Produced by the EZVI Treatment in Shallow Wells in and Around the Demonstration Plot

The Waterloo Profiler® data collected at discrete depths provide better support for reductive dechlorination (biotic) and/or abiotic degradation of TCE occurring inside the test plot in the Upper Sand Unit than the depth-averaged data from the monitoring wells.

- *Sulfate* levels in PA-23 increased slightly from 103 mg/L to 147 mg/L during the demonstration, and then decreased significantly after the demonstration to 13 mg/L. Sulfate levels in the perimeter wells and at deeper depths displayed minor fluctuations in sulfate but did not change significantly. Sulfate concentrations in PA-23 may have decreased after the demonstration due to an increase in a sulfate-reducing microbial organism population, which mediate electron transfer reactions that reduce sulfate.
- *Sodium* and *potassium* levels remained relatively constant in the aquifer during the demonstration.
- *Manganese* levels in well PA-23 decreased from 0.12 mg/L before the demonstration to 0.05 mg/L during the demonstration. After the demonstration, manganese concentrations rose to pre-demonstration levels of 0.12 mg/L. In the injection well (EIW-1), manganese concentrations rose from pre-demonstration levels of 0.21 mg/L to 0.65 mg/L after the demonstration, and manganese levels rose from 0.15 mg/L to 0.21 mg/L in the extraction well (EEW-1) after the demonstration. In general, manganese concentrations in the perimeter wells decreased during the demonstration and then rose slightly during post-demonstration characterization. Manganese levels exceeded the secondary drinking

water standard of 0.05 mg/L both before and after the demonstration; Mn^{2+} is not a health hazard, but can cause discoloration of the water at concentrations greater than 0.05 mg/L.

- *TDS* levels remained relatively unchanged by the EZVI demonstration. However, a significant decrease in TDS occurred in PA-25S, where TDS levels decreased from 1,230 mg/L before the demonstration to 663 mg/L after the demonstration. The low TDS level after the demonstration in PA-25S is somewhat anomalous with respect to the trends in all the other wells.
- *TOC* concentrations decreased in the majority of the monitoring wells after the demonstration. In PA-23, TOC concentrations decreased from 150 mg/L to 77 mg/L. In the shallow perimeter wells (PA-24S and PA-25S), TOC levels decreased from 108 mg/L and 114 mg/L to 45 mg/L and 21 mg/L, respectively. The decrease in TOC levels is somewhat anomalous, as the addition of vegetable oil would tend to increase groundwater TOC levels. The decreases in TOC are possibly the result of dissolution (mass transfer) of organic matter from the water phase to the EZVI oil phase.
- *BOD* levels in well PA-23 increased from below the detection limit (3 mg/L) up to 148 mg/L after the demonstration. Similar increases were seen in the injection and extraction wells (EIW-1 and EEW-1). This indicates that the vegetable oil portion in the EZVI emulsion is releasing as the emulsion is partitioning. The BOD results in the perimeter wells were difficult to interpret. In general, BOD levels remained relatively unchanged in the perimeter wells with the exception of PA-24S, where a large increase in BOD was observed. PA-24S also was the perimeter well where a large decrease in TCE concentration was observed.

5.2.3 Changes in Hydraulic Properties of the Aquifer

Slug tests were performed in well PA-23 in the center of the EZVI plot before and after the demonstrations to assess any effects on aquifer quality caused by the remediation technology. The remediation systems were applied to just the Upper Sand Unit, so slug tests were only performed in the shallow performance monitoring well in the center of the plot (PA-23) (see Appendix B). Pre-demonstration hydraulic conductivity averaged 43 ft/day (0.015 cm/sec) in well PA-23. Post-demonstration hydraulic conductivity averaged 38.2 ft/day (0.013 cm/sec). There was no substantial difference in the hydraulic conductivity due to the EZVI treatment. A change of 10 times or greater would indicate a substantial change in permeability at the site. Any buildup of iron oxides or vegetable oil due to the remediation technology does not seem to have affected the hydraulic properties of the aquifer.

5.2.4 Changes in Biology of the EZVI Plot

This section summarizes microbial characteristics of the aquifer observed in groundwater parameters after the EZVI treatment. Comparing the microbial characteristic parameters such as BOD, dissolved methane gas, and sulfate concentrations was used to determine the changes in biology of the EZVI plot:

- *BOD* concentrations in the Upper Sand Unit increased from <3 mg/L before the demonstration up to 148 mg/L after the demonstration, which indicates an increase in bioavailable organic matter, probably from the oil that partitions from the EZVI emulsion.
- *Sulfate* concentrations in PA-23 decreased from 103 mg/L to approximately 13 mg/L after the demonstration. The addition of vegetable oil to the aquifer as part of the EZVI mixture (i.e., a carbon source) may have stimulated growth of sulfate-reducing bacteria in the target depth of the Upper Sand Unit.
- *Polymerase chain reaction* (PCR) analysis indicates that the result from PA-23 shows not only a detection of *Dehalococcoides* group organisms, but also very high band intensity (see Table D-8 in Appendix D), which suggests that indigenous dehalorespiring microorganism in the aquifer may have enhanced the degradation of TCE. *Dehalococcoides* are known for their capability to dehalorespirate and dehalogenate TCE stepwise to less toxic products such as *cis*-1,2-DCE and VC and to nontoxic ethene (Major et al., 2002). The microorganisms appear to have grown in the anaerobic respiration environment created after the EZVI emulsion was applied in the target depth.
- Increases in *methane* concentrations also may indicate increased microbial activity from the indigenous microorganisms in the Upper Sand Unit beneath the test plot. As the *Dehalococcoides* microorganisms use inorganic chemicals as electron acceptors, methane byproduct gas is produced. Methane concentrations in PA-23 increased approximately 40 times, from 0.013 mg/L before the demonstration to 0.55 mg/L after the demonstration (see Table D-5 in Appendix D). Methane concentrations also increased in extraction well EEW-1 and in injection well EIW-1, from

0.016 mg/L and 0.015 mg/L respectively, to 0.98 mg/L and 0.61 mg/L, respectively, after the demonstration.

Although other direct detection methods of microbial activity (i.e., microbial population counting or live/dead stain test, or, PLFA analysis) were not used as part of the performance assessment, the use of indirect parameters such as BOD, methane, and sulfate concentrations and the PCR analysis suggests that the EZVI technology led to increased microbial activity in the Upper Sand Unit.

5.2.5 Summary of Changes in Aquifer Quality

In summary, the following changes in the aquifer occurred after application of the EZVI technology:

- TCE concentrations declined in the Upper Sand Unit of the demonstration area following the EZVI treatment. In the center well of the test plot (PA-23), TCE levels decreased from 1,180,000 µg/L to 8,790 µg/L. The level of *cis*-1,2-DCE rose tenfold, from 16,900 µg/L to 169,000 µg/L. VC concentrations in PA-23 increased from <1,000 µg/L to 21,600 µg/L after the demonstration. Ethene levels increased from 76 µg/L to 1,680 µg/L. The increases in *cis*-1,2-DCE and VC concentrations during the demonstration suggests that TCE in groundwater probably degraded through multiple mechanisms, including anaerobic reductive dechlorination (biotic) and abiotic reduction. These mechanisms probably are driven by the presence of the vegetable oil and zero-valent iron, respectively. Despite the difficulties encountered in injecting and distributing the EZVI mixture, the groundwater data indicate that the EZVI technology was effective in reducing TCE concentrations.
- ORP and dissolved oxygen levels decreased in the demonstration area after the EZVI injection. This indicates that strongly reducing anaerobic conditions were created in the Upper Sand Unit during the demonstration. Groundwater pH in the shallow wells increased from 6.4 to 6.6 before the demonstration to 7.0 to 7.2 during the demonstration. The increasing pH trend is the result of the production of OH^- as zero-valent iron corrodes in water.
- Anomalously, dissolved iron concentrations in well PA-23 in the center of the test plot decreased after the EZVI injection. Precipitation of ferric iron on soil was not visually seen (as tan color) during the post-demonstration characterization, but a full microscopic analysis of the soil was not conducted to verify the presence of precipitates. Total iron concentrations in all of the wells were very similar to dissolved iron concentrations, indicating that the nanoscale iron, a component of EZVI, is probably recognized as a dissolved form in groundwater samples. The secondary drinking water limit for iron is 0.3 mg/L, which was exceeded in all wells at all depths before, during, and after the demonstration.
- Chloride levels, which were already high due to saltwater intrusion in the aquifer, remained relatively constant in the monitoring wells, but increased slightly in the Waterloo Profiler® samples. Chloride increases suggest reductive dechlorination of the TCE occurred, which was supported by increases in *cis*-1,2-DCE and VC seen during post-demonstration characterization.
- Increases in dissolved methane, as well as decreases in sulfate concentrations, suggest an increase in biological activity occurred as a result of the EZVI injection. Methane is a common byproduct of microbial respiration. A decrease in sulfate concentrations may be the result of a stimulation of sulfate-reducing bacteria. BOD levels in the groundwater increased, indicating an increase in the bioavailable organic matter in the aquifer due to partial dissolution of oil from the EZVI. TOC levels decreased, probably due to dissolution of some organic matter in the EZVI oil phase.
- Hydraulic conductivity of the Upper Sand Unit does not appear to have been affected by the EZVI treatment, suggesting that the injected EZVI did not plug the aquifer. There were no substantial changes in permeability in the test plot according to slug tests conducted in the center well before and after the demonstration.

5.3 Evaluating the Fate of the TCE-DNAPL Mass

Determining the fate of the TCE-DNAPL mass following treatment is a difficult task because the TCE-DNAPL could have taken several pathways when subjected to the EZVI treatment. The pathways evaluated for this performance assessment included abiotic reductive dechlorination of TCE, microbial reductive dechlorination, and migration from the plot to the surrounding regions.

5.3.1 Abiotic Reductive Dechlorination of TCE

As shown on Figure 1-8, reductive dechlorination of TCE and other CVOCs by zero-valent iron particles leads to the formation of chloride, hydroxyl ions, and dissolved gases such as ethene and ethane. Any iron oxide that may be generated would be insoluble in water and is expected to deposit on the soil surfaces; however, no visual evidence of iron oxide formation (tan color) was observed during the post-demonstration soil characterization event. The soluble or partially soluble species — chloride and hydrogen ions (pH) — are more amenable to more direct measurement. Although minor amounts of *cis*-1,2-DCE and VC may be generated due to the abiotic iron mechanism, ethene and chloride are by far the predominant products of abiotic β-elimination reactions (Roberts et al., 1996).

Chloride is one of the strongest indicators of TCE dehalogenation because it is directly traceable to TCE. Although its level is relatively high in the aquifer, seawater intrusion is not expected to increase chloride level from tidal influences over the time period of the demonstration because the treatment was applied in the shallowest unit of the surficial aquifer (i.e., the Upper Sand Unit). Chloride generation due to reductive dechlorination would be expected to cause chloride levels to rise in the aquifer. Tables D-2 and D-4 in Appendix D show the pre- and post-demonstration chloride levels in the EZVI plot and surrounding aquifer. Chloride changes were not very obvious in the monitoring wells, but a slight increase in chloride levels was noticeable in the water samples from the Waterloo Profiler®.

Figure 5-8 shows the increase in chloride concentrations in the shallow wells that occurred after the EZVI treatment was complete (i.e., from pre-demonstration levels to post-demonstration levels); decreases in chloride are represented as zero. A decrease was observed in PA-25S (see Appendix D, Table D-2). The strongest increase in chloride was observed in PA-23 (Upper Sand Unit), where the pre-demonstration DNAPL mass was highest. The data suggest that most of the chloride increase in the test plot is attributable to reduction of TCE by the EZVI injection, for the following reasons: (1) The significant reduction in dissolved TCE that was measured in the test plot wells after the EZVI was injected. (2) The reduction in soil TCE concentrations that was seen during the intermediate soil sampling event (after the EZVI injection and prior to post-demonstration characterization). (3) The absence of continued significant reduction between the intermediate and post-demonstration soil sampling events indicates that the TCE in the areas nearest the EZVI was reduced as much as possible by the available EZVI mixture soon after injection.

A change in *groundwater pH* can be seen as an indirect indication of abiotic reductive dechlorination. As excess electrons are produced from the corrosion of zero-valent iron in water, hydrogen gas is produced from the following reaction:

$$2H_2O + 2e^- \rightarrow H_{2(gas)} + 2OH^- \qquad (5\text{-}1)$$

The OH^- produced from this reaction results in an increase in the pH of the surrounding water. An increase in pH was observed in the shallow wells in the test plot and around the perimeter from approximately 6.5 (pre-demonstration) to approximately 7.1 during the demonstration. The observed increase in pH is much smaller than the increase (up to pH 10 or 11) that has been observed during groundwater treatment with zero-valent iron at other sites. However, this may be due to the fact that the iron is sequestered in the oil. The effect of the EZVI technology on pH was short-lived, because pH levels returned to pre-demonstration levels by the time post-demonstration characterization was conducted. The drop in pH levels after the demonstration would be expected because, as the iron is exhausted, the production of hydrogen gas and OH^- slows, allowing the natural pH of the aquifer to be reestablished.

Dissolved hydrogen gases, such as ethene and ethane, are indications of TCE degradation. Ethene and end-product ethane are produced along the degradation pathways for TCE by zero-valent iron (see Figure 1-8). Ethene and ethane concentrations increased between pre- and post-demonstration groundwater sampling events in well PA-23 in the center of the test plot, and also in the injection and extraction wells (i.e., EIW-1 and EEW-1) at the edge of the test plot (see Table 5-6).

5.3.2 Microbial Reductive Dechlorination of TCE

The performance assessment of the EZVI technology suggested that biological reduction of TCE may have occurred in the test plot after the EZVI was injected and then continued until post-demonstration characterization was conducted. Although biological reduction of TCE was not considered prior to the demonstration based on the results of the laboratory investigation of EZVI by UCF, the use of vegetable oil in the emulsion would provide a carbon source (i.e., electron donor) to microbial species present in the subsurface.

Dissolved methane concentrations increased significantly in the shallow wells between pre- and post-demonstration characterization. Table 5-7 shows dissolved methane concentrations in groundwater during pre- and post-demonstration characterization events, and also one sampling event conducted during the technology demonstration. Methane concentrations also rose slightly in the perimeter wells at intermediate and deep depths, indicating that microbial activity may have increased in all three hydrostratigraphic units (i.e., the Upper Sand Unit, Middle Fine-Grained Unit, and the Lower Sand Unit).

Table 5-6. Dissolved Ethene and Ethane Concentrations in the EZVI Plot Before, During, and After the Demonstration

	Ethene (mg/L)			Ethane (mg/L)		
Well ID	**Pre-Demonstration**	**During the Demonstration**	**Post-Demonstration**	**Pre-Demonstration**	**During the Demonstration**	**Post-Demonstration**
EZVI Plot Well						
PA-23	0.076	0.010	1.68	0.002	0.002	0.023
Injection and Extraction Wells						
EIW-1	0.023	NA	0.137	<0.002	NA	<0.002
EEW-1	0.051	NA	0.978	0.004	NA	0.055

Well IDs: S = shallow well (Upper Sand Unit); I = intermediate well (Middle Fine-Grained Unit); D = deep well (Lower Sand Unit).
EIW-1 = injection well; EEW-1 = extraction well.
Pre-demonstration = March 2002; during the demonstration = August 2002; post-demonstration = November 2002.
NA = not analyzed.

Table 5-7. Dissolved Methane Concentrations in the EZVI Plot Before, During, and After the Demonstration

	Methane (mg/L)		
Well ID	**Pre-Demonstration**	**During the Demonstration**	**Post-Demonstration**
EZVI Plot Well			
PA-23	0.013	0.043	0.547
EZVI Perimeter Wells			
PA-24S	0.022	NA	0.140
PA-24I	0.017	NA	0.047
PA-24D	0.013	NA	0.034
PA-25S	0.007	NA	0.012
PA-25I	0.020	NA	0.061
PA-25D	0.005	NA	0.016
Injection and Extraction Wells			
EIW-1	0.015	NA	0.611
EEW-1	0.016	NA	0.978

Well IDs: S = shallow well (Upper Sand Unit); I = intermediate well (Middle Fine-Grained Unit); D = deep well (Lower Sand Unit).
EIW-1 = injection well; EEW-1 = extraction well.
Pre-demonstration = March 2002; during the demonstration = August 2002; post-demonstration = November 2002.
NA = not analyzed.

TCE degradation byproducts in groundwater, such as *cis*-1,2-DCE, *trans*-1,2,DCE, and VC, increased both at shallow depths where the EZVI was injected, and at intermediate and deep depths where there was no visible evidence of the emulsion mixture. Table 5-8 shows the concentrations of TCE degradation byproducts for the pre- and post-demonstration characterization, and for one sampling event conducted during the demonstration. Figure 5-9a presents the correlation between TCE and its degradation products in PA-23, the monitoring well in the center of the test plot. To account for the large difference in scale in Figure 5-9a, the TCE and ethene concentrations also are plotted on Figure 5-9b. The increase in degradation byproducts at depths greater than the target injection zone, coupled with the lack of evidence for EZVI migration below the Upper Sand Unit, suggest that microbial-assisted reductive dechlorination occurred in the Middle Fine-Grained Unit and Lower Sand Unit. The accumulation of VC, particularly in the shallow wells, may indicate that the more recalcitrant compounds need longer timeframes before complete reduction to ethene and ethane can occur. It is difficult to determine the significance of microbial-assisted degradation when compared to abiotic reductive dechlorination using EZVI.

Dehalococcoides, a group of microorganisms known to be capable of reductive dehalogenation at contaminated sites, was detected in groundwater from well PA-23 both before and after the EZVI demonstration by the technology vendor (GeoSyntec, 2003). Although a thorough investigation on the indigenous microbes of the *Dehalococcoides* group was not conducted as part of the EZVI performance assessment, its presence indicates that dehalorespiring microorganisms may have degraded TCE during the demonstration.

5.3.3 Potential for TCE-DNAPL Migration from the EZVI Plot

The following measurements or observations were used to evaluate the potential for TCE-DNAPL migration to the surrounding aquifer:

- Hydraulic gradient in the aquifer
- TCE measurements in perimeter wells
- Evidence of EZVI outside the plot perimeter

Pre-demonstration measurements of water levels in the Upper Sand Unit showed a slight depression in the area of the EZVI demonstration plot (see Figure 5-10a). During the demonstration, the recirculation system appeared to produce a relatively flat but slightly elevated gradient due to the injection across the Upper Sand Unit, which would have limited the potential for TCE-DNAPL migration from the Upper Sand Unit (see Figure 5-10b).

Table 5-8. TCE Degradation Byproducts in the EZVI Plot Before, During, and After the Demonstration

Well ID	Pre-Demonstration	During the Demonstration	Post-Demonstration	Pre-Demonstration	During the Demonstration	Post-Demonstration
		TCE (µg/L)			***cis*-1,2-DCE (µg/L)**	
EZVI Plot Well						
PA-23	1,180,000	92,100	8,790	16,900	17,900	169,000
EZVI Perimeter Wells						
PA-24S	772,000	474,000	12,100	47,400	15,800	31,700
PA-24I	258,000	110,000	86,400	149,000	161,000	181,000
PA-24D	469,000	497,000	656,000	61,800	83,400	99,400
PA-25S	71,300	69,600	129,000	69,200	9,320	42,800
PA-25I	534,000	784,000	944,000	116,000	104,000	90,900
PA-25D	2,760	36,200	53,200	60,800	101,000	117,000
Injection and Extraction Wells						
EIW-1	144,000	NA	7,820	38,300	NA	3,280
EEW-1	1,050,000	NA	471,000	67,100	NA	80,100
		***trans*-1,2-DCE (µg/L)**			**Vinyl Chloride (µg/L)**	
EZVI Plot Well						
PA-23	<1,000	68 J	245	<1,000	53 J	21,600
EZVI Perimeter Wells						
PA-24S	<1,000	<50	190 J	<1,000	<50	1,580
PA-24I	482	644	1,020	140 J	1,070	779
PA-24D	260 J	360 J	610	110 J	590	160 J
PA-25S	<1,000	46 J	381	<1,000	<100	75 J
PA-25I	320 J	230	270 J	<500	<100	170 J
PA-25D	278	395	544	<50	142	354
Injection and Extraction Wells						
EIW-1	556	NA	24 J	638	NA	322
EEW-1	550 J	NA	390 J	<1,000	NA	6,980

Well IDs: S = shallow well (Upper Sand Unit); I = intermediate well (Middle Fine-Grained Unit); D = deep well (Lower Sand Unit).
EIW-1 = injection well; EEW-1 = extraction well.
Pre-demonstration = March 2002; during the demonstration = August 2002; post-demonstration = November 2002
NA = not analyzed.
J = Estimated value, below reporting limit.

The water level measurements taken after the demonstration suggests a slight gradient from north to south across the site (see Figure 5-10c). However, it is difficult to draw conclusions with the limited number of water level measurements for each sampling event. Water level maps of the Middle Fine-Grained Unit before, during, and after the EZVI injection were prepared using water level measurements from wells around the EZVI plot. The contour maps are shown in Figures 5-11a through 5-11c. During the demonstration, a strong gradient appears to have developed in the Middle Fine-Grained Unit to create a depression into the EZVI plot (see Figure 5-11b). The gradient could be due to the injection of EZVI and water, which may have created a depression in the Middle Fine-Grained Unit in the vicinity of the EZVI plot. However, again it is difficult to draw conclusions with the limited number of water level measurements for each sampling event, and the lack of monitoring wells available in the plot during the injection. It is unlikely that the injection pressures forced EZVI deep into the Middle Fine-Grained Unit, a theory which is supported by the lack of visual observation of EZVI at depth during post-demonstration soil coring.

TCE and other CVOC concentrations in perimeter wells were monitored for evidence of TCE-DNAPL migration outside the boundaries of the EZVI plot. In well PA-24S, which is outside the eastern edge of the demonstration plot and in the Upper Sand Unit, dissolved TCE concentrations decreased from 772,000 µg/L to 474,000 µg/L during the demonstration, and then to 12,100 µg/L after the demonstration (see Table 5-8). The substantial decrease suggests that TCE-DNAPL did not migrate outside the plot boundaries on the eastern edge of the plot as a result of the EZVI injection itself. However, the decrease in TCE concentrations does suggest that the EZVI technology had an effect on groundwater outside the test plot boundaries. To determine if the EZVI mixture spread beyond the perimeter of the plot, soil borings in the vicinity of PA-24S would be needed to visually confirm the presence of EZVI, and low concentrations of TCE and elevated concentrations of other CVOCs would need to be present in those soil boring samples.

In well PA-25S along the western perimeter of the plot, TCE concentrations decreased slightly from 71,300 µg/L before the demonstration to 69,600 µg/L during the

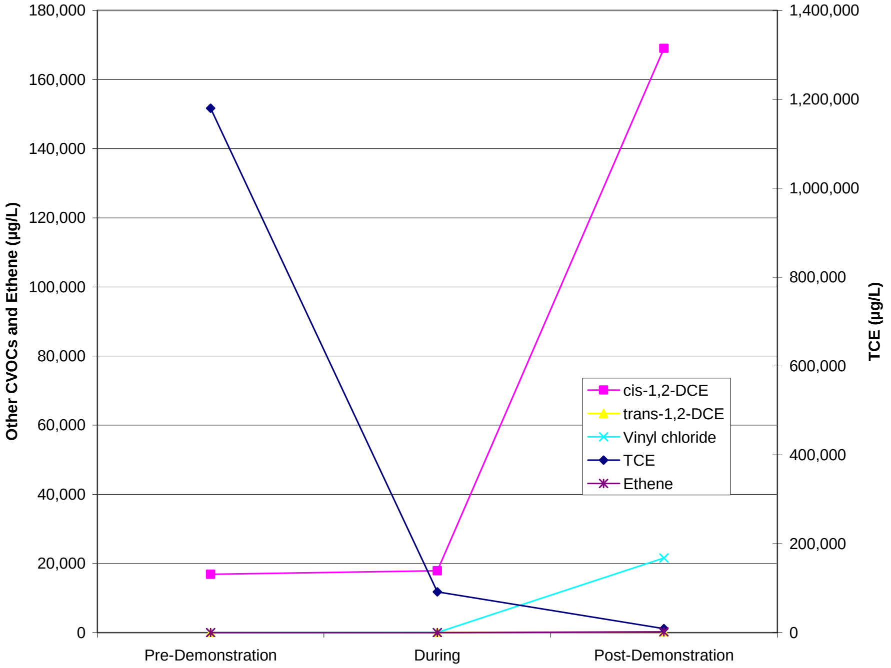


Figure 5-9a. Degradation Curve of TCE and Other CVOCs in PA-23 After EZVI Treatment

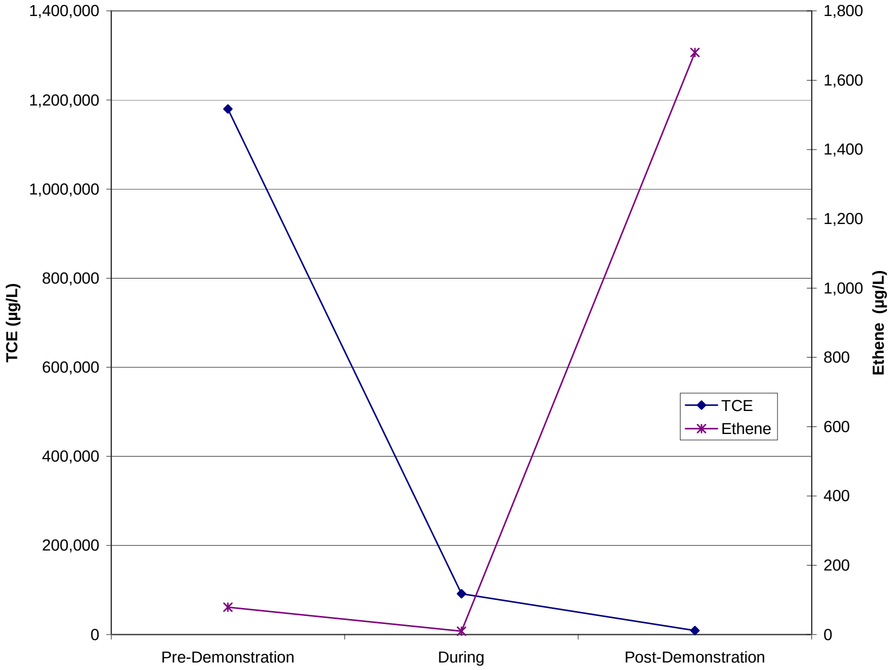


Figure 5-9b. Degradation Curve of TCE and Ethene in PA-23 After EZVI Treatment

demonstration, which suggests that the EZVI injection had little effect on TCE levels in groundwater along the western edge of the plot (see Table 5-8). However, post-demonstration concentrations of TCE in PA-25S increased to 129,000 µg/L. One soil boring (SB-210) was collected outside the western boundary of the EZVI plot to determine if the EZVI mixture had spread beyond the edges of the plot (see Appendix C). Evidence of EZVI was visually observed in soil collected from the Upper Sand Unit. Clearly, TCE concentrations at depths where EZVI was evidenced were quite low (between nondetect and 65 mg/kg of TCE) from the soil boring.

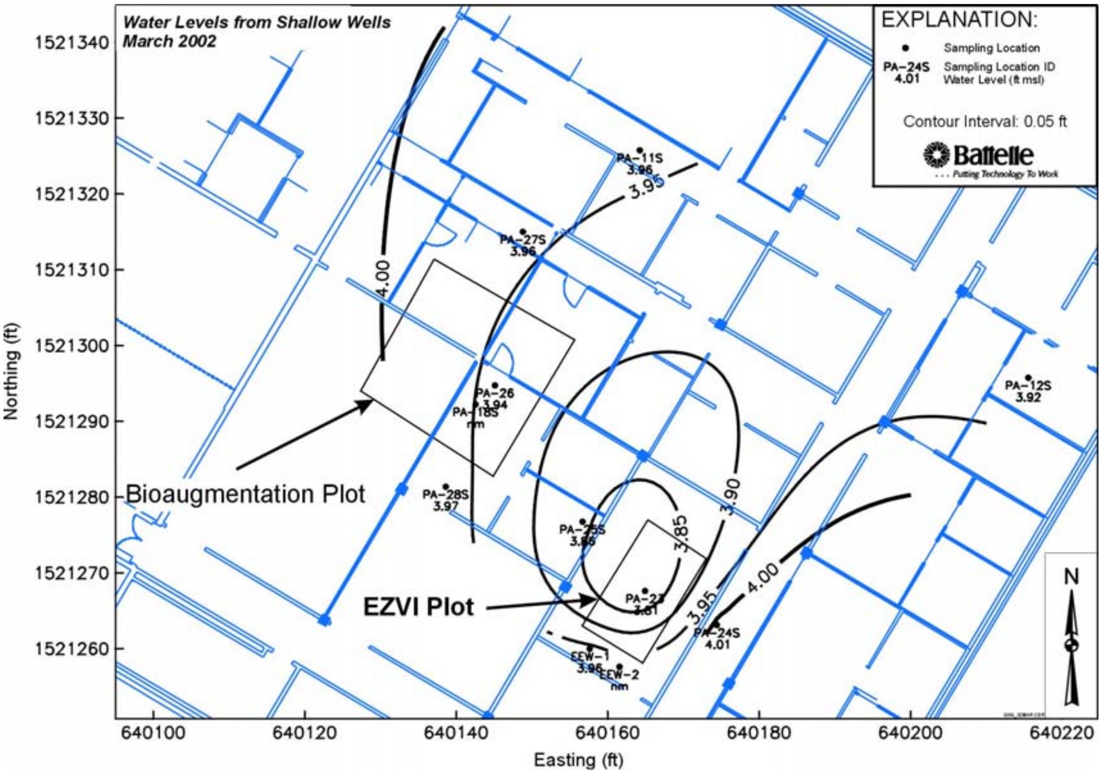


Figure 5-10a. Water Levels Measured in Shallow Wells in the Engineering Support Building During Pre-Demonstration Characterization (March 2002)

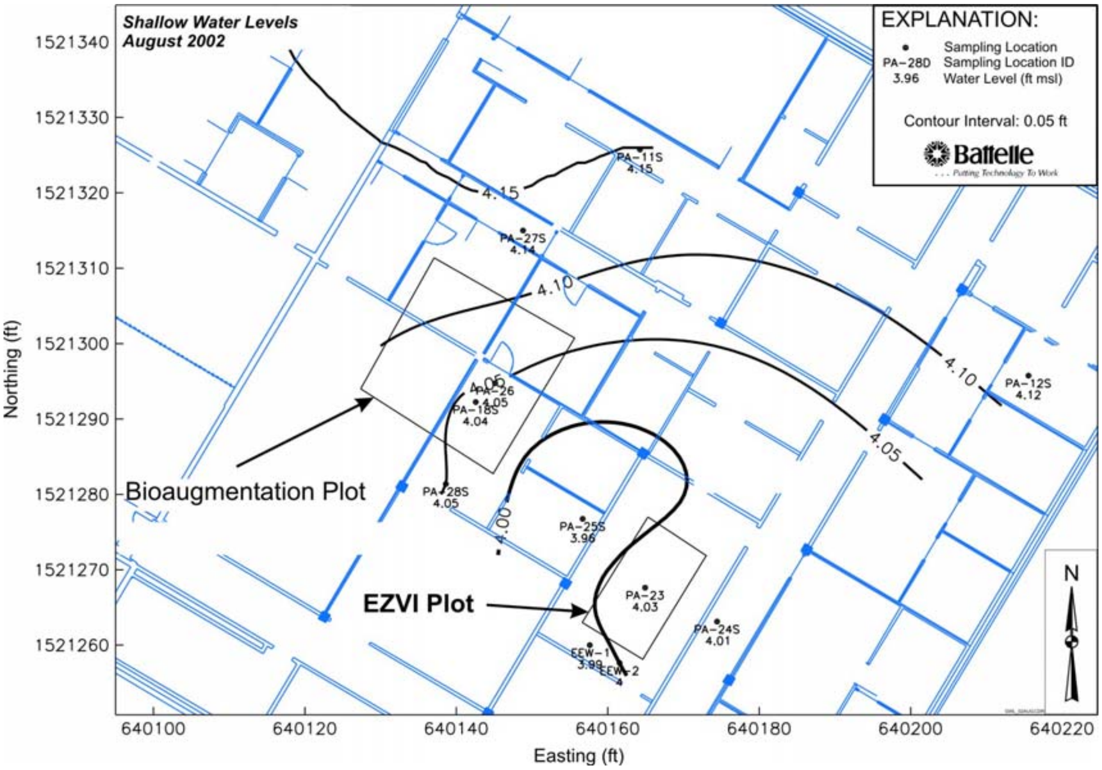


Figure 5-10b. Water Levels Measured in Shallow Wells in the Engineering Support Building During the EZVI Technology Demonstration (August 2002)

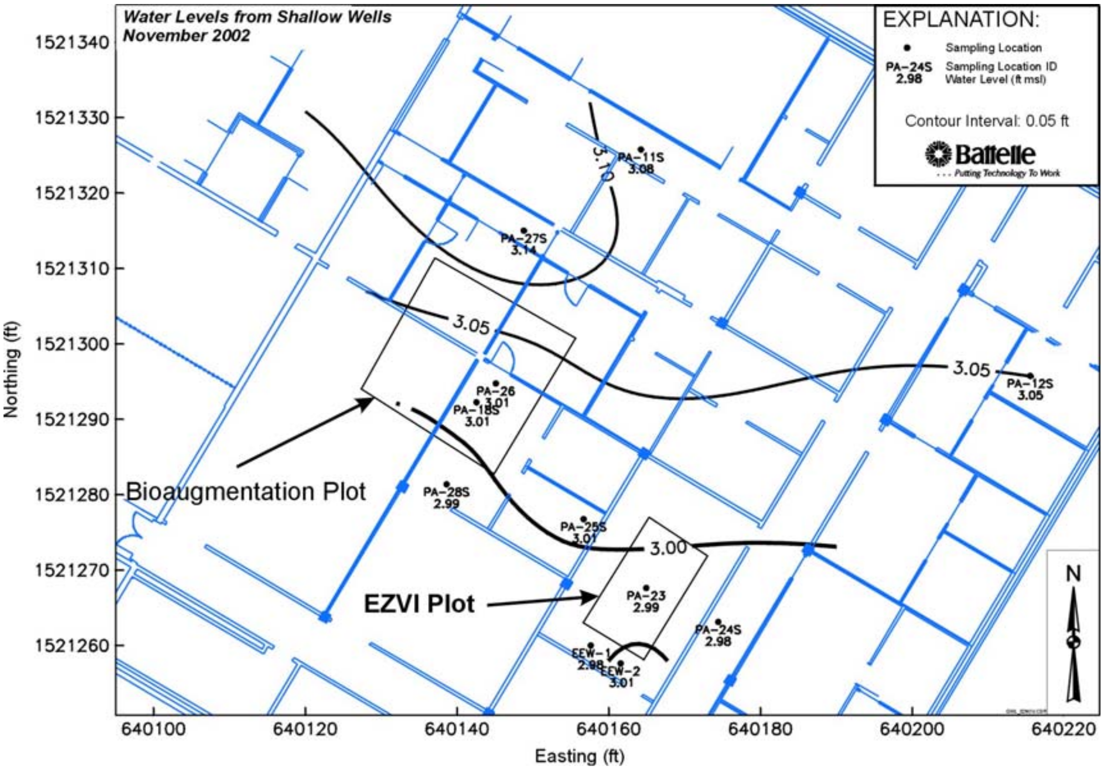


Figure 5-10c. Water Levels Measured in Shallow Wells in the Engineering Support Building During Post-Demonstration Characterization (November 2002)

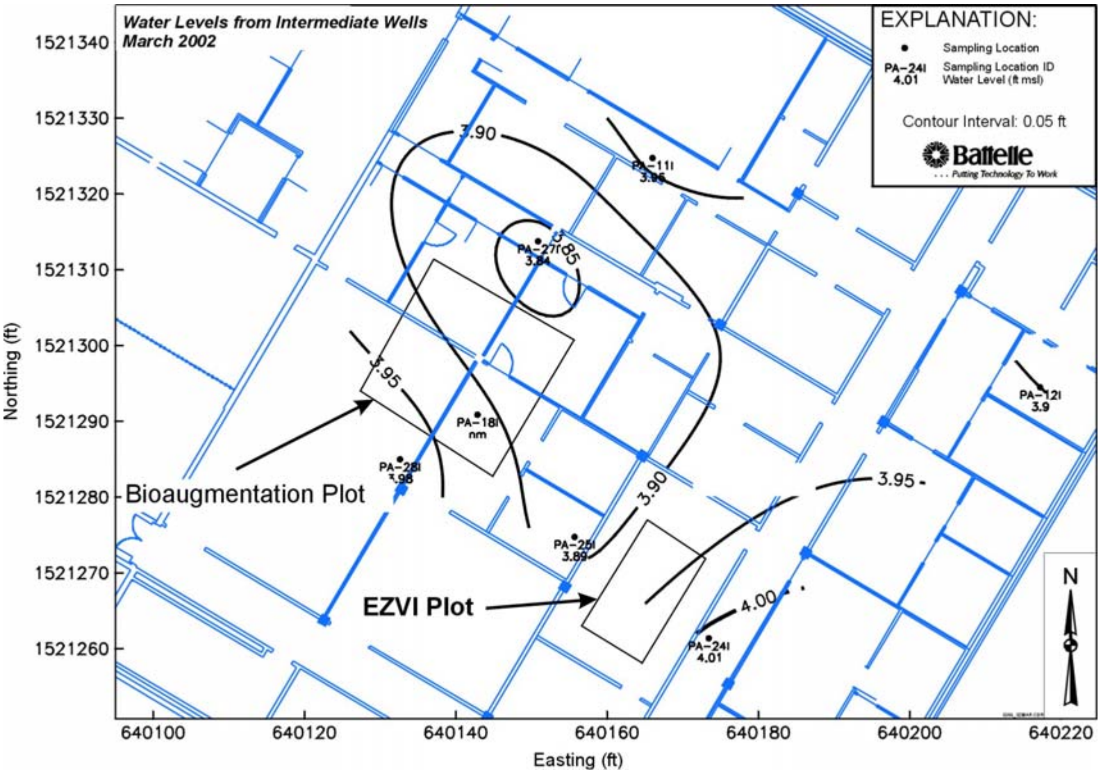


Figure 5-11a. Water Levels Measured in Intermediate Wells in the Engineering Support Building During Pre-Demonstration Characterization (March 2002)

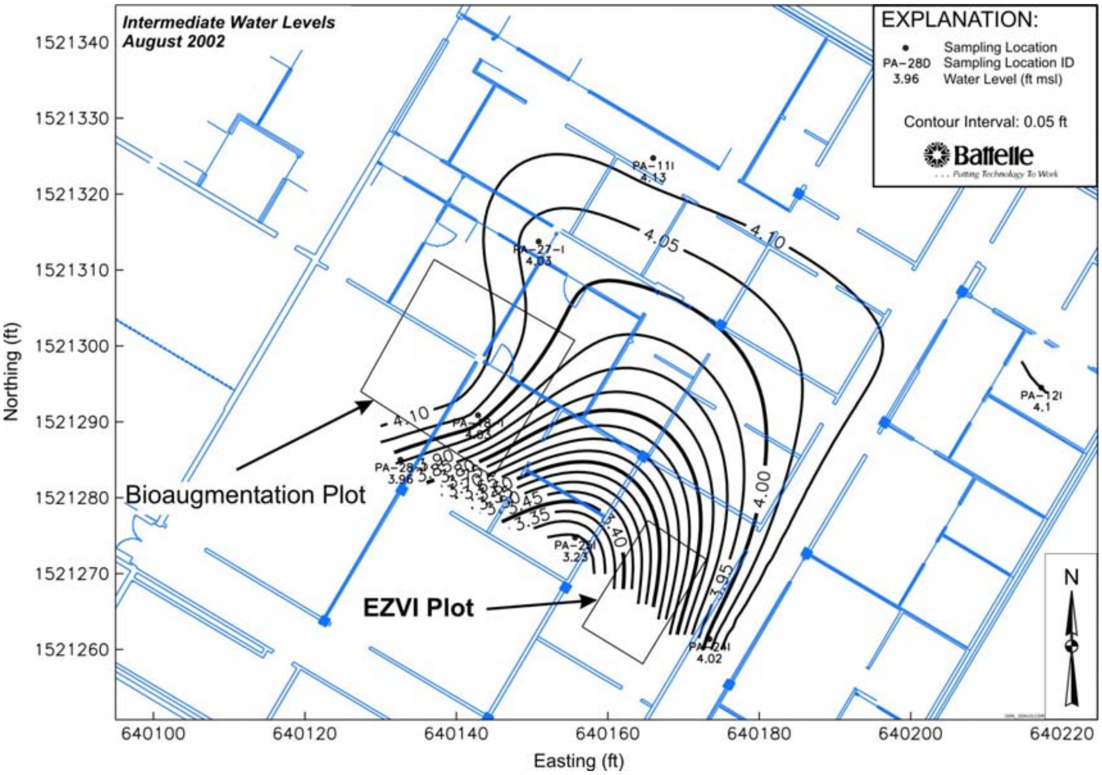


Figure 5-11b. Water Levels Measured in Intermediate Wells in the Engineering Support Building During the EZVI Technology Demonstration (August 2002)

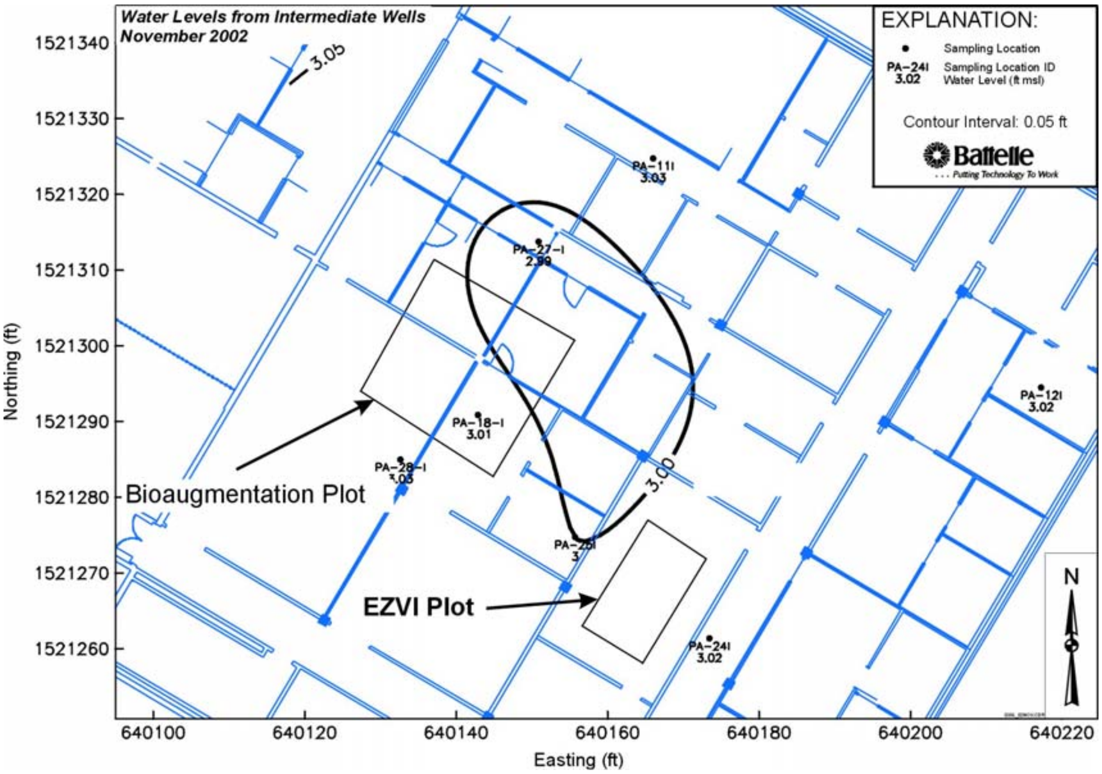


Figure 5-11c. Water Levels Measured in Intermediate Wells in the Engineering Support Building During Post-Demonstration Characterization (November 2002)

Yet, it is difficult to determine the cause of the increase in TCE concentration in PA-25S after the demonstration. It does not appear that the actual injection of the EZVI mixture with water caused TCE-DNAPL to migrate beyond the plot borders.

The potential for vertical TCE-DNAPL migration as a result of the injection was evaluated using soil samples collected from the Middle Fine-Grained Unit and Lower Sand Unit during post-demonstration characterization. Visual evidence of the black EZVI banding was not observed at depths below the Upper Sand Unit. Kriging estimates of total TCE mass in the Middle Fine-Grained Unit and Lower Sand Unit are presented in Table 5-2 to enable a quantitative assessment of any large TCE-DNAPL movement that may have occurred between the stratigraphic units as a result of the injection applied. Based on a comparison of the results between pre- and post-demonstration total TCE mass estimates, the EZVI injection does not appear to have caused vertical TCE-DNAPL migration during the demonstration. Further evidence that vertical migration of TCE-DNAPL did not occur as a result of the EZVI injection can be seen in Figures 5-12a and 5-12b, which are plots of TCE concentrations with depth before and after the demonstration (see Appendix C for tabulated data). The concentration plots do not indicate that the TCE plume shifted downward vertically as a result of the injection.

5.3.4 Summary Evaluation of the Fate of TCE-DNAPL

In summary, the field measurements indicate that significant DNAPL migration outside the test plot due to the EZVI technology demonstration is not likely to have occurred in the Launch Complex 34 aquifer. There is sufficient evidence that reductive dechlorination of TCE-DNAPL occurred as a result of the EZVI injection. There is also evidence that microorganism-assisted reductive dehalorespiration of TCE occurred when the indigenous microorganisms in the aquifer were stimulated by electrons generated after the EZVI application. Water level measurements indicate that the hydraulic gradients in the targeted Upper Sand Unit were not sufficiently strong to cause significant movement of TCE-DNAPL mass. However, some of the EZVI emulsion may have been transported with groundwater outside the boundaries of the plot, aiding in microbial-assisted reductive dechlorination. Visual evidence of EZVI was observed in soil samples of one soil core collected outside the western boundary of the plot; however, this is thought to be a result of the injection method and not the result of hydraulic gradients in or around the plot. TCE concentrations in soil samples collected in the test plot before and after the demonstration indicate that the EZVI injection did not create vertical migration of TCE-DNAPL. Also, EZVI was not visually observed in the soil below the targeted Upper Sand Unit, and no significant changes were observed in CVOCs in the Middle Fine-Grained Unit and Lower Sand Unit. In summary, the reduction in TCE-DNAPL concentrations in soil and groundwater are probably a result of biotic and abiotic reactions caused by the injection of EZVI.

In December 2003 and March 2004, groundwater samples were collected from various monitoring wells associated with the EZVI demonstration and analyzed for CVOCs. The purpose of these two individual sampling events was to collect observational data on the concentrations of CVOCs in groundwater after a significant amount of time had passed since the initial injection of EZVI. The results were not used for the performance assessment, so they are included in Section C-5 of Appendix C. These later samples indicated that contaminant degradation continued for several months after EZVI injection, leading to sharp reductions in TCE, *cis*-1,2-DCE, and (eventually) vinyl chloride in the test plot. Ethene levels increased substantially. The remaining EZVI in the plot area continued to complete dechlorination of TCE.

5.4 Verifying Operating Requirements

Section 3 describes the field operations for the injection of the EZVI emulsion at Launch Complex 34. Overall, two operational factors need to be improved: (1) the injection method and delivery mechanism of EZVI to the subsurface, and (2) hydraulic control by recirculation prior to, during, and after the EZVI injection. First, the injection method (pressure pulse technology) used for this technology demonstration had some advantages for injecting an exogenous, high-viscosity emulsion into the subsurface, especially when compared to the limits of direct-push technology. As discussed in Section 3, one half of each injection well screened cylinder was kept open in order to control the EZVI distribution into the plot and to prevent EZVI and TCE-DNAPL from moving outward and away from the plot during the application of EZVI. However, soil samples collected along the western perimeter of the plot indicated that EZVI did travel outside the test plot, practically moving behind the closed side of each screen cylinder. Also, evidence of EZVI was observed at shallower depths closer to the groundwater table, although the injection was applied only at deeper target depths. These two observations raise the issue of whether dissolved TCE has the potential to migrate outward during the injection process. Thus, it is necessary to improve injection techniques to distribute EZVI emulsion effectively while limiting dissolved plume migration at any remediation sites.

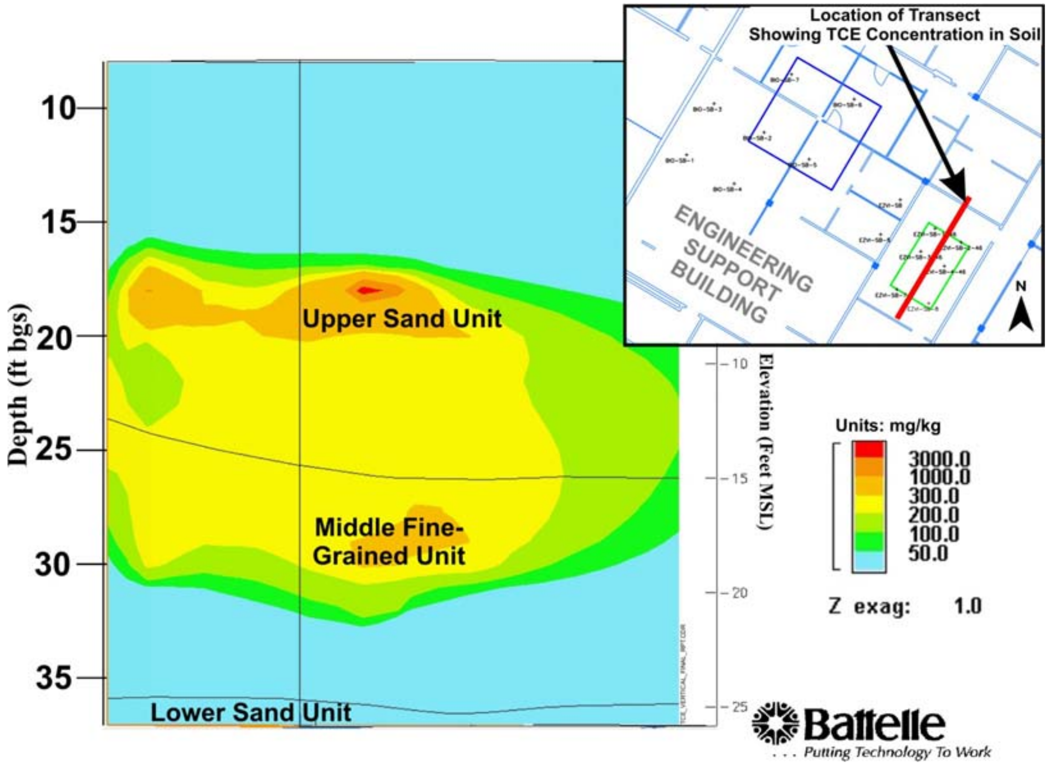


Figure 5-12a. Pre-Demonstration TCE Concentrations (mg/kg) in Soil with Depth

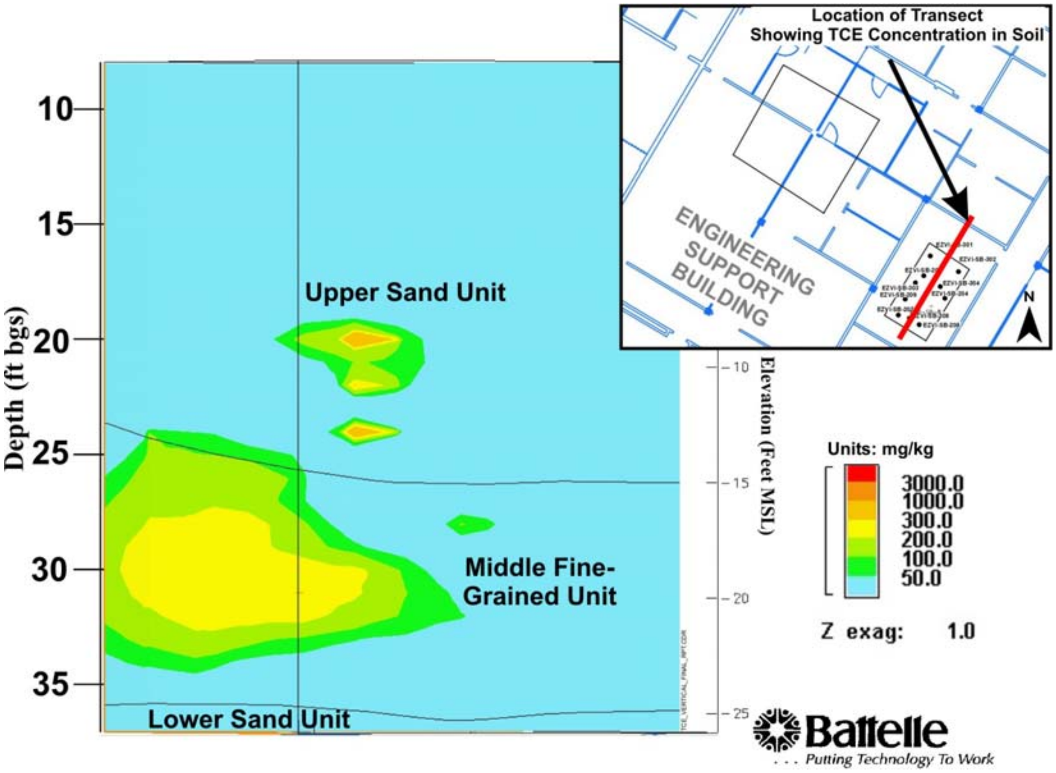


Figure 5-12b. Post-Demonstration TCE Concentrations (mg/kg) in Soil with Depth

Second, an artificial hydraulic gradient in the Upper Sand Unit was created by using two injection wells at the north end of the plot (EIW-1 and EIW-2) and two extraction wells at the south end of the plot (EEW-1 and EEW-2) to establish continuous recirculation in a rather flat aquifer and at a low flowrate. This system appeared to help advance the injected EZVI in the desired direction of treatment while controlling localized hydraulics. However, water extracted from the downgradient extraction wells was not treated before reinjection into the upgradient aquifer of the EZVI plot. In order to prevent introducing additional contamination into the gradient aquifer, it was necessary to continuously monitor the extracted liquids from the influent and effluent sample ports of a series of two GAC vessels. The CVOC results from the effluent port of the carbon vessels in this demonstration were all below a set of guidance levels, and appeared to undergo proper treatment via GAC. Note that the proper handling of liquids is required for future applications of the EZVI technology at any remediation site.

6. Quality Assurance

A QAPP (Battelle, 2002a) prepared before the demonstration outlined the performance assessment methodology and the quality assurance measures to be taken during the demonstration. The results of the field and laboratory QA for the critical soil and groundwater CVOC (primary) measurements and groundwater field parameter (secondary) measurements are described in this section. The results of the QA measurements for both soil and groundwater sampling events are described in Appendix E. The focus of the QA measures is on the critical TCE measurement in soil and groundwater, for which, in some cases, special sampling and analytical methods were used. For other measurements (chloride, calcium, etc.), standard sampling and analytical methods were used to ensure data quality.

6.1 QA Measures

This section describes the data quality in terms of representativeness and completeness of the sampling and analysis conducted for technology performance assessment. Chain-of-custody procedures also are described.

6.1.1 Representativeness

Representativeness is a measure that evaluates how closely the sampling and analysis represents the true value of the measured parameters in the target matrices. The critical parameter in this demonstration is TCE concentration in soil. The following steps were taken to achieve representativeness of the soil samples:

- Statistical design for determining the number and distribution of soil samples in the 9-ft × 15-ft EZVI plot, based on the horizontal and vertical variability observed during a preliminary characterization event (see Section 4.1). Six locations (one in each cell of a 3 × 2 grid in the plot) were cored before and after the demonstration. Each continuous core was collected and sampled in 2-ft sections from the ground surface to the aquitard at most coring locations except for the following: SB-8, SB-203, SB-204, SB-207, SB-208, and SB-209. Sampling did not proceed to the aquitard for these cores either due to loss of sample during coring or because drilling to the aquitard was not required to fulfill the sampling objective. At the 80% confidence level, the reduction of TCE mass between the pre- and post-demonstration was considered to be achieved relatively well by the EZVI technology.
- Continuous sampling of the soil column at each coring location enabled the sampling design to address the vertical variability in the TCE distribution. By extracting and analyzing the complete 2-ft depth in each sampled interval, essentially every vertical depth was sampled.
- Use of appropriate modifications to the standard methods for sampling and analysis of soil. To increase the representativeness of the soil sampling, the sampling and extraction procedures in U.S. EPA Method 5035 were modified so that an entire vertical section of each 2-ft core could be sampled and extracted, instead of the 5-g aliquots specified in the standard method (see Section 4.1). This was done to maximize the capture of TCE-DNAPL in the entire soil column at each coring location.

Steps taken to achieve representativeness of the groundwater samples included:

- Installation and sampling of one well in the center of the EZVI plot and two clusters of performance monitoring wells outside the plot. The well in the center was screened at the target depth in the Upper Sand Unit. Each performance well cluster consisted of three wells screened in the three stratigraphic units — Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit.
- Use of standard methods for sampling and analysis. Disposable tubing was used to collect samples from all monitoring wells to avoid persistence of TCE in the sample tubing after sampling wells with high TCE (DNAPL) levels.

6.1.2 Completeness

All the regular samples planned in the QAPP were collected and analyzed, with the exception of TOC analysis from post-demonstration soil sampling. Additional soil cores outside of the EZVI plot were collected during post-demonstration sampling to evaluate the variability in the subsurface distribution of the emulsion.

All the quality control (QC) samples planned in the QAPP were collected and analyzed, except for the equipment rinsate blanks during soil coring. Equipment rinsate blanks as planned in the QAPP were collected and analyzed during the pre- or post-demonstration soil sampling events. Based on the preliminary speed of the soil coring, one rinsate blank per day was thought to be sufficient to obtain a ratio of one blank per 20 samples (5%). One rinsate blank per core was determined to be the optimum collection frequency.

6.1.3 Chain of Custody

Chain-of-custody forms were used to track each batch of samples collected in the field and were to the off-site analytical laboratory. Copies of the chain-of-custody records can be found in Appendix E. Chain-of-custody seals were affixed to each shipment of samples to ensure that only laboratory personnel accessed the samples during transit. Upon arrival at the laboratory, the laboratory verified that the samples were received in good condition and the temperature blank sample sent with each shipment was measured to ensure that the required temperature was maintained during transit. Each sample received then was checked against the chain-of-custody form, and any discrepancies were brought to the attention of field personnel.

6.2 Field QC Measures

The field QC checks included calibration of field instruments, field blanks (5% of regular samples), field duplicates (5% of regular samples), and trip blanks; the results of these QC checks are discussed in this section.

Table 6-1 summarizes the instruments used for field groundwater measurements (pH, ORP, DO, temperature, water levels, and conductivity) and the associated calibration criteria. Instruments were calibrated at the beginning and end of the sampling period on each day. The field instruments were always within the acceptance criteria during the demonstration.

6.2.1 Field QC for Soil Sampling

As an overall determination of the extraction and analytical efficiency of the soil sampling, the modified U.S. EPA Method 5035 methanol extraction procedure was evaluated in a previous demonstration at Launch Complex 34 by spiking a known amount of TCE into soil samples from the Launch Complex 34 aquifer. Replicate samples from the spiked soil were extracted and analyzed; the results are listed in Appendix E (Table E-1). For the five replicate soil samples, the TCE spike recoveries were in the range of 72 to 86%, which fell within the acceptable range (70-130%) for quality assurance of the extraction and analysis procedure. The results demonstrate that a majority of the TCE was primarily extracted during the first extraction, and that diminishing returns were provided by the second and third extractions (Battelle, 2002b). Based on these results, the extraction procedure defined for subsequent soil sampling events and subsequent demonstrations at Launch Complex 34 involved extracting one time only from the soil before sending the methanol samples to the off-site laboratory for analysis.

A more detailed evaluation of the soil extraction efficiency was conducted in the field during a previous steam injection/extraction technology demonstration at Launch Complex 34 by spiking a surrogate compound (1,1,1-TCA) directly into the intact soil cores retrieved in a sleeve (Battelle, 2002b). The injection volume of 1,1,1-TCA was approximately 10 µL. The spiked soil samples were handled in the same manner as the remaining soil samples during the extraction procedure. Extraction efficiencies for the experiment ranged from 84 to 113%. The results of the experiment were compared to the

Table 6-1. Instruments and Calibration Acceptance Criteria Used for Field Measurements

Instrument	Measurement	Acceptance Criteria
YSI Meter Model 6820	pH	3 point, ±20% difference
YSI Meter Model 6820	ORP	1 point, ±20% difference
YSI Meter Model 6820	Conductivity	1 point, ±20% difference
YSI Meter Model 6820	Dissolved Oxygen	1 point, ±20% difference
YSI Meter Model 6820	Temperature	1 point, ±20% difference
OHaus Weight Balance	Soil – Dry/Wet Weight	3 point, ±20% difference
Hermit Water Level Indicator	Water Levels	±0.01 ft

results of the post-demonstration soil characterization, where soil samples also were spiked with 1,1,1-TCA. Of the 13 soil samples spiked with 1,1,1-TCA during the steam injection demonstration at Launch Complex 34, 12 soil samples were within the acceptable range of precision for the post-demonstration soil sampling, calculated as the relative percent difference (RPD), where RPD is less than 30% (Table E-2). The results indicate that the methanol extraction procedure used in the field is suitable for recovering CVOCs.

During the EZVI pre- and post-demonstration sampling events, duplicate soil samples were collected in the field and analyzed for TCE to evaluate sampling precision. Duplicate soil samples were collected by splitting each 2-ft soil core vertically in half and subsequently collecting approximately 250 g of soil into two separate containers, marked as SB#-Depth# and SB#-Depth#-DUP. Appendix E (Table E-3) shows the result of the field soil duplicate analysis and the precision, calculated as the RPD for the duplicate soil cores, which were collected before and after the demonstration. The precision of the field duplicate samples was generally within the acceptable range (RPD<30%) for the demonstration, indicating that the sampling procedure was representative of the soil column at the coring location. The RPD for one of the duplicate soil samples from the pre-demonstration sampling was greater than 30%, which indicated that the repeatability of some of the pre-demonstration soil samples was outside targeted acceptance criteria. However, given the heterogeneous nature of the contaminant distribution, a large RPD on occasion is not unexpected. The RPDs for three of the duplicate soil samples from the post-demonstration sampling were greater than 30%. This suggests that the EZVI treatment created greater variability in the contaminant distribution. Part of the reason for the higher RPD calculated in some post-demonstration soil samples is that TCE concentrations tended to be low (often near or below the detection limit). For example, the RPD between duplicate samples, one of which is below detection and the other is slightly above detection, tends to be high. In general, though, the variability in the two vertical halves of each 2-ft core was in a reasonable range, given the typically heterogeneous nature of the DNAPL distribution.

Field blanks for the soil sampling consisted of rinsate blank samples and methanol blank samples. The rinsate blank samples were collected approximately once per drilling borehole, or approximately once per 20 soil samples, to evaluate the decontamination efficiency of the sampling equipment used to collect each soil sample. Decontamination between samples consisted of a three-step process where the sampling equipment was washed with soapy water, rinsed in distilled water to remove soap and debris, and then rinsed a second time with distilled water. The rinsate blank samples were collected by pouring distilled water over the equipment after the equipment had been processed through the routine decontamination procedure. As seen in Appendix E (Table E-4), TCE levels in the rinsate blanks were below detection (<1.0 µg/L) for all but one of the 15 rinsate blanks collected, indicating that the decontamination procedure was helping control carryover of CVOCs between samples.

Methanol blank samples were collected in the field at the rate of one per soil boring, or approximately every 20 samples (5%), to evaluate the soil extraction process. The results are listed in Appendix E (Table E-5). These samples were generally below the targeted detection limit of 100 µg/L of TCE in methanol. Detectable levels of TCE were present in methanol blanks collected during the post-demonstration phase of the project, but were still relatively low. Because several of the methanol blanks with detectable levels of TCE were collected during the same sampling event in October 2002, it is possible that the methanol may have become contaminated during storage at the site. However, the TCE concentrations in these blanks were generally below 10% of the concentrations in the associated batch of soil samples. All the pre-demonstration methanol blanks were below detection.

Trip blanks were sent with every sample shipment, both soil and groundwater, to the off-site analytical laboratory. The results are discussed in Section 6.2.2.

6.2.2 *Field QC for Groundwater Sampling*

QC checks for groundwater sampling included field duplicates (5%), field blanks (5%), and trip blanks. Field duplicate samples were collected once per sampling event, or approximately once per eight to ten wells sampled. Appendix E (Table E-6) contains the analysis of the field duplicate groundwater samples that were collected before, during, and after the demonstration. The RPD (precision) calculated for these samples always met the QA/QC target criteria of RPD<30%.

In previous demonstrations carried out at Launch Complex 34, decontamination of the sample tubing between groundwater samples initially consisted of a detergent rinse and two distilled water rinses. However, the results from these earlier demonstrations revealed that, despite the most thorough decontamination, rinsate blanks contained elevated levels of TCE, especially following the sampling of wells containing TCE levels near or greater than its solubility (1,100,000 µg/L); this indicated that some free-phase solvent may have been drawn into the tubing. When TCE levels in such rinsate blanks refused to go down, even when a methanol rinse was added to the decontamination procedure, a decision was made to switch to disposable Teflon® tubing. All groundwater sampling events conducted for the EZVI demonstration used disposable Teflon® tubing. Each new piece of tubing was used for sampling each well once and then discarded, despite the associated costs. TCE levels in the rinsate blanks (Appendix E, Table E-7) were below the targeted detection limit (3.0 µg/L) throughout the demonstration.

Trip blanks supplied by the off-site laboratory were included for CVOC analysis with every sample shipment sent to the laboratory. TCE levels in trip blank samples were below the QA/QC target level of 3 µg/L for 17 of the 19 trip blanks analyzed for the demonstration (Appendix E, Table E-8). Of the two trip blanks that failed to meet the target level, the laboratory was able to determine that the trip blanks were part of an older batch of blanks sent to the site during the previous month and concluded that the trip blanks had become contaminated during storage at the site and not during shipment.

6.3 Laboratory QC Measures

The off-site analytical laboratories performed QA/QC checks consisting of 5% matrix spikes (MS) and matrix spike duplicates (MSD). MS and MSD were used to calculate analytical accuracy (percent recovery) and precision (RPD between MS and MSD). Laboratory control spikes (LCS) and method blanks (MB) also were analyzed with every batch of samples.

6.3.1 Analytical QC for Soil Sampling

Analytical accuracy for the soil samples (methanol extracts) analyzed were generally within acceptance limits for TCE (70-130%) for the pre- and post-demonstration period (Appendix E, Tables E-9 and E-10). Matrix spike recoveries were outside this range for three of the MS/MSD samples conducted during the pre-demonstration sampling period, and three during the post-demonstration period. The spike recovery was outside of the control limits due to either very high or very low (i.e., near detection limit) concentrations of TCE present in the reference sample. No corrective actions were required and sample results were not adversely affected by the MS/MSD spike recoveries that were outside the control limits. The precision between MS and MSD was always within acceptance limits (RPD <30%). Laboratory control spike recoveries for all pre- and post-demonstration samples were within the acceptance criteria (Appendix E, Table E-11).

Method blanks were below the target level of 3.0 µg/L for TCE for 40 of the 41 method blanks analyzed during pre- and post-demonstration sampling. The single sample that did not meet the criteria was measured with a TCE recovery <1,000 µg/L due to a change in the method detection limit for that sample; therefore it is unknown if that particular method blank met the QA/QC target criteria (Appendix E, Table E-12).

The laboratory conducted surrogate spikes in 5% of the total number of methanol extracts prepared from the soil samples for CVOC analysis. Table 6-2 lists the surrogate compounds used by the laboratory to perform the QA/QC checks. Surrogate recoveries were within the specified acceptance limits.

Table 6-2. List of Surrogate Compounds and Their Target Recoveries for Soil and Groundwater Analysis by the Analytical Laboratory

Surrogate Compound	Target Recovery for Soil (Methanol Extracts) (%)	Target Recovery for Groundwater (%)
Dibromofluoromethane	65-135	75-125
1,2-Dichloroethane – d4	52-149	62-139
Toluene – d8	65-135	75-125
Bromofluorobenzene	65-135	75-125

6.3.2 Laboratory QC for Groundwater Sampling

Pre- and post-demonstration MS and MSD results for groundwater are listed in Appendix E (Table E-13). The MS and MSD recoveries (75 to 125%) were generally within acceptance criteria. The only exceptions were one MS/MSD sample set during the demonstration and one MS/MSD sample set during post-demonstration groundwater sampling. The spike recovery was outside of the control limits due to either very high or very low (i.e., near detection limit) concentrations of TCE present in the reference sample. No corrective actions were required and sample results were not adversely affected by the MS/MSD spike recoveries that were outside the control limits. The precision for all of the MS/MSD samples met the QA/QC criteria of RPD <20%. Recoveries for LCS samples were always within the acceptance range of 75-125% (Appendix E, Table E-14).

Method blanks (Appendix E, Table E-15) for the groundwater samples were always below the targeted 3.0 µg/L detection limit.

6.3.3 Analytical Detection Limits

Detection limits for TCE in groundwater and in the methanol extracts from soil generally were met. The detection limits most affected were those for *cis*-1,2-DCE and VC, due to the masking effect of high levels of TCE. The laboratories verified and reported that analytical instrumentation calibrations were within an acceptable range on the days of the analyses.

6.4 QA/QC Summary

Given the challenges posed by the typically heterogeneous TCE distribution in a DNAPL source zone, the collected data were an acceptable representation of the TCE distribution in the Launch Complex 34 aquifer before, during, and after the demonstration.

- Six spatially distributed locations were sampled within the plot to adequately capture the horizontal variability in the TCE distribution. The continuous sampling of the soil at each coring location ensured that the vertical variability of the TCE distribution was captured. Sampling and analytical procedures were appropriately modified to address the expected variability. Standard sampling and analysis methods were used for all other measurements to ensure that data were comparable between sampling events.
- Accuracy and precision of the soil and groundwater measurements were generally in the acceptable range for the field sampling and laboratory analysis. In the few instances that QC data were outside the targeted range, the reason was generally interference from extremely low (near detection) or extremely high levels of TCE in the sample that caused higher deviation in the precision (repeatability) of the data.
- The masking effect of high TCE levels on other CVOCs and the need for sample dilution as a result caused detection limits for TCE to rise in certain instances. However, because the surrogate recoveries were all within acceptable range, the rise in detection limits did not interfere with reporting acceptable CVOC concentrations.
- Rinsate blanks associated with the soil and groundwater samples generally had acceptably low or undetected levels of TCE.

7. Economic Analysis

The cost estimation for the EZVI technology application involves the following three major components:

- Application cost of EZVI at the demonstration site. These costs include material procurement and material production. Costs of the technology application at Launch Complex 34 were tracked by the technology vendor GeoSyntec and their subcontractor UCF.
- Site preparation and waste disposal costs, which were incurred by the owner.
- Site characterization and performance assessment costs. Battelle estimated these costs based on the site characterization and performance assessment that was generally based on U.S. EPA's SITE Program guidelines.

An economic analysis for an innovative technology generally is based on a comparison of the cost of the innovative technology with a conventional alternative. In this section, the economic analysis involves a comparison of the EZVI cost with the cost of a conventional pump-and-treat system.

7.1 EZVI Application Treatment Costs

The costs of the EZVI technology were tracked and reported by the vendor. Table 7-1 summarizes the cost breakdown for the treatment. The total cost of the EZVI demonstration incurred by the vendor was approximately $327,000 (not including waste disposal incurred by the site owner, see Section 7.2). This total includes the design, permitting support, implementation, process monitoring, and reporting costs incurred by the vendor. The total does not include the costs of waste disposal by the site owner, NASA, and site characterization, which was conducted by other organizations (Remedial Investigation/Feasibility Study [RI/FS] by NASA, preliminary characterization by Westinghouse Savannah River Company, and detailed characterization by Battelle).

Table 7-1. EZVI Treatment Cost Summary Provided by Vendor

Cost Item	Actual Cost ($)	Percentage (%)
Design and submittals	10,000	3
Design and Installation of Recirculation System and wells	75,000	21
Baseline Characterization	17,000	5
Injection Method Evaluation/Testing	60,000	17
EZVI Production	25,000	7
Performance monitoring and post-treatment characterization	75,000	21
Data evaluation and reporting	65,000	18
Subtotal	**327,000**	**93**
Site preparation and waste disposal[(a)]	25,000	7
Total Cost	**352,000**	**100**

(a) Costs incurred by the site owner.
Source: GeoSyntec, 2003.

7.2 Site Preparation and Waste Disposal Costs

Actual costs incurred by the site owner, NASA, for site preparation and waste disposal can be estimated based on the support received from the site owner. NASA had prepared and cleared the site for the technology demonstration. This includes removal of tiles inside the building, surveying of the boundary of the plot, establishment of utilities (water and electricity for the system operation), and disposal of waste generated during the site preparation and performance monitoring. Although waste generation was minimal for this demonstration due to the use of nonintrusive direct-push rig and the nature of in situ technology, minimal waste was contained and stored for proper disposal incurred by NASA. The total cost for all these activities was estimated at approximately $25,000.

7.3 Site Characterization and Performance Assessment Costs

This section describes two categories of costs:

- **Site characterization costs.** These are the costs that a site would incur in an effort to bridge the gap between the general site information in an RI/FS or RFI report and the more detailed information required for DNAPL source delineation and remediation technology design. This cost component is perhaps the most reflective of the type of costs incurred when a site of the size and geology of Launch Complex 34 undergoes site characterization in preparation for remediation. Presuming that groundwater monitoring and plume delineation at a site indicates the presence of DNAPL, these site characterization costs are incurred in an effort to define the boundaries of the DNAPL source zone, obtain an order-of-magnitude estimate of the DNAPL mass present, and define the local hydrogeology and geochemistry of the DNAPL source zone.
- **Performance assessment costs.** These are primarily demonstration-related costs. Most of these costs were incurred in an effort to further delineate the portion of the DNAPL source contained in the EZVI plot and determine the TCE-DNAPL mass reduction achieved by the EZVI treatment. Only a fraction of these costs would be incurred during full-scale deployment of this technology; depending on the site-specific regulatory requirements, only the costs related to determining compliance with cleanup criteria would be incurred in a full-scale deployment.

Table 7-2 summarizes the costs incurred by Battelle for the February 1999 site characterization at Launch Complex 34. The February 1999 site characterization event was a suitable combination of soil coring and groundwater sampling and analysis for organics and inorganics, and hydraulic testing (water levels and slug tests) that may be expected to bridge the gap between the RI/FS or RFI data usually available at a site and the typical data needs for DNAPL source delineation and remediation design.

Table 7-3 summarizes performance assessment costs incurred by Battelle for the EZVI technology demonstration. Note that the total cost for post-demonstration assessment includes the cost incurred during the intermediate soil coring in October 2002.

Table 7-2. Estimated Site Characterization Costs

Activity	Cost
Site Characterization Work Plan • Additional characterization to delineate DNAPL source • Collect hydrogeologic and geochemical data for technology design	$25,000
Site Characterization • Drilling – soil coring and well installation (12 continuous soil cores to 45 ft bgs; installation of 24 monitoring wells) • Soil and groundwater sampling (36 monitoring wells; 300 soil samples collection and field extraction) • Laboratory analysis (organic and inorganic analysis) • Field measurements (water quality; hydraulic testing)	$160,000
Data Analysis and Site Characterization Report	$65,000
Total	**$ 250,000**

Table 7-3. Estimated Performance Assessment Costs

Activity	Cost
Pre-Demonstration Assessment • Drilling – 4 continuous soil cores; installation of 7 monitoring wells • Soil and groundwater sampling for TCE-DNAPL boundary and mass estimation (9 monitoring wells; collection and field extraction of 80 soil samples) • Laboratory analysis (organic and inorganic analysis) • Field measurements (water quality; hydraulic testing)	$75,000
Demonstration Assessment • Groundwater sampling (EZVI plot and perimeter wells) • Laboratory analysis (organic and inorganic analysis) • Field measurements (water quality; hydraulic testing; EZVI plot and perimeter wells)	$50,000
Post-Demonstration Assessment • Drilling – 12 continuous soil cores (6 from the intermediate soil coring event; 6 from the post-demonstration characterization) • Soil and groundwater sampling (9 monitoring wells; collection and field extraction of 160 soil samples-approximate 80 from the intermediate soil coring event; 80 from the post-demonstration characterization) • Laboratory analysis (organic and inorganic analysis) • Field measurements (water quality; hydraulic testing)	$150,000
Total	**$275,000**

7.4 Present Value Analysis of EZVI Technology and Pump-and-Treat System Costs

DNAPL, especially of the magnitude present at Launch Complex 34, is likely to persist in the aquifer for several decades or centuries. The resulting groundwater contamination and plume also will persist for several decades. The conventional approach to this type of contamination has been the use of pump-and-treat systems that extract and treat the groundwater above ground. This conventional technology is basically a plume control technology and would have to be implemented as long as groundwater contamination exists. The EZVI application technology is an innovative in situ technology that may be comparable to the conventional pump-and-treat approach. The economic analysis therefore compares the costs of these two alternatives.

Because a pump-and-treat system would have to be operated for the next several decades, the life-cycle cost of this long-term treatment has to be calculated and compared with the cost of the EZVI treatment technology, a short-term treatment. The present value (PV) of a long-term pump-and-treat application is calculated as described in Appendix F. The PV analysis is conducted over a 30-year period, as is typical for long-term remediation programs at Superfund sites. Site characterization and performance (compliance) assessment costs are assumed to be the same for both alternatives and are not included in this analysis.

For the purpose of comparison, it is assumed that a pump-and-treat system would have to treat the plume emanating from a DNAPL source. However, the demonstration was limited to a plot that was 9-ft wide × 15-ft long × 30-ft deep. For a more realistic cost comparison, the remediation site is assumed to be spatially three times bigger (27-ft wide × 45-ft long × 30-ft deep) than the EZVI plot for this cost evaluation. Recent research (Pankow and Cherry, 1996) indicates that the most efficient pump-and-treat system for source containment would capture all the groundwater flowing through the DNAPL source region. For a 27-ft-long × 45-ft-wide × 30-ft-deep (Upper Sand Unit) DNAPL source region at Launch Complex 34, a single extraction well pumping at 2 gpm is assumed to be sufficient to contain the source in an aquifer where the hydraulic gradient (and therefore, the groundwater flow velocity) is extremely low. This type of minimal containment pumping ensures that the source is contained without having to extract and treat groundwater from cleaner surrounding regions, as would be the case in more aggressive conventional pump-and-treat systems. The extracted groundwater is treated with an air stripper, polishing carbon (liquid phase), and a catalytic oxidation unit (for air effluent).

As shown in Tables F-1 and F-2 of Appendix F, the total capital investment for an equivalent pump-and-treat system would be approximately $161,000, and would be followed by an annual operation and maintenance (O&M) cost of $50,000 (including quarterly monitoring). Periodic maintenance requirements (replacements of pumps, etc.) would raise the O&M cost every five years to $69,000 and every 10 years to $97,000. A discount rate (real rate of return) of 2.9%, based on the current recommendation for government projects, was used to calculate the PV. The PV of the pump-and-treat costs over 30 years is estimated to be **$1,365,000**.

An equivalent treatment cost for full-scale deployment of the EZVI treatment technology in a source area approximately for the same size of treatment area as the one used for the pump-and-treat system would be at least $452,000. This estimate is based on a total EZVI treatment ($352,000 [see Table 7-1]) incurred for the demonstration. The assumed dimension to be treated is approximately three times of the EZVI plot. An equal number (8) of injection wells could be used for the injection, and twice as much of the EZVI could be used in the source treatment, although two additional volumes of waste would be generated. Additional costs of $100,000 would be necessary for the additional EZVI production cost ($25,000 times two) and waste disposal cost ($25,000 times two) based on the demonstration cost in Table 7-1. Therefore, if the TCE remaining after EZVI treatment was allowed to attenuate naturally, the total treatment cost with the EZVI technology would be approximately **$452,000**. Given the presence of vegetable oil residuals from the EZVI, a slow-release carbon source is available to aid biodegradation of TCE residuals. Another assumption here is that the full-scale deployment of the EZVI treatment system would entail design, equipment, and deployment similar to the kind done during the demonstration.

Therefore, the EZVI treatment technology is cost-competitive with an equivalent pump-and-treat system. An investment in the EZVI treatment has a lower PV than the long-term investment in a pump-and-treat system. The up-front capital investment incurred for the EZVI treatment may by recovered after the fifth year (see Table F-3 in Appendix F), when the PV of the pump-and-treat system surpasses the cost of the EZVI treatment.

In addition to a lower PV or life-cycle cost, there may be other tangible and intangible economic benefits to using a source remediation technology. For example, the economic analysis in Appendix F assumes that the pump-and-treat system is operational at all times over the next 30 years or more, with most of the annual expense associated with operation and routine (scheduled) maintenance. Experience with pump-and-treat systems at several sites has shown that downtime associated with pump-and-treat systems is fairly high (as much as 50% downtime reported from some sites). This may negatively impact both maintenance requirements (tangible cost) and the integrity of plume containment (intangible cost) with the pump-and-treat alternative.

Another factor to consider is that although the economic analysis for long-term remediation programs typically is conducted for a 30-year period, the DNAPL source and therefore the pump-and-treat requirement may persist for many more years or decades. This would lead to concomitantly higher remediation costs for the pump-and-treat or plume containment option (without source removal). As seen in Appendix F, the PV of a pump-and-treat system operated for 100 years would be $2,126,000. Even if the DNAPL source is only partially removed by the EZVI treatment, and natural attenuation is insufficient to meet downgradient cleanup goals, it is anticipated that the reduced source leads to a reduction in the size and timeframe for a pump-and-treat system.

8. Technology Applications Analysis

This section evaluates the general applicability of the EZVI technology to sites with contaminated groundwater and soil. The analysis is based on the results and lessons learned from the demonstration, as well as general information available about the technology and its application at other sites.

8.1 Objectives

This section evaluates the EZVI technology against the nine evaluation criteria used for detailed analysis of remedial alternatives in feasibility studies under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Much of the discussion in this section applies to DNAPL source removal in general and the EZVI technology in particular.

8.1.1 Overall Protection of Human Health and the Environment

EZVI is protective of human health and environment in both the short and long term. Because DNAPL acts as a secondary source that can contaminate an aquifer for decades or centuries, DNAPL source removal or mitigation considerably reduces the duration over which the source is active. Even if DNAPL mass removal is not 100%, the resulting long-term weakening of the plume and the reduced duration over which the DNAPL source contributes to the plume reduces the threat to potential receptors.

8.1.2 Compliance with ARARs

This section describes the technology performance versus applicable or relevant and appropriate requirements (ARARs). Compliance with location-, action-, and chemical-specific ARARs should be determined on a site-specific basis. Location-specific ARARs may apply during a remediation project if the technology has the potential to affect resources in and around the site location. Examples of resources that fall under location-specific ARARs include cultural resources, biological resources, flood plains and wetlands, hydrologic resources, and critical habitat. In general, the design of the EZVI technology is flexible enough that location-specific ARARs could be met.

Action-specific ARARs correspond to waste discharge requirements associated with the technology, such as discharging to the air or hazardous waste generation, management, and disposal. In general, action-specific ARARs could be met with the EZVI technology. One advantage of the EZVI technology is the potential for the emulsion to be injected without the accompanying recirculating groundwater system. The recirculating system produces groundwater that must be treated prior to reinjection according to the requirements of RCRA 3020(b) (U.S. EPA, 2000). Further testing of the EZVI technology is necessary to optimize injection strategies in the absence of a recirculating groundwater system.

Chemical-specific ARARs are generally health- or risk-based numerical values or methodologies applied to site-specific conditions that result in the establishment of a cleanup level. Compliance with chemical-specific ARARs depends on the efficiency of the EZVI process at the site and the cleanup goals agreed on by various stakeholders. In general, reasonable DNAPL mass removal goals are more achievable and should lead to eventual and earlier compliance with long-term groundwater cleanup goals. Achieving short-term groundwater cleanup goals (e.g., federal or state maximum contaminant levels [MCLs]), especially in the DNAPL source zone, is more difficult because various studies (Pankow and Cherry, 1996) have shown that almost 100% DNAPL mass removal may be required before a significant change in groundwater concentrations is observed. However, removal of DNAPL, even if most of the removal takes place from the more accessible pores, probably would result in a weakened plume that may allow risk-based cleanup goals to be met in the downgradient aquifer.

The specific federal environmental regulations that are potentially impacted by remediation of a DNAPL source with EZVI are described below.

8.1.2.1 Comprehensive Environmental Response, Compensation, and Liability Act

CERCLA, as amended by the Superfund Amendment and Reauthorization Act (SARA), provides for federal authority to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or the environment. Remedial alternatives that significantly reduce the volume, toxicity, or mobility of hazardous materials and that provide long-term protection are preferred. Selected remedies also must be cost-effective and protective of human health and the environment. The EZVI technology meets several of these criteria relating to a preferred alternative. EZVI reduces the toxicity of chlorinated contaminants by converting them into potentially nontoxic forms. For example, at Launch Complex 34, as described in Section 5.3.1, increases in ethene and chloride concentrations in groundwater collected during post-demonstration characterization indicate that some portion of the TCE was converted into nontoxic forms by the EZVI treatment. This elimination of solvent hazard is permanent and leads to a considerable reduction in the time it takes for the DNAPL source to deplete fully. Although aquifer heterogeneities and technology limitations often result in less than 100% (complete) removal of the contaminant and elevated levels of dissolved solvent may persist in the groundwater over the short term, there is faster and eventual elimination of groundwater contamination in the long term. Section 7.4 shows that EZVI technology is cost-effective compared with the conventional alternative of long-term pump and treat.

8.1.2.2 Resource Conservation and Recovery Act

RCRA, as amended by the Hazardous and Solid Waste Amendments (HSWA) of 1984, regulates management and disposal of municipal and industrial solid wastes. The U.S. EPA and RCRA-authorized states (listed in 40 CFR Part 272) implement and enforce RCRA and state regulations. Generally, RCRA does not apply to in situ groundwater treatment because the contaminated groundwater may not be considered hazardous waste while it is still in the aquifer. The contaminated groundwater becomes regulated if it is extracted from the ground, as would happen with the conventional alternative of pump and treat. At Launch Complex 34, the recirculation system required for hydraulic control of the test plot necessitated treatment of the extracted groundwater prior to reinjection. At similar sites, and under similar circumstances, RCRA may be invoked as an ARAR.

8.1.2.3 Clean Water Act

The CWA is designed to restore and maintain the chemical, physical, and biological quality of navigable surface waters by establishing federal, state, and local discharge standards. The CWA may apply if groundwater extraction is conducted in conjunction with EZVI injection, and the resulting water stream needs to be treated and discharged to a surface water body or a publicly owned treatment works (POTW). On-site discharges to a surface water body must meet National Pollutant Discharge Elimination System (NPDES) requirements; consequently, an NPDES permit may be needed under the NPDES requirements. Off-site discharges to a surface water body must meet NPDES limits and require an NPDES permit. Discharge to a POTW, even if it is through an on-site sewer, is considered an off-site activity and requires an NPDES permit. Sometimes, soil or groundwater monitoring may lead to small amounts of purge and decontamination water wastes that may be subject to CWA requirements. Micropurging was one measure implemented at Launch Complex 34 to minimize such wastes during site characterization and technology performance assessment.

8.1.2.4 Safe Drinking Water Act

The SDWA, as amended in 1986, requires U.S. EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorizes national drinking water standards and a joint federal-state system for ensuring compliance with these standards. The SDWA also regulates underground injection of fluids through the Underground Injection Control (UIC) Program and includes sole-source aquifer and wellhead protection programs. A UIC variance was obtained from the FDEP to inject the EZVI into the aquifer during this demonstration.

The National Primary Drinking Water Standards are found at 40 CFR Parts 141 through 149. The health-based SDWA primary standards (e.g., MCL) are more critical to meet; SDWA secondary standards (e.g., for iron, chloride, or TDS) are based on other factors, such as aesthetics (discoloration) or odor. The MCLs based on these standards generally apply as cleanup standards for water that is, or potentially could be, used for drinking water supply. In some cases, such as when multiple contaminants are present, alternative concentration limits (ACLs) may be used. CERCLA and RCRA standards and guidance are used in establishing ACLs. In addition, some states may set more stringent standards for specific contaminants. For example, the federally mandated MCL for VC is 2 µg/L, whereas the State of

Florida drinking water standard is 1 µg/L. In such instances, the more stringent standard is usually the cleanup goal.

Although the long-term goal of DNAPL source zone treatment is meeting applicable drinking water standards or other risk-based groundwater cleanup goals agreed on between site owners and regulatory authorities, the short-term objective of the EZVI technology and source remediation is DNAPL mass removal. Because technology, site, and economic limitations may limit DNAPL mass removal to less than 100%, it may not always be possible to meet groundwater cleanup targets in the source region in the short term. Depending on other factors, such as the distance of the compliance point (e.g., property boundary, at which groundwater cleanup targets have to be met) from the source (as negotiated between the site owner and regulators), the degree of weakening of the plume due to DNAPL source treatment, and the degree of natural attenuation in the aquifer, it may be possible to meet groundwater cleanup targets at the compliance point in the short term. DNAPL mass removal will always lead to faster attainment of groundwater cleanup goals in the long term, as compared to the condition in which no source removal action is taken.

One aspect of using EZVI as a reductant for DNAPL source remediation is the potential for an increase in iron concentrations in groundwater as a result of the treatment. Iron is a secondary drinking water standard under the SDWA, with a maximum concentration of 0.3 mg/L. At Launch Complex 34, the concentrations of dissolved iron measured in the shallow monitoring wells during the pre-demonstration characterization were much higher than the secondary drinking water standard, and ranged from 7.2 to 27 mg/L (see Table 5-5). Total iron concentrations were approximately the same as those for dissolved iron, indicating that dissolved iron is the predominant form in the aquifer. Both total and dissolved iron concentrations decreased after the EZVI injection. Precipitation of ferric iron on soil was not observed visually (as tan color) during post-demonstration characterization, but a full microscopic analysis of the soil was not conducted to verify the presence of precipitates. The post-demonstration data were inconclusive regarding the impact of the EZVI technology on iron concentrations in the targeted Upper Sand Unit following the EZVI injection. However, because the shallow aquifer at Launch Complex 34 is not used for drinking water, the secondary standard for iron did not apply to the EZVI demonstration.

8.1.2.5 Clean Air Act

The CAA and the 1990 amendments establish primary and secondary ambient air quality standards for protection of public health, as well as emission limitations for certain hazardous pollutants. Permitting requirements under CAA are administered by each state as part of State Implementation Plans (SIPs) developed to bring each state in compliance with National Ambient Air Quality Standards (NAAQS).

Unlike pump-and-treat systems, which often generate air emissions (when an air stripper is used), and unlike other source removal technologies that use thermal energy (e.g., steam injection or resistive heating) or result in exothermic reactions (e.g., oxidation with Fenton’s reagent), the potential for atmospheric releases is absent when injecting EZVI.

8.1.2.6 Occupational Safety and Health Administration

CERCLA remedial actions and RCRA corrective actions must be carried out in accordance with Occupational Safety and Health Administration (OSHA) requirements detailed in 20 CFR Parts 1900 through 1926, especially Part 1910.120, which provide for the health and safety of workers at hazardous waste sites. On-site construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part 1926 of RCRA, which provides safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than federal standards, also must be met.

The health and safety aspects of EZVI injection are minimal. The main working hazards encountered during the demonstration were operating heavy equipment (e.g., drill rig) and handling the emulsified iron mixture. These hazards were dealt with by using trained personnel and appropriate personal protective equipment. Level D personal protective equipment generally would be sufficient during implementation. During the injection phase of the demonstration, Tyvek® suits were worn to prevent workers’ clothing from being covered in the emulsion. All operating and sampling personnel were required to have completed the 40-hour Hazardous Waste Operations training course and 8-hour refresher courses.

8.1.3 Long-Term Effectiveness

The EZVI technology leads to removal of TCE-DNAPL mass and therefore permanent removal of contamination from the aquifer. Although dissolved solvent concentrations may rebound in the short term when groundwater flow redistributes through the treated source zone containing DNAPL remnants, depletion of the source through dissolution will continue in the long term, and lead to eventual and earlier compliance with groundwater cleanup goals.

8.1.4 Reduction of Toxicity, Mobility, or Volume through Treatment

The EZVI technology effects treatment by reducing the volume and toxicity of contamination through the dehalogenation process, which results in potentially nontoxic compounds such as chloride, ethene, or ethane. Multiple injections of the emulsified iron mixture may be necessary to bring about complete dehalogenation and prevent accumulation of degradation byproducts, such as VC. The mobility of the contaminant is not affected by the EZVI treatment.

8.1.5 Short-Term Effectiveness

The short-term effectiveness of the EZVI technology depends on a number of factors. If the short-term goal is to remove as much DNAPL mass as possible, this goal can be achieved. If the short-term goal is to reduce dissolved contaminant levels in the source zone, achievement of this goal will depend on the hydrogeology and DNAPL distribution in the treated region. As seen in Section 5.2.1, TCE levels declined sharply in some monitoring wells and in some multilevel chamber wells. Geologic heterogeneities, preferential flowpaths taken by the emulsion and localized permeability changes that determine flow in the treated region may lead to such variability in post-treatment groundwater levels of contamination. As discussed in Section 8.1.2.4, the chances of DNAPL mass removal resulting in reduced contaminant levels at a compliance point downgradient from the source is more likely in the short term. In the long term, DNAPL mass removal will always shorten the time period required to bring the entire affected aquifer in compliance with applicable standards.

If necessary, multiple injections of the iron emulsion may be used to promote complete dehalogenation to ethane or ethene and prevent the accumulation of degradation byproducts, such as VC. However, multiple injections may not be cost-effective due to intensive labor requirements and relatively high material cost.

8.1.6 Implementability

The implementability criterion addresses the technical and administrative feasibility of implementing the EZVI technology and the availability of various services and materials required during its implementation. The technical feasibility of implementing the EZVI technology is based on factors such as construction and operation, reliability of the technology, the ease of undertaking additional remedial action, and monitoring considerations. For the EZVI technology, constructing and operating the equipment associated with the recirculating system and the injection is fairly straightforward in theory. Technical difficulties that may be encountered include problems with injecting the emulsion (e.g., emulsion backing up in the injection well) and predicting the radius of influence. These technical difficulties affect the reliability of the technology, leading to schedule delays and making it difficult to have confidence in the predicted direction and travel distance of the emulsion without confirmatory sampling. Many of the technical difficulties seen during the EZVI demonstration may be mitigated by improving the method of injection into the subsurface. Further testing is needed in this area.

The administrative feasibility of implementing the EZVI technology at Launch Complex 34 was straightforward. A site-specific UIC variance was obtained by the vendor from the FDEP to inject the emulsion mixture. Because the Engineering Support Building at Launch Complex 34 was abandoned and in a remote location, the site was accessible for the equipment and supplies needed to conduct the demonstration without interfering with the surrounding community. Adequate storage capacity and disposal services for the waste generated during well installation, soil sampling, and groundwater sampling also was available at the Engineering Support Building. The zero-valent iron, vegetable oil, and surfactant were commercially available through various vendors. Due to the innovative use of the iron emulsion, the number of vendors trained and available to conduct the injection was limited; however, this may change as the technology advances in the remediation field.

At Launch Complex 34, aboveground wastes were generated during the demonstration due to the hydraulic controls required to contain the plot and measure mass flux. The groundwater extracted from the plot required treatment before being reinjected into the aquifer. Although the groundwater was treated using a common, commercially available technology (i.e., GAC), the complexity of the operation increased to some degree as a result.

8.1.7 Cost

As described in Section 7.4, the cost of the EZVI treatment is competitive with the life-cycle cost of traditional pump-and-treat technologies (over a 30-year period of comparison). The cost comparison becomes even more favorable for source remediation in general and EZVI in particular when other tangible and intangible factors are taken into account. For example, a DNAPL source, such as the one at Launch Complex 34, is likely to persist much longer than 30 years (the normal evaluation time for long-term remedies), thus necessitating continued costs for pump and treat into the distant future (perhaps 100 years or more). Annual O&M costs also do not take into account the nonroutine maintenance costs associated with the large amount of downtime typically experienced by site owners with pump-and-treat systems.

Factors that may increase the cost of the EZVI application are:

- Operating requirements associated with any contamination under a building
- Need for additional hydraulic control (e.g., with extraction wells) and any associated need to treat and dispose/reinject extracted fluids.

8.1.8 State (Support Agency) Acceptance

Because of the technical limitations and costs of conventional approaches to DNAPL remediation, state environmental agencies (or support agencies in the case of State-lead sites) have shown growing acceptance of innovative technologies. The demonstration at Launch Complex 34 provided evidence that the emulsified iron mixture may be effective in reductive dehalogenation of chlorinated solvents, despite difficulties in distributing the EZVI to the subsurface.

8.1.9 Community Acceptance

The EZVI technology's low profile, limited space requirements, absence of air emissions, absence of waste storage, handling, and off-site transportation requirements, low noise levels, and ability to reduce short- and long-term risks posed by DNAPL contamination are expected to promote local community acceptance.

8.2 Operability

Unlike a pump-and-treat system that may involve continuous long-term operation by trained operators for the next 30 or 100 years, a source remediation technology is a short-term application. The field application (actual injection) of EZVI in the 14-ft × 9.5-ft plot at Launch Complex 34 only took a few days to complete. The remediation generally is done as a turnkey project by multiple vendors, who will design, build, and operate the EZVI delivery system. Site characterization, site preparation (utilities, etc.), monitoring, and any waste disposal often are done by the site owner.

Other factors affecting the operability of the EZVI technology include the commercial availability of the supplies and the availability of the necessary injection equipment and specialists. The nanoscale zero-valent iron is available from a small number of commercial vendors. The surfactant and vegetable oil are widely available commercially. Handling of the iron, surfactant, and vegetable oil requires minimal health and safety measures. A specialized vendor was required for injecting the emulsion.

Although the use of zero-valent iron in the reductive dechlorination of solvents has been known for many years, the use of an injectable, emulsified form of zero-valent iron is a new application and is in the process of being patented.

8.3 Applicable Wastes

The ability of zero-valent iron to remediate chlorinated hydrocarbons has long been known. EZVI was designed for remediation of aquifers contaminated with chlorinated solvents. Source zones consisting of PCE and TCE in DNAPL form, as well as dissolved *cis*-1,2-DCE and VC, can be addressed. The EZVI technology can be implemented in source zones present in saturated or vadose zones.

8.4 Key Features

The following are some of the key features of EZVI that make the technology attractive for DNAPL source zone and groundwater treatment:

- In situ application
- Potential for injection-only mode at some sites that prevents the generation of aboveground wastes, which would need additional treatment or handling
- Potentially nontoxic products
- Fast field application time
- Longer-lived emulsion distributes in the aquifer through both advection and diffusion, thus achieving better contact with contaminants
- At many sites, a one-time application has the potential to reduce a DNAPL source to the point where either natural attenuation is sufficient to address a weakened plume, or pump and treat needs to be applied for over a shorter duration in the future.

8.5 Availability/Transportability

Nanoscale zero-valent iron is commercially available from a few vendors. The food-grade vegetable oil and surfactant are commercially available from a variety of vendors. Mixing the emulsion of iron, oil, surfactant, and water generally would take place on site just prior to injection. Until the difficulties associated with injecting and distributing the emulsion mixture into the subsurface are resolved, a specialized vendor is recommended. The EZVI technology is not yet available in the form of a mobile mixing/injection unit.

8.6 Materials Handling Requirements

The nanoscale zero-valent iron was available as a solid suspended in water. The food-grade vegetable oil and surfactant do not require any special handling. Mixing equipment is required to form the emulsion.

8.7 Ranges of Suitable Site Characteristics

The following factors should be considered when determining the suitability of a site for the EZVI application. None of these factors necessarily eliminate EZVI from consideration. Rather, these are factors that may make the application less or more economical.

- **Type of contaminants.** Contaminants should be amenable to reduction by zero-valent iron. They types of contaminants most suited for this technology are chlorinated hydrocarbons.
- **Site geology.** The emulsion mixture can be distributed more effectively in sandy soils. Silts or clays can make the application more difficult. Aquifer heterogeneities and preferential flowpaths can make contact between the emulsion and the contaminants much more difficult. DNAPL source zones in fractured bedrock also may pose a challenge.
- **Soil characteristics.** Soils with high organic carbon content may require more emulsion because the organic matter may compete with the contaminant for the reductive capacity of the iron. More testing is needed to explore the influence of soil characteristics on the EZVI technology.
- **Regulatory acceptance.** EZVI has long-term benefits in terms of a diminished DNAPL source. However, use of the emulsified iron may temporarily increase the concentrations of dissolved iron beyond secondary drinking water standards. More testing is needed to explore this possibility. Regulatory acceptance is important for this application and a UIC permit or variance may be required. In addition, hydraulic control requirements and economics at some sites may necessitate extraction, treatment, and reinjection of the groundwater. A reinjection permit will be required.
- **Site accessibility.** Sites that have no aboveground structures and fewer utilities are easier to remediate with EZVI. The presence of buildings or a network of utilities can make the application more difficult because of the need for injection wells.

8.8 Limitations

The EZVI technology has the following limitations:

- Not all types of contaminants are amenable to reductive transformation.
- Currently, EZVI is not commercially available. However, bulk volumes can be produced by a limited number of vendors. Nanoscale zero-valent iron particulate is available in bulk from a (limited) number of vendors. Also, the handling of nanoscale zero-valent iron requires extreme care: the particulates are flammable when exposed to air, and the iron may stain the site during emulsion preparation. Once the required volume of emulsion is prepared, it can be stored in drums.
- Byproducts of reduction may make EZVI unsuitable for application in a region very close to a receptor. Certain byproducts (such as dissolved iron and chloride) are subject to secondary, nonhealth-based drinking water standards, and require sufficient time and distance to dissipate. Also, EZVI byproducts may promote the growth of some indigenous microbes, which could adversely inhibit other activities in the aquifer.
- Aquifer heterogeneities can make the application of EZVI more difficult, necessitating more complex application schemes, greater amounts of emulsion, longer injection times, and/or multiple injections. EZVI injection may not be suitable in tight aquifer materials, such as clay or silt.
- Multiple injections of the emulsion mixture may be necessary to prevent the accumulation of degradation products, such as VC.
- Some sites may require greater hydraulic control to minimize the spread of contaminants. This may necessitate the use of extraction, aboveground treatment, and disposal/reinjection of groundwater.

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Appendix A

Performance Assessment Methods

A.1 Summary of Statistics
A.2 Sample Collection and Extraction Methods
A.3 List of Standard Sample Collection and Analytical Methods

Appendix A.1 Summary of Statistics

This summarizes the results of our statistical analyses of TCE monitoring data for the EZVI plot. The basic approach we used is the same as for previous remediation technologies (e.g., Steam). This approach consists of three main steps: (1) perform a semivariogram analysis to assess spatial correlation, (2) perform a kriging analysis to estimate the global (i.e., overall) average TCE concentration, and (3) using a normal distribution assumption, calculate confidence bounds for the estimates and assess the statistical significance of any observed average TCE reductions. In addition, for the EZVI plot, we considered two other topics: (1) the effect on the conclusions due to one high, post-demonstration TCE concentration in soil, and (2) analysis of TCE concentrations in groundwater.

Soil Monitoring Data (Full Data Set)

Although soil monitoring data were collected for all three stratigraphic layers (i.e., lower sand unit, middle fine-grained unit, and upper sand unit [USU]), statistical analyses were only conducted with the USU data. This is because the pre-demonstration soil data for the LSU and MFGU layers indicated only relatively small amounts of TCE, and it was decided these lower two layers might not provide an adequate setting for the demonstration.

Based on the spatial coordinates provided, the EZVI plot was defined to be an area of 14.92 ft. by 9.46 ft. The USU layer is assumed to be a horizontal stratigraphic unit with a constant thickness of 20 ft., centered at a vertical midpoint of -4.79 ft. (i.e., 4.79 ft. below mean sea level). For the purposes of kriging the global average TCE concentration, these dimensions are held constant for all calculations with the pre-demonstration and post-demonstration data.

In the semivariogram and kriging analyses, only those data were used which were classified by the geologists as belonging to the USU layer as shown in Table A-1. This layer was sampled pre-demonstration by a series of 8 drill holes, and post-demonstration by a series of 11 drill holes. In both cases, the drill holes were placed to provide roughly uniform spatial coverage of the EZVI plot. The resulting pre-demonstration data set consisted of N=81 TCE measurements with a sample average of 175.9 mg/kg and a sample standard deviation of 680.7 mg/kg. The resulting post-demonstration data set consisted of N=104 TCE measurements with a sample average of 105.5 mg/kg and a sample standard deviation of 468.0 mg/kg.

Table A-2 summarizes that the estimated (kriged) pre-demonstration global average TCE concentration is 220.1 mg/kg, with a two-sided, 80% confidence interval from 82.3 to 357.9 mg/kg. The kriged post-demonstration global average TCE concentration is 92.4 mg/kg, with a two-sided, 80% confidence interval from 19.3 to 165.4 mg/kg. To test whether the average TCE reduction is significant, we calculated an 80% lower confidence bound (LCB) on the difference of the Pre-demo minus Post-demo TCE concentrations. If this LCB is greater than 0 (zero), then the average reduction is significant at the 20% significance level. The estimated average TCE concentration reduction (i.e., Pre-demo minus Post-demo) is 127.7 mg/kg (i.e., 58% of the TCE was removed), with an 80% LCB of 25.6 mg/kg, which is significant at the 20% significance level. In fact, this reduction is significant up to about the 15% level of significance.

Effect of a Single High Soil Datum

As noted above, N=104 post-demonstration TCE data were collected from the EZVI plot. The majority of these data were found to be below 10 mg/kg, with 83% of the data being below 100 mg/kg, and all but two of the data being below 1000 mg/kg. The single highest measured TCE concentration was 4,502 mg/kg and the second highest TCE concentration was 1,023 mg/kg. Because the highest TCE datum was well above the rest of the data set, there was a question as to how strongly this single datum might affect the overall statistical results. Generally speaking, if the results of an analysis can be significantly influenced by a single data point, then it is important to confirm the accuracy of that data point, and perhaps to caution reviewers that the study conclusions might be heavily tied to this one datum.

To address this potential question, the kriging analysis of the soil monitoring data was repeated after eliminating the single highest post-demonstration datum from the data set (see Table A-3). The reduced post-demonstration data set included N=103 TCE measurements with a sample average of 62.8 mg/kg and a sample standard deviation of 172.7 mg/kg. With the reduced data set, the kriged post-demonstration global average TCE concentration is 59.2 mg/kg, with a two-sided, 80% confidence interval from 35.9 to 82.6 mg/kg. The estimated average TCE concentration reduction (i.e., Pre-demo minus Post-demo) is 160.9 mg/kg (i.e., 73% of the TCE was removed), with an 80% LCB of 69.3 mg/kg, which is significant at the 20% significance level and up to about the 7% level of significance.

Clearly, eliminating the single highest post-demonstration data point would result in several predictable changes to the statistical results (in Table A-4): (a) the kriged post-demonstration average TCE concentration would drop (i.e., from 92.4 to 59.2 mg/kg), (b) the variability in post-demonstration data would drop and result in tighter confidence bounds on the post-demonstration average (i.e., width of the confidence interval (upper confidence bound minus lower confidence bound) would decrease from 146.1 to 46.7 mg/kg), the average TCE reduction and percentage reduction would increase (i.e., increase from 127.7 to 160.9 mg/kg, and from 58% to 73%, respectively), and the statistical significance of the average TCE concentration reduction would also increase (i.e., from 15% to 7% significance level).

Groundwater Monitoring Data

In addition to the soil monitoring data, a limited number of samples were collected from the groundwater in the EZVI plot before and after the demonstration. Although they may not be direct measurements of TCE levels in the soil, they may provide indirect evidence of TCE reductions.

A total of N=20 pairs of groundwater TCE concentrations were collected from four wells in the EZVI plot, each pair consisting of a pre-demonstration and post-demonstration TCE concentration at the same depth. In addition, a 21st pair of pre-demo and post-demo TCE concentrations was collected from a fifth well in the EZVI plot. Unfortunately, these data included too few discrete spatial locations to allow for a semivariogram and kriging analysis, and the overall sample size is probably too small to allow for strong statistical conclusions to be drawn. However, recognizing these limitations, a paired t-test analysis was conducted to estimate the groundwater average TCE reductions and assess possible statistical significance.

In the paired t-test analysis (Table A-5), the difference between the pre-demonstration and post-demonstration TCE concentrations (i.e., the TCE reduction) is calculated at each discrete sampling location, and then the average difference in this data set is estimated. The corresponding statistical test (using the Student's t distribution instead of the normal distribution) evaluates whether the average difference (i.e., reduction) is significantly greater than zero (0). The results of this analysis indicate that the average TCE reduction for the 21 pairs of data was 804 umoles/L, and the statistical significance of the reduction is 0.66%. Even though the groundwater data set is small, the average TCE reductions still appear to be quite significant.

Table A-1. Summary Statistics of TCE Concentrations in Soil from Upper Sand Unit

			Concentration (mg/Kg)						
Survey	**Unit**	**N**	**Mean**	**Stdev**	**Min**	**1st Qu.**	**Median**	**3rd Qu.**	**Max**
Pre Demo	USU	81	175.85	680.69	0.18	0.36	44	187	6,067
Post Combined	USU	104	105.46	467.99	0.18	0.18	1	17.5	4,502

Table A-2. Summary of Kriged TCE Soil Data from both Pre- and Post-demonstration soil results in Upper Sand Unit

Soil density = 1,590 kg/m^3

	Depth	Area	Volume	Concentration (mg/Kg)				Mass (Kg)			
Pre-Demo	ft	ft^2	^{3}	Mean	Var	Lower	Upper	Mean	Var	Lower	Upper
	20.00	141.14	79.93	220.10	11550.00	82.32	357.88	27.97	186.56	10.46	45.48
Post-Demo	Depth	Area m	Volume	Concentration (mg/Kg)				Mass (Kg)			
	ft	ft^2	^{3}	Mean	Var	Lower	Upper	Mean	Var	Lower	Upper
	20.00	141.14	79.93	92.37	3245.87	19.33	165.40	11.74	52.43	2.46	21.02
Pre-Post	Depth	Area m	Volume	Concentration (mg/Kg)				Mass (Kg)			
	ft	ft^2	^{3}		Var	Lower	Upper	Mean	Var		Upper
		141.14	79.93	127.73	14795.87	25.56	283.67	16.23	238.99	3.25	36.05
% Reduction = (1 - Post / Pre) * 100		Area m	Volume	Mean							
		ft^2	^{3}			Lower	Upper				
		141.14	79.93	58		22	94				

20.00 Depth m Mean

ft
20.00

Table A-3. Summary Statistics of TCE Concentrations in Soil from Upper Sand Unit without Highest TCE Datum

						Concentration (mg/Kg)			
Survey	**Unit**	**N**	**Mean**	**Stdev**	**Min**	**1st Qu.**	**Median**	**3rd Qu.**	**Max**
Pre-Demo	USU	81	175.85	680.69	0.18	0.36	44	187	6,067
Post Combined	USU	103	62.77	172.67	0.18	0.18	1	17	1,023

Table A-4. Summary of Kriged TCE Soil Data from both Pre- and Post-demonstration soil results in Upper Sand Unit without Highest TCE Datum

Pre-Demo

	Depth	Area	Volume	Concentration (mg/Kg)				Mass (Kg)			
	ft	ft^2	^{3}	Mean	Var	Lower	Upper	Mean	Var	Lower	Upper
USU	20.00	141.14	79.93	220.10	11550.00	82.32	357.88	27.97	186.56	10.46	45.48

m

PostDemo (Combined)

	Depth	Area	Volume	Concentration (mg/Kg)				Mass (Kg)			
	ft	ft^2	^{3}	Mean	Var	Lower	Upper	Mean	Var	Lower	Upper
USU	20.00	141.14	79.93	59.22	331.57	35.88	82.57	7.53	5.36	4.56	10.49

m

Pre - Post

	Depth	Area	Volume	Concentration (mg/Kg)				Mass (Kg)			
	ft	ft^2	^{3}	Mean	Var	Lower	Upper	Mean	Var	Lower	Upper
USU	20.00	141.14	79.93	160.88	11881.57	69.32	300.62		191.92	8.81	38.21

m

% Reduction = (1 - Post / Pre) * 100

	Depth	Area	Volume				
		ft^2	^{3}	Mean	Lower	Upper	
USU	20.00	141.14	79.93	73	55	88	20.45

m

ft

Table A-5. Summary Statistics of TCE Concentrations in Groundwater from Upper Sand Unit

			Concentration µmoles/L		
Pre-Demo	**N**	**Mean**	**Stderr**	**LCL**	**UCL**
All	21	1,424	446	833	2,015
Low	13	33	12	17	49
High	8	3,685	560	2,893	4,477
Post-Demo	**N**	**Mean**	**Stderr**	**LCL**	**UCL**
All	21	620	280	249	992
Low	13	14	5	7	21
High	8	1,605	604	751	2,460
Pre - Post	**N**	**Mean**	**Stderr**	**LCL**	**UCL**
All	21	804	295	413	1,195
Low	13	19	14	0	37
High	8	2,079	527	1,334	2,825

One Sample t-Test for "Pre - Post"

		T	**p-value**
All	21	2.72	1.31%
Low	13	1.36	19.86%
High	8	3.95	0.55%

Reduction

N		**Mean**	**Stderr**	**LCL**	**UCL**
All	21	25%	27%	-11%	60%
Low	13	1%	42%	-56%	58%
High	8	63%	12%	46%	80%

LCL **N** 80% Lower confidence limit (for a 2 side confidence interval)
UCL 80% Upper confidence limit (for a 2 side confidence interval)

Table A-6. Summary Statistics of EZVI Demonstration for TCE Concentrations in Soil (mg/kg)

			Concentration (mg/Kg)						
Survey	**Unit**	**N**	**Mean**	**Stdev**	**Min**	**1st Qu.**	**Median**	**3rd Qu.**	**Max**
Pre-demonstration	USU	81	175.8514	680.6889	0.18	0.36	44	187	6067
Pre-demonstration	MFGU	44	123.793	122.995	0.18	1	55.5	248	340
Pre-demonstration	LSU	34	3.792941	9.388218	0.18	0.18	0.18	1	33
Intermediate	USU	49	95.98082	229.4949	0.18	0.18	1	35	1023
Intermediate	MFGU	9	186.5556	108.3295	1	133	247	252	296
Intermediate	LSU	0	NA	NA	NA	NA	NA	NA	NA
Post-Demonstration	USU	55	113.8985	608.9154	0.18	0.18	1	12	4502
Post-Demonstration	MFGU	28	77.18143	89.70052	0.18	5	40	131.5	293
Post-Demonstration	LSU	30	2.204667	6.424438	0.18	0.18	0.18	0.18	27
Post Combined	USU	104	105.4565	467.9888	0.18	0.18	1	17.5	4502
Post Combined	MFGU	37	103.7859	104.4303	0.18	9	58	204	296
Post Combined	LSU	30	2.204667	6.424438	0.18	0.18	0.18	0.18	27

USU: Upper Sand Unit
MFGU: Middle Fine-Grained Unit
LSU: Lower Sand Unit

A.2 Sample Collection and Extraction Methods

This section describes the modification made to the EPA standard methods to address the lithologic heterogeneities and extreme variability of the contaminant distribution expected in the DNAPL source region at Launch Complex 34. Horizontal variability was addressed by collecting a statistically determined number of soil cores in the EZVI Plot. The vertical variability at each soil coring location was addressed with this modified sampling and extraction procedure, which involved extraction of much larger quantities of soil in each extracted sample, as well as allowed collection and extraction of samples in the field per event. This extraction allowed the extraction and analysis of the entire vertical column of soil at a given coring location.

A.2.1 Soil Sample Collection (Modified ASTM D4547-91) (1997a)

The soil samples collected before and after the demonstration were sampled using a stainless steel sleeve driven into the subsurface by a Vibra-push LD-2 rig. After the sleeve had been driven the required distance, it was brought to the surface and the soil sample was examined and characterized for lithology. One quarter of the sample was sliced from the core and placed into a pre-weighed 500-mL polyethylene container containing methanol. At locations where a field duplicate sample was collected, a second one-quarter sample was split from the core and placed into another pre-weighed 500-mL polyethylene container containing methanol. The remaining portion of the core was placed into a 55-gallon drum and disposed of as waste. The samples were labeled with the date, time, and sample identification code, and stored on ice at 4°C until they were brought inside to the on-site laboratory for the extraction procedure.

After receiving the samples from the drilling activities, personnel staffing the field laboratory performed the methanol extraction procedure as outlined in Section A.2.2 of this appendix. The amount of methanol used to perform the extraction technique was 250 mL. The extraction procedure was performed on all of the primary samples collected during drilling activities and on 5% of the field duplicate samples collected for quality assurance. Samples were stored at 4°C until extraction procedures were performed. After the extraction procedure was finished, the soil samples were dried in an oven at 105°C and the dry weight of each sample was determined. The samples were then disposed of as waste. The remaining three-quarter section of each core previously stored in a separate 500-mL polyethylene bottle were archived until the off-site laboratory had completed the analysis of the methanol extract. The samples were then disposed of in an appropriate manner.

A.2.2 Soil Extraction Procedure (Modified EPA SW846-Method 5035)

After the soil samples were collected from the drilling operations, samples were placed in pre-labeled and pre-weighed 500-mL polyethylene containers with methanol and then stored in a refrigerator at 4°C until the extraction procedure was performed. Extraction procedures were performed on all of the “A” samples from the outdoor and indoor soil sampling. Extraction procedures also were performed on 5% of the duplicate (or “B”) samples to provide adequate quality assurance/quality control (QA/QC) on the extraction technique.

Extreme care was taken to minimize the disturbance of the soil sample so that loss of volatile components was minimal. Nitrile gloves were worn by field personnel whenever handling sample cores or pre-weighed sample containers. A modification of EPA SW846-Method 5035 was used to procure the cored samples in the field. Method 5035 lists different procedures for processing samples that are expected to contain low concentrations (0.5 to 200 μg/kg) or high concentrations

(>200 µg/kg) of volatile organic compounds (VOCs). Procedures for high levels of VOCs were used in the field because those procedures facilitated the processing of large-volume sample cores collected during soil sampling activities.

Two sample collection options and corresponding sample purging procedures are described in Method 5035; however, the procedure chosen for this study was based on collecting approximately 150 to 200 g of wet soil sample in a pre-weighed bottle that contains 250 mL of methanol. A modification of this method was used in the study, as described by the following procedure:

- The 150 to 200 g wet soil sample was collected and placed in a pre-weighed 500 mL polypropylene bottle filled with 250 mL of methanol. After capping, the bottle was reweighed to determine the total weight of the soil and the bottle with methanol. The bottle was marked with the location and the depth at which the sample was collected.
- After the containers were filled with methanol and the soil sample they were placed on an orbital shaker table and agitated for approximately 30 min.
- Containers were removed from the shaker table and reweighed to ensure that no methanol was lost during the agitation period. The containers were then placed upright and suspended soil matter was allowed to settle for approximately 15 min.
- The 500 mL containers were then placed in a floor-mounted centrifuge. The centrifuge speed was set at 3,000 rpm and the samples were centrifuged for 10 min.
- Methanol extract was then decanted into disposable 20-mL glass volatile organic analysis (VOA) vials using 10-mL disposable pipettes. The 20-mL glass VOA vials containing the extract then were capped, labeled, and stored in a refrigerator at 4°C until they were shipped on ice to the analytical laboratory.
- Methanol samples in VOA vials were placed in ice chests and maintained at approximately 4°C with ice. Samples were then shipped with properly completed chain-of-custody forms and custody seals to the subcontracted off-site laboratory.
- The dry weight of each of the soil samples was determined gravimetrically after decanting the remaining solvent and drying the soil in an oven at 105°C. Final concentrations of VOCs were calculated per the dry weight of soil.

Three potential concerns existed with the modified solvent extraction method. The first concern was that the United States Environmental Protection Agency (U.S. EPA) had not formally evaluated the use of methanol as a preservative for VOCs. However, methanol extraction often is used in site characterization studies including three technology demonstrations at Launch Complex 34 under U.S. EPA Superfund Innovative Technology Evaluation (SITE) program, so the uncertainty in using this approach was reasonable. The second concern was that the extraction procedure itself would introduce a significant dilution factor that could raise the method quantitation limit beyond that of a direct purge-and-trap procedure. The third concern was that excess methanol used in the extractions would likely fail the ignitability characteristic, thereby making the unused sample volume a hazardous waste. During characterization activities, the used methanol extract was disposed of as hazardous waste into a 55-gallon drum. This methanol extraction method was tested during preliminary site characterization activities at this site (see Appendix G, Table G-1) and, after a few refinements, was found to perform acceptably in terms of matrix spike recoveries. Spiked TCE recoveries in replicate samples ranged from 72 to 86%.

The analytical portion of Method 5035 describes a closed-system purge-and-trap process for use on solid media such as soils, sediments, and solid waste. The purge-and-trap system consists of a unit that automatically adds water, surrogates, and internals standards to a vial containing the sample. DHL Analytical performed the analysis of the solvent extraction samples by Gas chromatogram/mass spectrum (GC/MS). Soil samples were analyzed for organic constituents according to the parameters summarized in Table A-7. Laboratory instruments were calibrated for VOCs listed under U.S. EPA Method 601 and 602. Samples were analyzed as soon as was practical and within the designated holding time from collection (14 days). No samples were analyzed outside of the designated 14-day holding time.

Table A-7. Soil Sampling and Analytical Parameters

Analytes	Extraction Method	Analytical Method	Sample Holding Time	Matrix
VOCs[(a)]	SW846-5035	SW846-8260	14 days	Methanol

(a) EPA 601/602 list.

A.3 List of Standard Sample Collection and Analytical Methods

Table A-8. Sample Collection Procedures

Measurements	Task/Sample Collection Method	Equipment Used
Primary Objectives		
CVOCs	Soil sampling/ Mod.[(a)] ASTM D4547-98 (1997a)	Butyrate or acetate sleeves 500-mL plastic bottle
CVOCs	Groundwater sampling/ Mod.[(a)] ASTM D4448-01 (1997b)	Peristaltic pump Teflon™ tubing
DHG[(b)]	Groundwater sampling/ Mod.[(a)] ASTM D4448-01 (1997b)	Peristaltic pump Teflon™ tubing
Secondary Objectives		
Field parameters[(c)] Inorganics–cations Inorganics–anions TOC, BOD, TDS, dissolved silica Alkalinity	Groundwater sampling/ Mod.[(a)] ASTM D4448-01 (1997b)	Peristaltic pump Teflon™ tubing
Hydraulic conductivity	Hydraulic conductivity/ ASTM D4044-96 (1997c)	Winsitu® data logger Laptop computer
Groundwater level	Water levels	Water level indicator

(a) Modifications to ASTM.
ASTM = American Society for Testing and Materials.
American Society for Testing and Materials. 1997a. *Standard Practice for Waste and Soils for Volatile Organics*. Designation: D 4547-98.
American Society for Testing and Materials. 1997b. *Standard Guide for Sampling Groundwater Monitoring Wells*. Designation: D 4448-01.
American Society for Testing and Materials. 1997c. *Standard Test Method (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers*. Designation: D 4044-96.

(b) DHG: methane, ethene, and ethane (see Appendix D).

(c) Field parameters include pH, ORP, temperature, DO, and conductivity. A flow-through cell will be attached to the peristaltic pump when measuring field parameters.

Table A-9. Sample Handling and Analytical Procedures

Measurements	Matrix	Amount Collected	Analytical Method	Maximum Holding Time(a)	Sample Preservation(b)	Sample Container	Sample Type
Primary Objectives							
CVOCs	Soil	250 g	Mod. EPA 8260(c)	14 days	4°C	Plastic	Grab
CVOCs	Groundwater	40-mL × 3	EPA 8260	14 days	4°C, pH < 2 HCl	Glass	Grab
DHG(d)	Groundwater	40 mL x 3	RS Kerr Method	7 days	4°C	Glass	Grab
Dehalococcoidis Ethenogenes(e)	Groundwater	2 x 1L	GeneTrac™ (e)	30 days	4°C	Plastic	Grab
Secondary Objectives							
Hydraulic conductivity	Aquifer	NA	ASTM D4044-96 (1997d)	NA	NA	NA	NA
Inorganics–cations(f)	Groundwater	100 mL	EPA 200.8	28 days	4°C	Plastic	Grab
Inorganics–anions(f)	Groundwater	50 mL	EPA 300.0	28 days	4°C	Plastic	Grab
Dissolved silica	Groundwater	250 mL	SW6010	28 days	None	Plastic	Grab
TOC	Soil	20 g	Based on SW9060	28 days	None	Plastic	Grab
TOC	Groundwater	500 mL	EPA 415.1	7 days	4°C, pH < 2 H_2SO_4	Plastic	Grab
TDS	Groundwater	500 mL	EPA 160.1	7 days	4°C	Plastic	Grab
BOD	Groundwater	1,000 mL	EPA 405.1	48 hours	4°C	Plastic	Grab
DHG(d)	Groundwater	40 mL x 3	RS Kerr Method	7 days	4°C	Glass	Grab
Alkalinity	Groundwater	200 mL	EPA 310.1	14 days	4°C	Plastic	Grab
Water levels	Aquifer	NA	Water level from the top of well casing	NA	NA	NA	NA

(a) Samples will be analyzed as soon as possible after the samples arrive in an off-site laboratory. The times listed are the maximum holding times that samples will be held before analysis and still be considered valid. All data obtained beyond the maximum holding times will be flagged.

(b) Samples will be preserved immediately upon sample collection, if required.

(c) Samples will be extracted using methanol on site. For the detailed extraction procedure see Appendix B.

(d) Dissolved hydrocarbon gases are analyzed by R.S. Kerr Method (see Appendix D).

(e) GeneTrac™ is a proprietary method (see Appendix D).

(f) Cations include Ca, Mg, total and dissolved Fe, Mn, K, and Na. Anions include Br, Cl, SO_4, PO_4, NO_3/NO_2 and Alkalinity.

HCl = Hydrochloric acid, H_2SO_4 = Sulfuric acid.

NA = Not applicable.

Appendix B

Hydrogeologic Measurements

- B.1 Performance Monitoring Slug Tests
- B.2 Well Completion Diagrams
- B.3 Soil Coring Logsheets

B.1 Performance Monitoring Slug Tests

Slug tests were performed on well PA-23 within the EZVI plot before and after the demonstrations to assess any effects on aquifer quality caused by the remediation technologies. Pre-demonstration tests were conducted in the wells in March 2002. Post-demonstration tests were completed in December 2002. As the remediation system was applied to just the upper sand unit, slug tests were only performed in the shallow performance monitoring wells in the center of each plot. PA-23 is 24 ft deep with a 5 ft long screen. The test consisted of placing a pressure transducer and 1.5-inch-diameter by 5-ft-long solid PVC slug within the well. After the water level reached equilibrium, the slug was quickly removed. Removal of the slug created approximately 1.5 ft of change in water level within the well. Water level recovery was then monitored for at least 10 minutes using a TROLL pressure transducer/data logger. The data was then downloaded to a notebook computer. Three replicate tests were conducted in each well to ensure repeatable results.

The recovery rates of the water levels were analyzed with the Bouwer (1989) and Bouwer and Rice (1976) methods for slug tests in unconfined aquifers with partially penetrating wells. Graphs were made showing the changes in water level versus time and curve fitted on a semi-logarithmic graph. The slope of the fitted line then was used in conjunction with the well parameters to provide a value of the hydraulic conductivity of the aquifer materials surrounding the well.

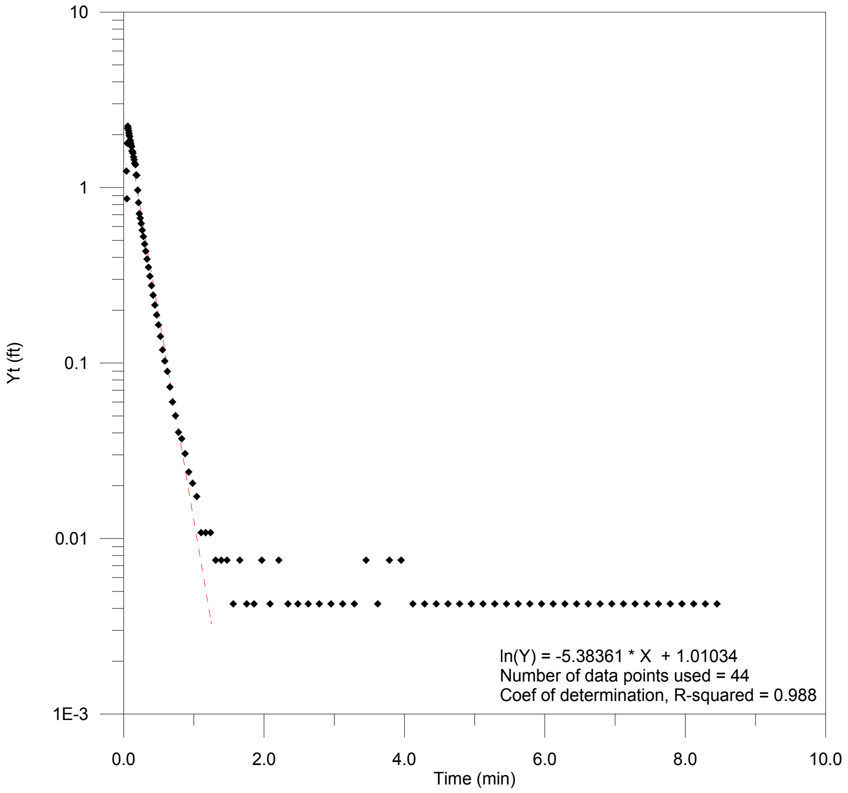
Slug test response curves are presented in this appendix. Water levels returned to equilibrium within 5 minutes for all the tests. Response curves were excellent with coefficients of determination of 0.95 or greater. Table 1 summarizes the results of the slug tests. The results show a very good agreement between the replicate tests. Comparison of the pre-demonstration and post-demonstration slug test results shows mostly negligible changes due to inherent variations in the testing methods. A change of 10 times or greater would indicate a substantial change in permeability at the site. Pre-demonstration hydraulic conductivity averaged 43 ft/day (0.015 cm/sec) in well PA-23. This value is comparable to the typical hydraulic conductivity range in the USU at LC34, which is usually higher than in the underlying hydrostratigraphic units. Post-demonstration hydraulic conductivity averaged 38.2 ft/day (0.013 cm/sec) in PA-23.

Table 1. Slug Test Results

Well	Test	Hydraulic Conductivity (ft/day)	Hydraulic Conductivity (cm/s)	Response (r^2)
PA-23 (EZVI Plot)	Pre-Demonstration			
	A	47.4	0.017	Excellent (0.988)
	B	40.9	0.014	Excellent (0.984)
	C	39.6	0.014	Excellent (0.957)
	Post-Demonstration			
	A	40.5	0.014	Excellent (0.999)
	B	36.1	0.013	Excellent (0.988)
	C	37.9	0.013	Excellent (0.992)

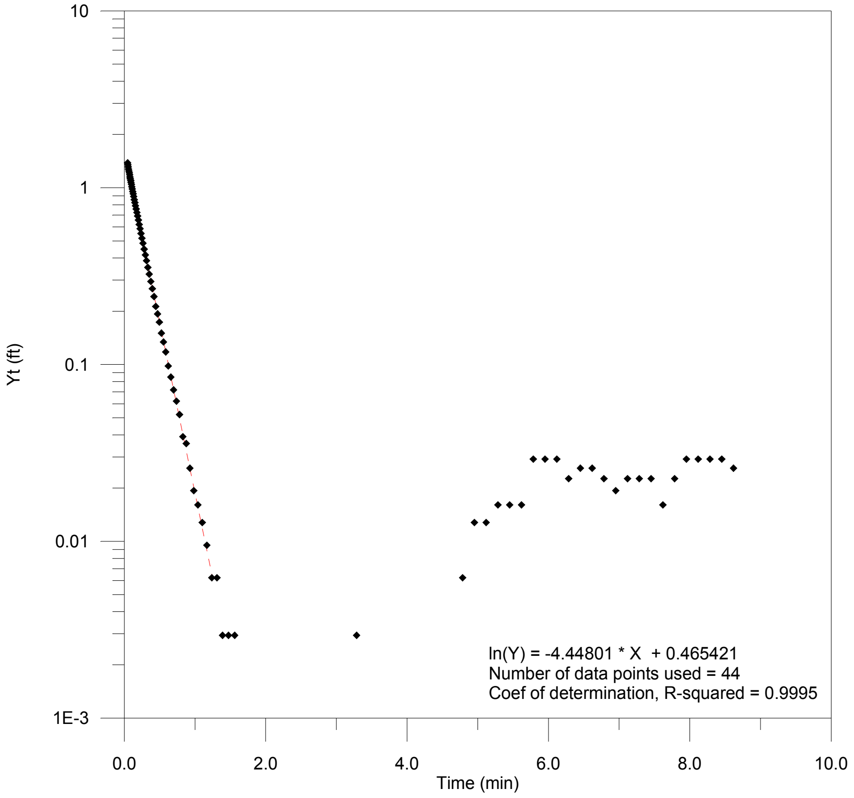
Bouwer, H., and R.C. Rice, 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, Water Resources Research, v.12, n.3, pp. 423-428.
Bouwer, H., 1989, The Bouwer and Rice slug test- an update, Ground Water, v. 27, n.3, pp. 304-309.

Well PA-23: Pre Demo Replicate A

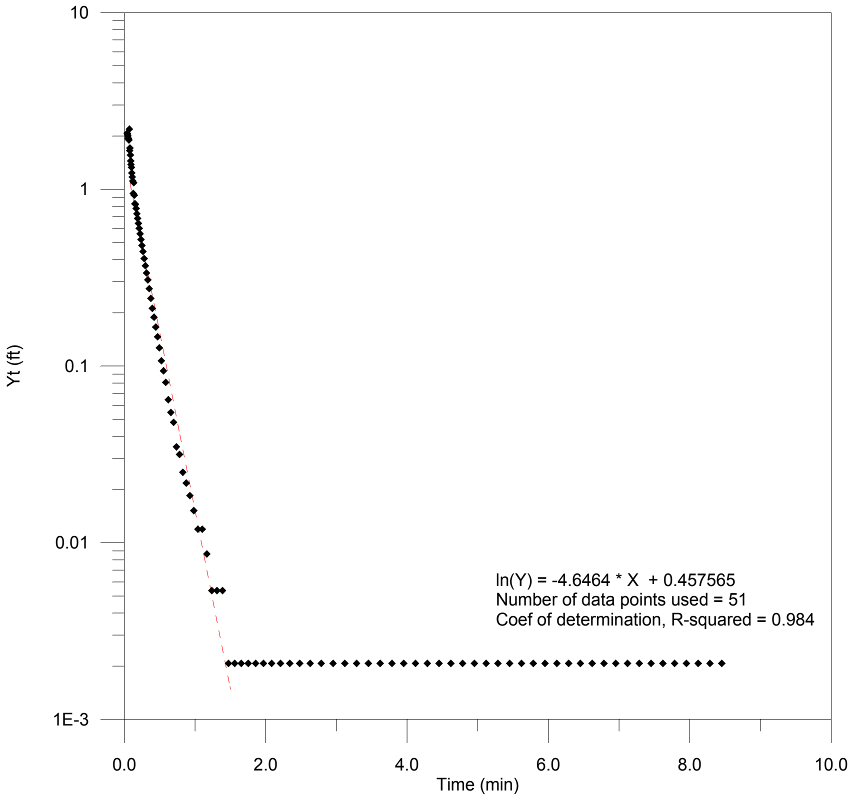


ln(Y) = -5.38361 * X + 1.01034
Number of data points used = 44
Coef of determination, R-squared = 0.988

Well PA-23: Post Demo Replicate A

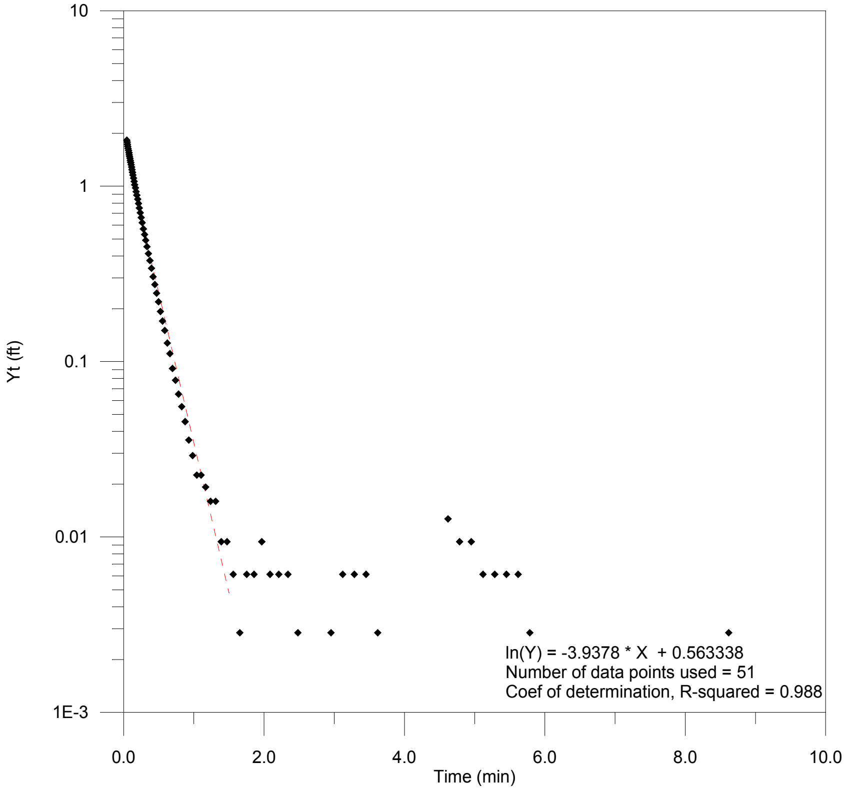


ln(Y) = -4.44801 * X + 0.465421
Number of data points used = 44
Coef of determination, R-squared = 0.9995



Well PA-23: Pre Demo Replicate B

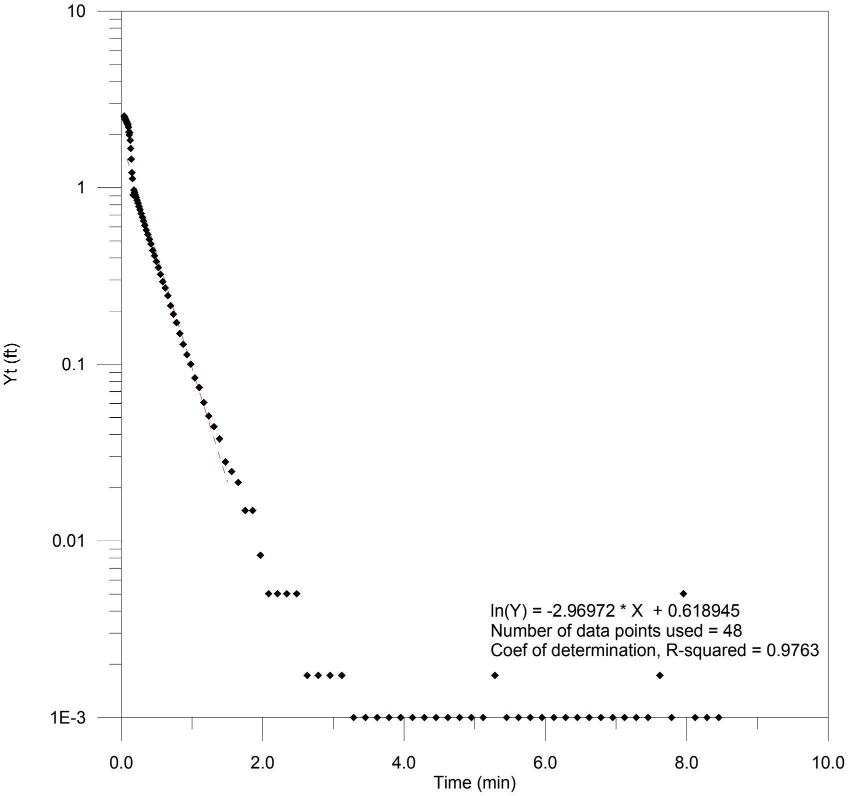
ln(Y) = -4.6464 * X + 0.457565
Number of data points used = 51
Coef of determination, R-squared = 0.984



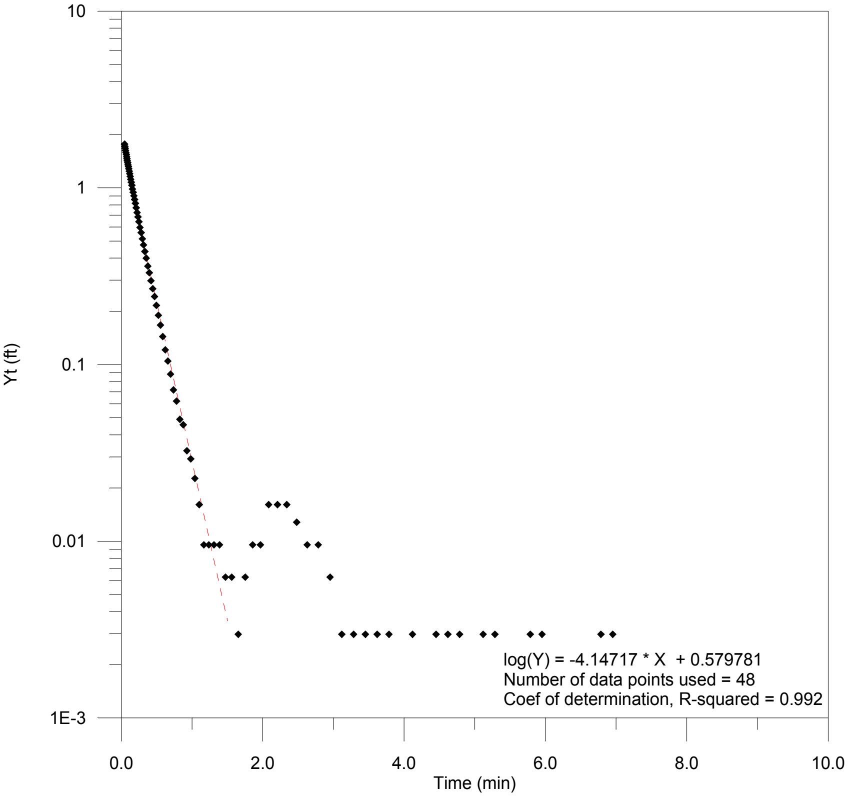
Well PA-23: Post Demo Replicate B

ln(Y) = -3.9378 * X + 0.563338
Number of data points used = 51
Coef of determination, R-squared = 0.988

Well PA-23: Pre Demo Replicate C



Well PA-23: Post Demo Replicate C



B.2 Well Completion Diagrams

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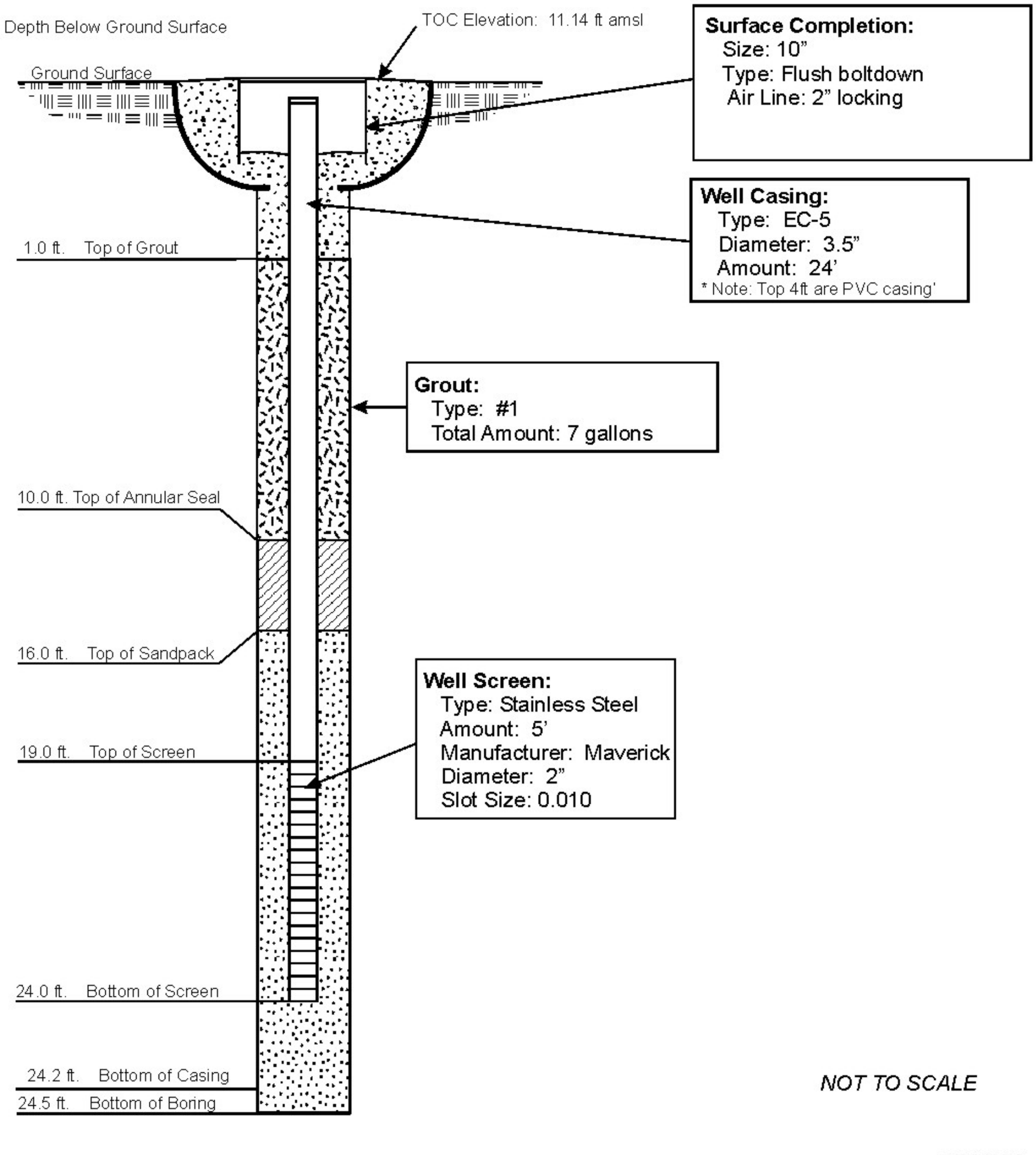
CAPE CANAVERAL
WELL COMPLETION DIAGRAM
PA-23

Project #: G482010-EPA41	Site: CCAS LC34	Well #: EZVI PA-23	Northing (NAD 83): 1521268.57
Drilling Contractor: Precision Sampling	Rig Type and Drilling Method: LD-2 Direct Push	Date: Mar 7, 2002	Easting (NAD 83): 640164.96
Reviewed by: Sam Yoon	Driller: Precision Sampling John Malo	Geologist: MG	Surface Elevation (NAVD 88): 11.14



Surface Completion:
Size: 10”
Type: Flush boltdown
Air Line: 2” locking

Well Casing:
Type: EC-5
Diameter: 3.5”
Amount: 24’
* Note: Top 4ft are PVC casing’

Grout:
Type: #1
Total Amount: 7 gallons

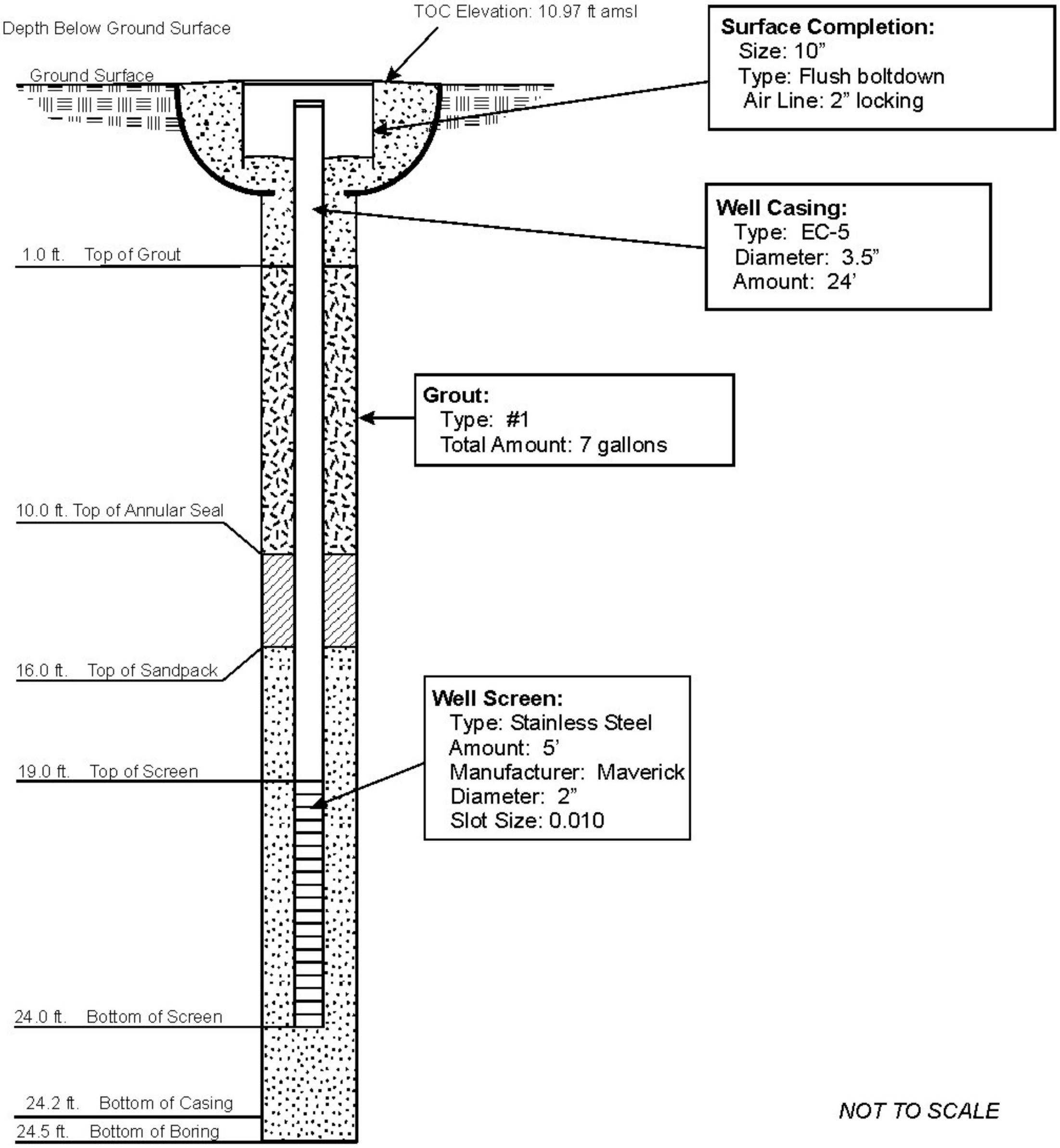
Well Screen:
Type: Stainless Steel
Amount: 5’
Manufacturer: Maverick
Diameter: 2”
Slot Size: 0.010

NOT TO SCALE

WCD-PA23.CDR

CAPE CANAVERAL
WELL COMPLETION DIAGRAM
PA-24S

Project #: G482010-EPA41	Site: CCAS LC34	Well #: EZVI PA-24S	Northing (NAD 83): 1521263.09
Drilling Contractor: Precision Sampling	Rig Type and Drilling Method: LD-2 Direct Push	Date: Mar 18, 2002	Easting (NAD 83): 640174.46
Reviewed by: Sam Yoon	Driller: Precision Sampling John Malo	Geologist: MG	Surface Elevation (NAVD 88): 10.97



Surface Completion:
Size: 10”
Type: Flush boltdown
Air Line: 2” locking

Well Casing:
Type: EC-5
Diameter: 3.5”
Amount: 24’

Grout:
Type: #1
Total Amount: 7 gallons

Well Screen:
Type: Stainless Steel
Amount: 5’
Manufacturer: Maverick
Diameter: 2”
Slot Size: 0.010

NOT TO SCALE

WCD-PA24-S.CDR

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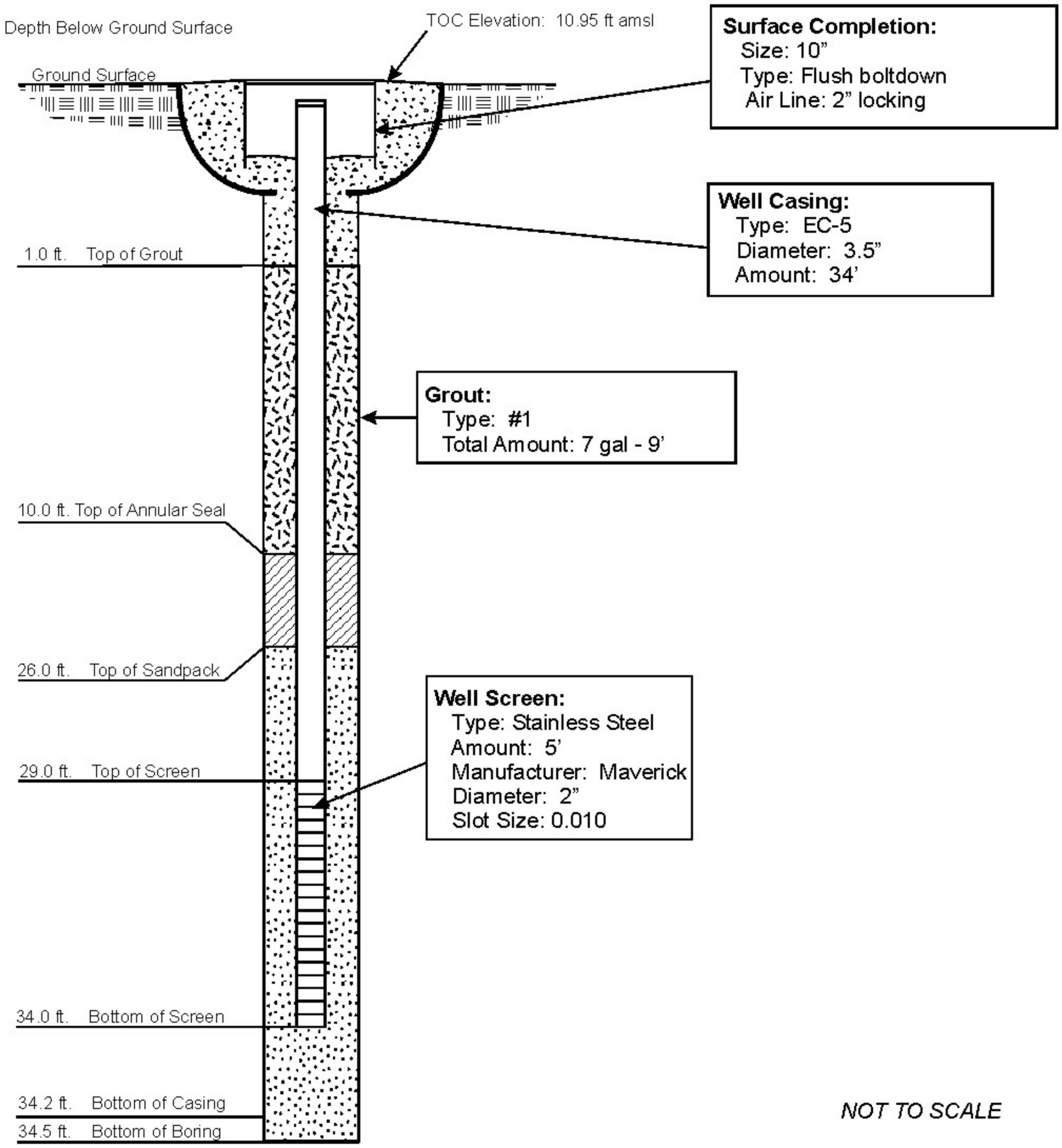
CAPE CANAVERAL
WELL COMPLETION DIAGRAM
PA-24I

Project #: G482010-EPA31	Site: CCAS LC34	Well #: EZVI PA-24I	Northing (NAD 83): 1521261.37
Drilling Contractor: Precision Sampling	Rig Type and Drilling Method: LD-2 Direct Push	Date: Mar 18, 2002	Easting (NAD 83): 640173.44
Reviewed by: Sam Yoon	Driller: Precision Sampling John Malo	Geologist: MG	Surface Elevation (NAVD 88): 10.95



Surface Completion:
Size: 10”
Type: Flush boltdown
Air Line: 2” locking

Well Casing:
Type: EC-5
Diameter: 3.5”
Amount: 34’

Grout:
Type: #1
Total Amount: 7 gal - 9’

Well Screen:
Type: Stainless Steel
Amount: 5’
Manufacturer: Maverick
Diameter: 2”
Slot Size: 0.010

NOT TO SCALE

WCD-PA24-I.CDR

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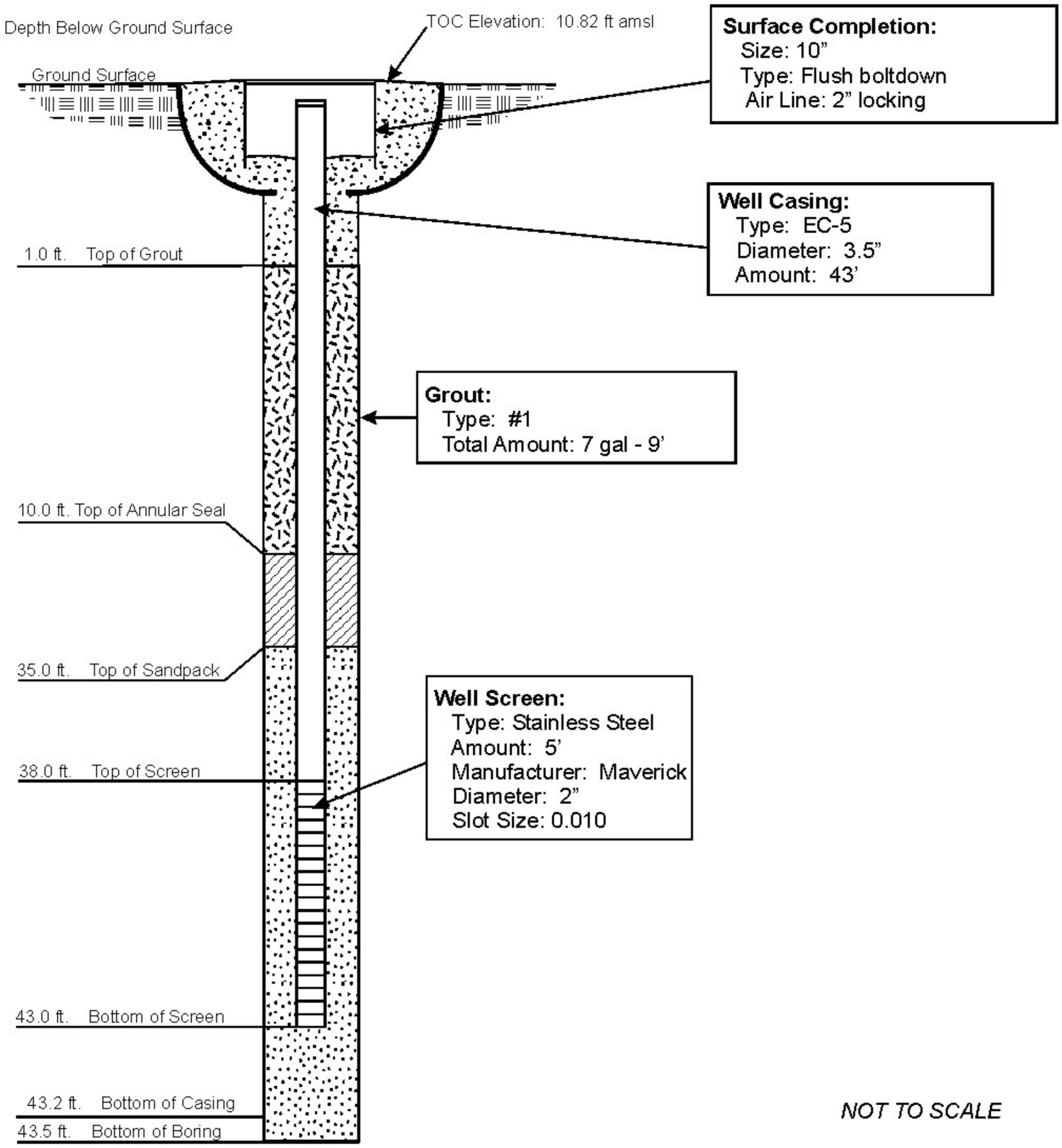
CAPE CANAVERAL
WELL COMPLETION DIAGRAM
PA-24D

Project #: G482010-EPA31	Site: CCAS LC34	Well #: EZVI PA-24D	Northing (NAD 83): 1521259.65
Drilling Contractor: Precision Sampling	Rig Type and Drilling Method: LD-2 Direct Push	Date: Mar 15, 2002	Easting (NAD 83): 640172.42
Reviewed by: Sam Yoon	Driller: Precision Sampling John Malo	Geologist: MG	Surface Elevation (NAVD 88): 10.82



Surface Completion:
Size: 10”
Type: Flush boltdown
Air Line: 2” locking

Well Casing:
Type: EC-5
Diameter: 3.5”
Amount: 43’

Grout:
Type: #1
Total Amount: 7 gal - 9’

Well Screen:
Type: Stainless Steel
Amount: 5’
Manufacturer: Maverick
Diameter: 2”
Slot Size: 0.010

NOT TO SCALE

WCD-PA24-D.CDR

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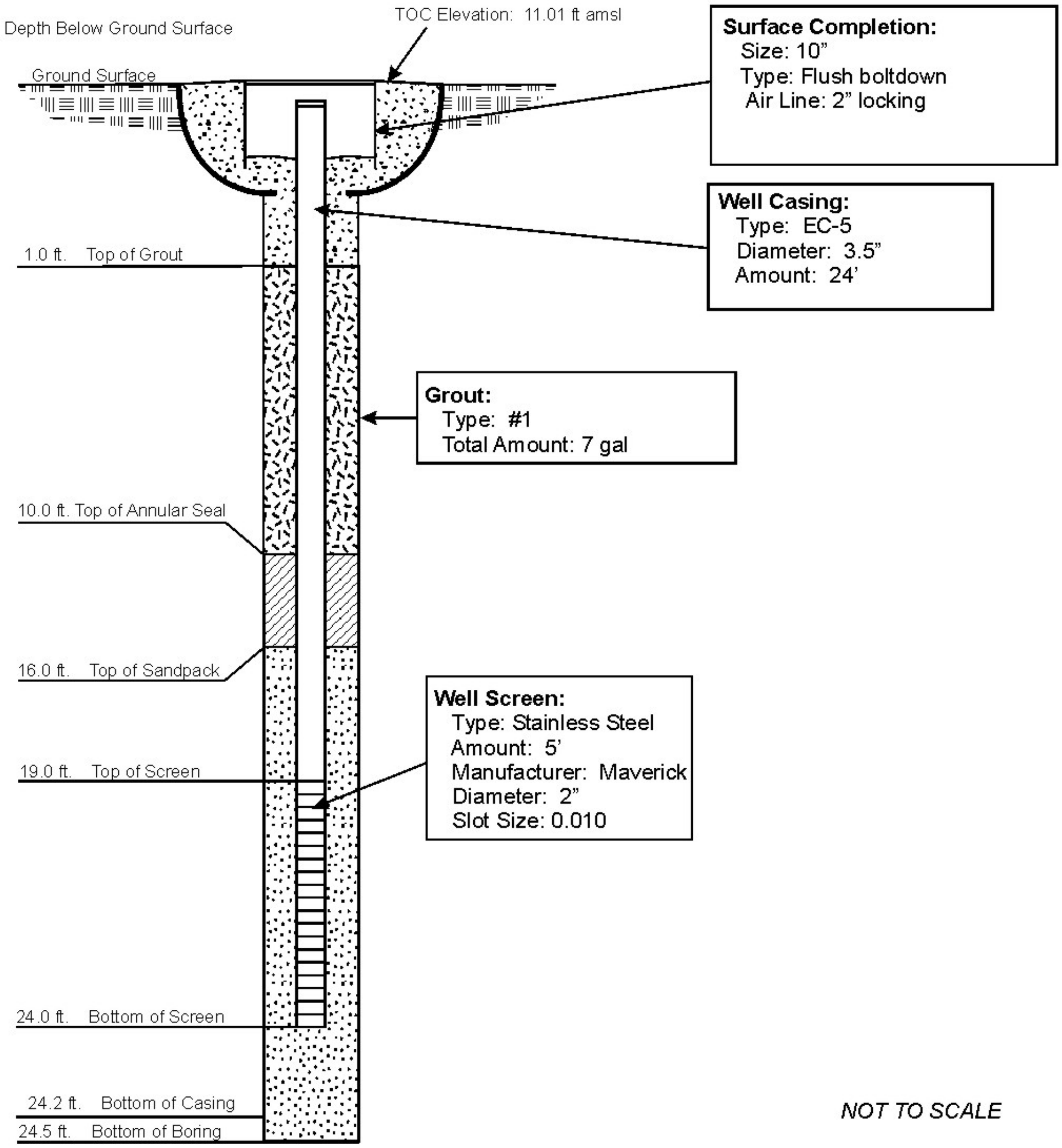
CAPE CANAVERAL
WELL COMPLETION DIAGRAM
PA-25S

Project #: G482010-EPA31	Site: CCAS LC34	Well #: EZVI PA-25S	Northing (NAD 83): 640156.69
Drilling Contractor: Precision Sampling	Rig Type and Drilling Method: LD-2 Direct Push	Date: Mar 11, 2002	Easting (NAD 83): 1521276.77
Reviewed by: Sam Yoon	Driller: Precision Sampling John Malo	Geologist: MG	Surface Elevation (NAVD 88): 11.01



Surface Completion:
Size: 10”
Type: Flush boltdown
Air Line: 2” locking

Well Casing:
Type: EC-5
Diameter: 3.5”
Amount: 24’

Grout:
Type: #1
Total Amount: 7 gal

Well Screen:
Type: Stainless Steel
Amount: 5’
Manufacturer: Maverick
Diameter: 2”
Slot Size: 0.010

NOT TO SCALE

WCD-PA25-S.CDR

Battelle
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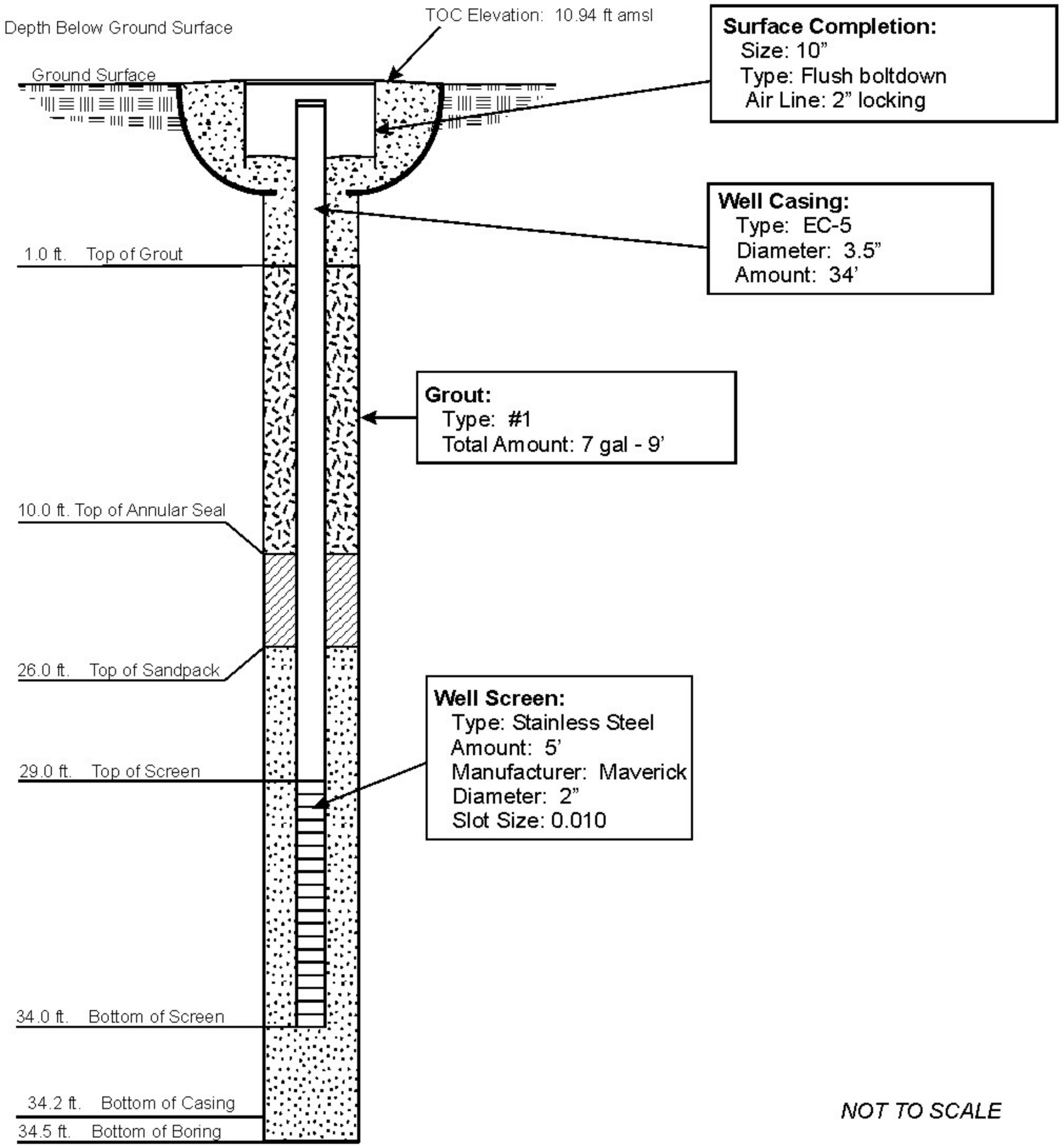
CAPE CANAVERAL
WELL COMPLETION DIAGRAM
PA-25I

Project #: G482010-EPA31	Site: CCAS LC34	Well #: EZVI PA-25I	Northing (NAD 83): 1521274.69
Drilling Contractor: Precision Sampling	Rig Type and Drilling Method: LD-2 Direct Push	Date: Mar 7, 2002	Easting (NAD 83): 640155.68
Reviewed by: Sam Yoon	Driller: Precision Sampling John Malo	Geologist: MG	Surface Elevation (NAVD 88): 10.94



Surface Completion:
Size: 10”
Type: Flush boltdown
Air Line: 2” locking

Well Casing:
Type: EC-5
Diameter: 3.5”
Amount: 34’

Grout:
Type: #1
Total Amount: 7 gal - 9’

Well Screen:
Type: Stainless Steel
Amount: 5’
Manufacturer: Maverick
Diameter: 2”
Slot Size: 0.010

NOT TO SCALE

WCD-PA25-LCDR

Battelle
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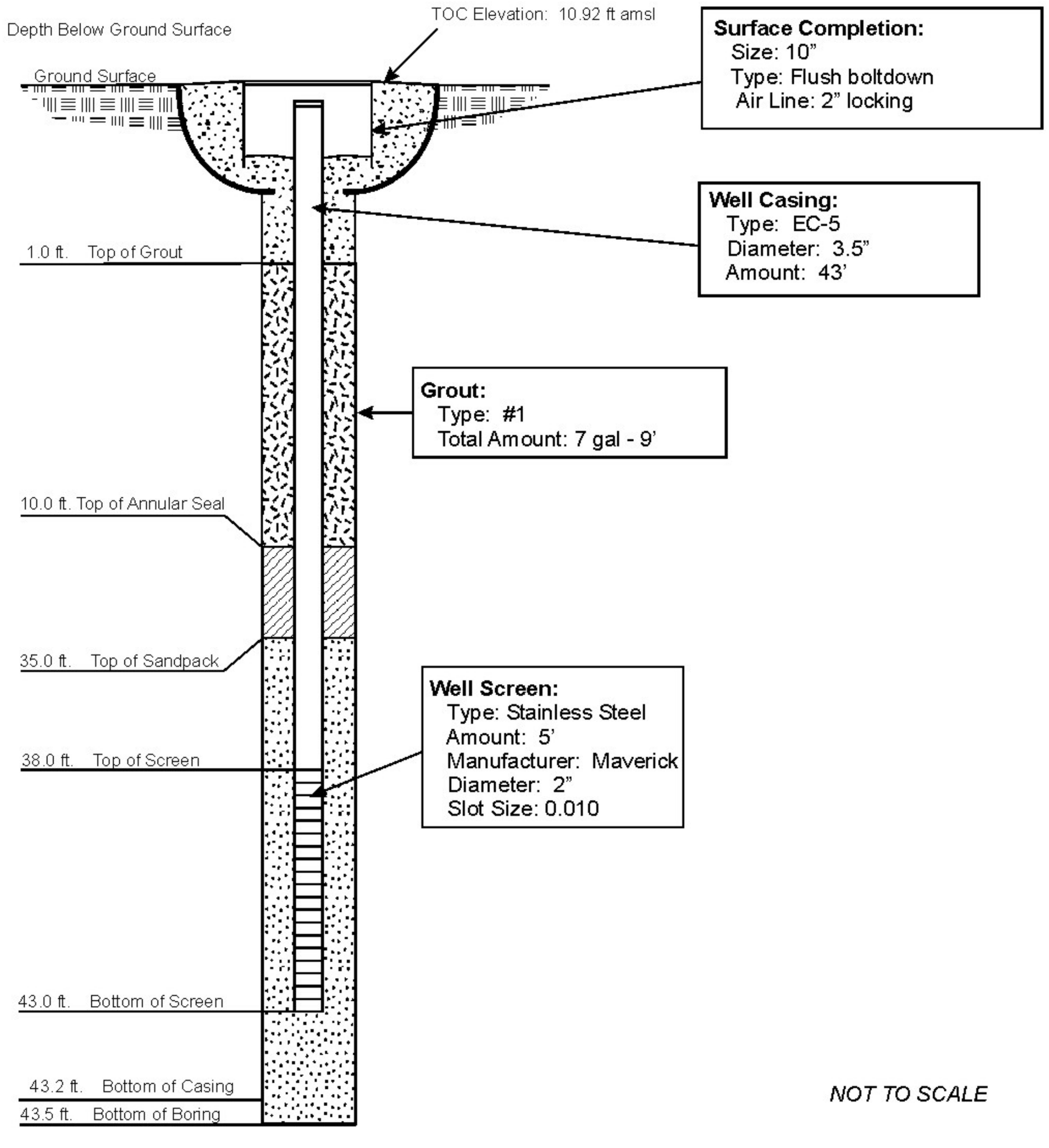
CAPE CANAVERAL
WELL COMPLETION DIAGRAM
PA-25D

Project #: G482010-EPA31	Site: CCAS LC34	Well #: EZVI PA-25D	Northing (NAD 83): 1521272.76
Drilling Contractor: Precision Sampling	Rig Type and Drilling Method: LD-2 Direct Push	Date: Mar 8, 2002	Easting (NAD 83): 640154.65
Reviewed by: Sam Yoon	Driller: Precision Sampling John Malo	Geologist: MG	Surface Elevation (NAVD 88): 10.92



Surface Completion:
Size: 10”
Type: Flush boltdown
Air Line: 2” locking

Well Casing:
Type: EC-5
Diameter: 3.5”
Amount: 43’

Grout:
Type: #1
Total Amount: 7 gal - 9’

Well Screen:
Type: Stainless Steel
Amount: 5’
Manufacturer: Maverick
Diameter: 2”
Slot Size: 0.010

NOT TO SCALE

WCD-PA25-D.CDR

B.3 Soil Coring Logsheets

LC34 Coring Logsheet

Boring ID EZVI-SB1

Date 1/15/02

Location EZVI Plot

Battelle
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Boring Diameter 2 in

Casing Outer Diameter 2 in

Casing Inner Diameter --- in

Casing Material ---

Screen Type ---

Screen Slot ---

Screen Length --- ft

Screen Depth from --- to --- ft

Total Depth 46 ft

Sand Pack ---

Sand Pack Depth from --- to --- ft

Grout Material Portland 15 gal.

Grout Depth from 0 to Depth ft

Surface Completion Grout flush

Drilling Method Direct Push Vibra-core

Driller Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine-med. tan sand	0-5		SP	---	---
Fine-med. tan sand and shell fragments	6-8	EZVI-SBI-8	SP	50	0
Fine-med. tan sand and shells to fine-med. tan-gray sand	8-10	EZVI-SBI-10	SP	75	0
Fine-med. tan-gray sand	10-12	EZVI-SBI-12	SP	75	0
Fine-med. gray sand	12-14	EZVI-SBI-14	SP	75	0
Fine-med. gray sand	14-16	EZVI-SBI-16	SP	75	0
Fine-med. gray sand	16-18	EZVI-SBI-18	SP	75	2.5
Fine-med. gray sand	18-20	EZVI-SBI-20	SP	90	51
Fine-med. gray sand	20-22	EZVI-SBI-22	SP	90	8.3
Fine-med. gray sand	22-24	EZVI-SBI-24	SP	25	15
Fine-med. gray sand and silt	24-26	EZVI-SBI-26	SP	25	53
Silty fine gray sand	26-28	EZVI-SBI-28	SP-SM	75	75
Silty fine gray sand	28-30	EZVI-SBI-30	SP-SM	75	88

Logged by: J. Sminchak

Completion Date: 1/16/02

Construction Notes: 4’ Macro-core acetate sleeves, rinseate = EZVI-SB1 -Rinseate, Dup = EZVI-SB1-8DUP

LC34 Coring Logsheet

Boring ID EZVI-SB1

Date 1/16/02

Location EZVI Plot

Battelle
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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty fine gray sand with some clay	30-32	EZVI-SBI-32	SP-SM	75	90
Silty fine gray sand	32-34	EZVI-SBI-34	SP-SM	75	28
Silty-clayey fine gray sand	34-36	EZVI-SBI-36	SM-SC	90	0
Silty fine gray sand to fine-med. sand and shells	36-38	EZVI-SBI-38	SM-SP	90	0
Silty fine sand to clayey fine gray sand	38-40	EZVI-SBI-40	SM-SC	90	0
Silty-clayey fine gray sand	40-42	EZVI-SBI-42	SC-SM	90	0
Silty fine gray sand with 20% shells	42-44	EZVI-SBI-44	SM-GC	90	0
Coarse shell material in silt to fine gray sand to silty clayey fine sand	44-46	EZVI-SBI-46	GC-SM-SC	90	0.6
Terminate boring at 46' to avoid penetrating confining layer					

LC34 Coring Logsheet

Date 1/15/02

Boring ID EZVI-SB2

Location EZVI Plot

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Boring Diameter	2 in	Total Depth	46 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland 15 gal.
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine-med. tan sand and shell material	0-5	---	SP	---	---
Fine tan sand	6-8	EZVI-SB2-8	SP	75	0
Fine coarse tan-orange-brown sand and shell material	8-10	EZVI-SB2-10	SP	75	0
Fine coarse tan-orange-brown sand and shell material	10-12	EZVI-SB2-12	SP	75	0
Fine coarse tan-orange-brown sand and shell material	12-14	EZVI-SB2-14	SP	75	0
Fine-med. gray sand	14-16	EZVI-SB2-16	SP	90	0.8
Fine-med. gray sand	16-18	EZVI-SB2-18	SP	90	33
Fine-med. gray sand	18-20	EZVI-SB2-20	SP	90	8.2
Fine-med. gray sand with trace silt	20-22	EZVI-SB2-22	SP	90	836
Fine gray sand	22-24	EZVI-SB2-24	SP	90	114
Fine gray sand	24-26	EZVI-SB2-26	SP	90	25
Silty fine gray sand	26-28	EZVI-SB2-28	SP-SM	90	25
Silty fine gray sand	28-30	EZVI-SB2-30	SP-SM	90	6.2

Logged by: J. Sminchak

Completion Date: 1/16/02

Construction Notes: 4' Macro-core acetate sleeves, rinseate = EZVI-SB2

-Rinseate, Dup = EZVI-SB2-24DUP

LC34 Coring Logsheet

Date 1/16/02

Boring ID EZVI-SB2

Location EZVI Plot

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Silty fine gray sand	30-32	EZVI-SB2-32	SM	90	6.2
Silty fine gray sand	32-34	EZVI-SB2-34	SM	90	1.2
Silty fine gray sand to coarse shells	34-36	EZVI-SB2-36	SM-GP	90	0.4
Coarse shells to silty-clayer fine gray sand	36-38	EZVI-SB2-38	GP-SM	90	0.8
Silty-clayey fine sand (plug at 38-38.1’)	38-40	EZVI-SB2-40	SC-SM	90	0
Silty-clayey fine gray sand	40-42	EZVI-SB2-42	SM-SC	90	0
Silty soupy fine gray sand	42-44	EZVI-SB2-44	SM	90	0
Silty to fine sand to coarse shells with silt and clay	44-46	EZVI-SB2-46	SM-GC	90	0
Terminate boring at 46’ to avoid penetrating confining layer					

LC34 Coring Logsheet

Date 1/17/02

Boring ID EZVI-SB3

Location EZVI Plot

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Boring Diameter	2 in	Total Depth	46 ft	
Casing Outer Diameter	2 in	Sand Pack	---	
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft	
Casing Material	---	Grout Material	Portland 15 gal.	
Screen Type	---	Grout Depth	from 0 to Depth ft	
Screen Slot	---	Surface Completion	Grout flush	
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core	
Screen Depth	from --- to --- ft	Driller	Precision	

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Hand auger tan fine-med. sand	0-5	---	SP	---	---
Tan to orange-brown fine sand	6-8	EZVI-SB3-8	SP	75	0
Tan to orange-brown fine sand	8-10	EZVI-SB3-10	SP	75	0
Tan to orange-brown fine sand	10-12	EZVI-SB3-12	SP	75	0
Fine-med. gray sand	12-14	EZVI-SB3-14	SP	75	0
Med-coarse gray sand and shell material	14-16	EZVI-SB3-16	SP	90	0.4
Fine-med. gray sand	16-18	EZVI-SB3-18	SP	90	31
Fine-med. gray sand	18-20	EZVI-SB3-20	SP	90	271
Fine-med. gray sand	20-22	EZVI-SB3-22	SP	90	300
Fine-med. gray sand	22-24	EZVI-SB3-24	SP	75	206
Fine gray sand with trace silt	24-26	EZVI-SB3-26	SP	75	129
Silty fine gray sand	26-28	EZVI-SB3-28	SP-SM	100	18.7
Silty fine gray sand	28-30	EZVI-SB3-30	SP-SM	100	36.1

Logged by: J. Sminchak

Completion Date: 1/17/02

Construction Notes: 4' Macro-core acetate sleeves, rinseate = EZVI-SB3 -Rinseate, Dup = EZVI-SB3-40DUP

LC34 Coring Logsheet

Date 1/16/02

Boring ID EZVI-SB3

Location EZVI Plot

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Lithologic Description	Depth	Sample	USCS	Rec.	PID
Silty fine gray sand	30-32	EZVI-SB3-32	SM	100	2.2
Silty fine gray sand	32-34	EZVI-SB3-34	SM	100	6.3
Silty fine gray sand to coarse shells	34-36	EZVI-SB3-36	SM-SP	90	0.4
Silty fine gray sand, shells, trace clay	36-38	EZVI-SB3-38	SM-SP	90	0.2
Silty-clayey fine gray sand with shells	38-40	EZVI-SB3-40	SM-GC	25	0
Silty-clayey fine gray sand with shells	40-42	EZVI-SB3-42	SM-GC	50	0
Silty clayey fine sand and shells	42-44	EZVI-SB3-44	SM-GC	100	0
Silty clayey fine sand	44-46	EZVI-SB3-46	SM-SC	100	0
Terminate boring at 46’ to avoid penetrating confining layer					

LC34 Coring Logsheet

Date 1/17/02

Boring ID EZVI-SB4

Location EZVI Plot

Battelle
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Boring Diameter	2 in	Total Depth	46 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland 15 gal.
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Hand auger fine tan sand	0-5	---	SP	---	---
Tan to gray fine sand	6-8	EZVI-SB4-8	SP	90	0
Tan to orange fine-med. sand	8-10	EZVI-SB4-10	SP	90	0
Tan to orange fine-med. sand (TOC)	10-12	EZVI-SB4-12	SP	100	0
Fine-med. gray sand	12-14	EZVI-SB4-14	SP	100	0
Fine-med. gray sand	14-16	EZVI-SB4-16	SP	90	78
Fine-med. gray sand	16-18	EZVI-SB4-18	SP	90	64
Silty fine gray sand	18-20	EZVI-SB4-20	SP	90	0.4
Gray fine sand	20-22	EZVI-SB4-22	SP	90	18
Gray fine sand	22-24	EZVI-SB4-24	SP	75	21
Gray fine sand	24-26	EZVI-SB4-26	SP	75	36
Silty fine gray sand	26-28	EZVI-SB4-28	SP-SM	90	35
Silty fine gray sand	28-30	EZVI-SB4-30	SP-SM	90	9.5

Logged by: J. Sminchak

Completion Date: 1/18/02

Construction Notes: 4' Macro-core acetate sleeves, rinseate = EZVI-SB4-Rinseate, Dup = EZVI-SB4-40DUP

LC34 Coring Logsheet

Boring ID EZVI-SB4

Date 1/17/02

Location EZVI Plot

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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty fine gray sand (TOC)	30-32	EZVI-SB4-32	SM-SP	90	8.0
Silty fine gray sand (TOC)	32-34	EZVI-SB4-34	SP-SM	90	5.0
Silty fine gray sand	34-36	EZVI-SB4-36	SM	90	0.5
Coarse shells to fine gray sand	36-38	EZVI-SB4-38	GP-SP	100	0.2
Silty-clayey fine gray sand (TOC)	38-40	EZVI-SB4-40	SM-SC	90	0.4
Coarse shells with gray fine sand (TOC)	40-42	EZVI-SB4-42	GP	50	0
Coarse shells with minor fine gray sand	42-44	EZVI-SB4-44	GP	90	0
Silty fine gray sand to silty clayey fine gray sand	44-46	EZVI-SB4-46	SM-SC	90	0
Terminate boring at 46' to avoid penetrating confining layer					

LC34 Coring Logsheet

Boring ID	EZVI-SB5
Date	1/31/02
Location	EZVI Plot

Battelle
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Boring Diameter	2 in	Total Depth	42 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Flush
Screen Length	--- ft	Drilling Method	Direct Push
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Light brown, light gray, orange-brown med.-fine sand	6-8	EZVI-SB5-8	SP	50	5.9
Orange brown med.-fine sand, trace shells	8-10	EZVI-SB5-10	SP	100	15.6
Orange-brown med-fine sand	10-12	EZVI-SB5-12	SP	75	14.1
Orange-brown med sand with shells to gray med-fine sand w/shells	12-14	EZVI-SB5-14	SP	100	61.2
Gray fine sand with trace shells	14-16	EZVI-SB5-16	SP	95	384
Gray fine sand with trace shells	16-18	EZVI-SB5-18	SP	95	1876
Gray med-fine sand	18-20	EZVI-SB5-20	SP	85	> 2000
Gray med-fine sand	20-22	EZVI-SB5-22	SP	100	> 2000
Gray fine sand	22-24	EZVI-SB5-24	SP	100	> 2000
Gray fine sand	24-26	EZVI-SB5-26	SP	100	> 2000
Gray silty fine sand, trace shells	26-28	EZVI-SB5-28	SM	100	> 2000
Gray silty fine sand	28-30	EZVI-SB5-30	SM	100	> 2000
Gray silty fine sand	30-32	EZVI-SB5-32	SM	75	1800

Logged by: M. Gaberell, L. Cumming

Completion Date: 1/31/02

Construction Notes: 4’ Macro-core acetate sleeves, Dup = EZVI-SB5-38DUP

LC34 Coring Logsheet

Boring ID EZVI-SB5

Date 1/31/02

Location EZVI Plot

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Gray silty fine sand to silty med sand with shells	32-34	EZVI-SB-34	SM	100	1904
Gray silty fine sand to silty med sand with shells	34-36	EZVI-SB5-36	SM	60	1652
Silty med sand with medium to coarse shells	36-38	EZVI-SB5-38	SP	100	1312
Clayey silty sand with shells	38-40	EZVI-SB5-40	SM	100	195
Clayey silty sand with shells	40-42	EZVI-SB5-42	SM	100	220
End at 42’					

LC34 Coring Logsheet

Date 2/1/02

Boring ID EZVI-SB6

Location EZVI Plot

Battelle
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Boring Diameter	2 in	Total Depth	46 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine tan sand	0-5	---	SP	---	---
Brown to yellow to gray fine sand	6-8	EZVI-SB6-8	SP	100	21
Brown fine-med. sand	8-10	EZVI-SB6-10	SP	100	16
Gray fine-med sand	10-12	EZVI-SB6-12	SP	50	15
Fine-med gray sand	12-14	EZVI-SB6-14	SP	100	15
Fine-med gray sand	14-16	EZVI-SB6-16	SP	100	21
Fine-med gray sand	16-18	EZVI-SB6-18	SP	100	603
Fine-med gray sand	18-20	EZVI-SB6-20	SP	100	1317
Fine-med gray sand	20-22	EZVI-SB6-22	SP	100	1202
Gray fine sand, trace shells	22-24	EZVI-SB6-24	SP	80	1200
Gray fine sand, trace shells, med. sand at bottom	24-26	EZVI-SB6-26	SP	80	1600
Gray silty fine to medium sand, little shells	26-28	EZVI-SB6-28	SP-SM	100	96
Gray silty fine to medium sand, trace shells	28-30	EZVI-SB6-30	SM	100	156

Logged by: L. Cumming

Completion Date: 2/1/02

Construction Notes: 4’ Macro-core acetate sleeves, rinseate = EZVI-SB6 -Rinseate, Dup = EZVI-SB6-32DUP

LC34 Coring Logsheet

Boring ID EZVI-SB6

Date 2/2/02

Location EZVI Plot

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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Gray silty fine to medium sand, trace shells	30-32	EZVI-SB6-32	SM	100	601
Gray silty fine to medium sand, trace shells	32-34	EZVI-SB6-34	SM	100	1600
Gray silty fine to medium sand, trace shells	34-36	EZVI-SB6-36	SM	100	45
Gray silty fine to medium sand with shells	36-38	EZVI-SB6-38	SM	100	280
Gray silty fine to medium sand and shells	38-40	EZVI-SB6-40	SM-GM	100	308
Gray silty fine to medium sand and shells to silty sand and clay	40-42	EZVI-SB6-42	GM-SM	50	168
End of core					

LC34 Coring Logsheet

Boring ID EZVI-SB7

Date 2/7/02

Location EZVI Plot

Battelle . . . Putting Technology To Work

Boring Diameter	2 in	Total Depth	46 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Hand auger fine tan sand	0-5	---	SP	---	---
Whte to lt brown fine to med sand	6-8	EZVI-SB7-8	SP	90	45
Lt brown fine sand to lt brown med sand and shell frags	8-10	EZVI-SB7-10	SP	100	12.4
White to lt brown f-m sand to lt brown med sand and shell frags	10-12	EZVI-SB7-12	SP	100	5.1
Brownish gray fine sand to lit brown sand and shells to fine-med sand	12-14	EZVI-SB7-14	SP	100	35.5
Gray fined sand to med sand and shell frags (strong odor)	14-16	EZVI-SB7-16	SP	80	230
Gray fine to med sand (strong odor)	16-18	EZVI-SB7-18	SP	100	17175
Gray fine to med sand (strong odor)	18-20	EZVI-SB7-20	SP	50	8210
Gray fine sand, trace shells, silt	20-22	EZVI-SB7-22	SP	100	2243
Gray fine sand, trace shells, silt	22-24	EZVI-SB7-24	SP-SM	90	1885
Gray fine sand, trace shells	24-26	EZVI-SB7-26	SP-SM	100	2958
Gray fine sand, trace shells	26-28	EZVI-SB7-28	SM	90	3412
Gray fine sand, trace shells	28-30	EZVI-SB7-30	SM	100	4225

Logged by: L. Cumming

Completion Date: 2/7/02

Construction Notes: 4' Macro-core acetate sleeves, rinseate = EZVI-SB7-Rinseate, Dup = EZVI-SB7-44DUP

LC34 Coring Logsheet Boring ID EZVI-SB7

Date 2/7/02 Location EZVI Plot

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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Gray silty fine sand, trace shells, more silty	30-32	EZVI-SB7-32	SM	100	1421
Gray silty fine sand, shells	32-34	EZVI-SB7-34	SM	100	691
Gray silty fine sand, some shells	34-36	EZVI-SB7-36	SM	90	66
Gray silty fine sand, some shells	36-38	EZVI-SB7-38	SM	100	70
Gray silty fine sand and shells to clayey sand	38-40	EZVI-SB7-40	SM-SC	100	395
Gray silty sand and shells to silty sand, trace shells	40-42	EZVI-SB7-42	SM	100	220
Gray silty fine sand, trace shells	40-44	EZVI-SB7-44	SM	100	12.5
Gray silty fine sand and med gravel shells	40-46	EZVI-SB7-46	SM-GM	100	28.8
End of core					

LC34 Coring Logsheet

Boring ID EZVI-WP1

Date 1/18/02

Location EZVI Plot

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Boring Diameter	2 in	Total Depth	40 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland 10gal
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Hand auger fine tan sand	0-5	---	SP	---	---
Direct push	5-15	EZVI-SB7-8	---	---	---
Cl sample	15	EZVI-WP1-15	---	500 ml	---
Direct push	15-20	---	---	---	---
Cl sample	20	EZVI-WP1-20	---	500 ml	---
Direct push	20-30	---	---	---	---
Cl sample	30	EZVI-WP1-30	---	500 ml	---
Direct push	30-38	---	---	---	---
Cl sample silty, low flow	38	EZVI-WP1-38	---	500 ml	---
Direct push	38-40	---	---	---	---
Cl sample, silty, low flow	40	EZVI-WP1-40	---	500 ml	---

Logged by: J. Sminchak

Completion Date: 1/18/02

Construction Notes:

Waterloo Profiler, purge 0.7 L each

Sample

LC34 Coring Logsheet

Date 1/19/02

Boring ID EZVI-WP2

Location EZVI Plot

Battelle
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Boring Diameter 2 in

Casing Outer Diameter 2 in

Casing Inner Diameter --- in

Casing Material ---

Screen Type ---

Screen Slot ---

Screen Length --- ft

Screen Depth from --- to --- ft

Total Depth 38 ft

Sand Pack ---

Sand Pack Depth from --- to --- ft

Grout Material Portland 10gal

Grout Depth from 0 to Depth ft

Surface Completion Grout flush

Drilling Method Direct Push Vibra-core

Driller Precision

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Hand auger fine tan sand	0-5	---	SP	---	---
Direct push	5-15	---	---	---	---
Cl sample	15	EZVI-WP2-15	---	500 ml	---
Direct push	15-20	---	---	---	---
Cl sample	20	EZVI-WP2-20	---	500 ml	---
Direct push	20-30	---	---	---	---
Cl sample	30	EZVI-WP2-30	---	500 ml	---
Direct push	30-36	---	---	---	---
Cl sample silty, low flow	36	EZVI-WP2-36	---	500 ml	---
Direct push	36-38	---	---	---	---
Cl sample, silty, low flow	38	EZVI-WP2-38	---	500 ml	---

Logged by: J. Sminchak

Completion Date: 1/19/02

Construction Notes:

Waterloo Profiler, purge 0.7 L each

Sample

LC34 Coring Logsheet

Boring ID EZVI-SB203

Date 10/9/02

Location EZVI Plot

Battelle
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Boring Diameter	2	in	Total Depth	32	ft
Casing Outer Diameter	2	in	Sand Pack	---	
Casing Inner Diameter	---	in	Sand Pack Depth	from --- to ---	ft
Casing Material	---		Grout Material	Portland	
Screen Type	---		Grout Depth	from 0 to Depth	ft
Screen Slot	---		Surface Completion	Grout flush	
Screen Length	---	ft	Drilling Method	Direct Push Vibra-core	
Screen Depth	from --- to ---	ft	Driller	Precision	

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine tan sand, no sample	0-6	---	SP	---	---
Brown to medium sand; orange-brown medium sand	6-8	EZVI-SB203-8	SP	100	0.0
No recovery	8-10	---	---	0	---
Brown medium sand with trace shells; dark brown med sand; 1” EZVI band at 12’ in medium sand	10-12	EZVI-SB203-12	SP	80	0.0
Fine-med orange brown sand	12-14	EZVI-SB203-14	SP	30	0.0
1” EZVI band at 14’ in medium fine sand (evidence of smearing) gray medium sand with trace shells; dark gray coarse sand with shells; fine gray sand at 16’	14-16	EZVI-SB203-16	SP	100	6
Orange-brown medium-coarse sand with trace shells, gray med. sand, dark gray sand with shells @17.5’, evidence of EZVI smearing at 17’	16-18	EZVI-SB203-18	SP	100	37 peak
Dark gray medium-fine sand with shells, medium gray sand, fine gray sand (no evidence of EZVI)	18-20	EZVI-SB203-20	SP	100	> 2000
Brown medium sand with shells, silty fine gray sand (no evidence of EZVI)	20-22	EZVI-SB203-22	SP	100	> 2000
Very fine gray sand (no evidence of EZVI)	22-24	EZVI-SB203-24	SP	100	> 2000
Silty gray fine sand (no evidence of EZVI)	24-26	EZVI-SB203-26	SP	10	7
Silty gray fine sand (no evidence of EZVI)	26-28	EZVI-SB203-28	SP-SM	70	3
Silty gray fine sand (no evidence of EZVI)	28-30	EZVI-SB203-30	SM	30	151

Logged by: M. Gaberell

Completion Date: 10/9/02

Construction Notes: EZVI-SB203-18-DUP, equipment rinseate at 07:30

LC34 Coring Logsheet

Date 10/9/02

Boring ID EZVI-SB203

Location EZVI Plot

Battelle
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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty gray fine sand (no evidence of EZVI)	30-32	EZVI-SB203-32	SM	80	> 2000

LC34 Coring Logsheet

Boring ID EZVI-SB204

Date 10/9/02

Location EZVI Plot

Battelle
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Boring Diameter	2 in	Total Depth	32 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Hand auger fine tan sand, no sample	0-6	---	SP	---	---
Brown medium sand; white medium sand; orange-brown medium sand with trace shells (no EZVI)	6-8	EZVI-SB203-8	SP	40	0.0
No recovery	8-10	---	---	0	---
Orange-brown medium sand with trace shells, gray, gray fine-med sand w/ trace shells (no EZVI)	10-12	EZVI-SB204-12	SP	90	0.0
Orange brown med sand w/trace shells (no EZVI)	12-14	EZVI-SB204-14	SP	20	0.0
Dark gray med sand with trace shells to fine gray sand to med sand (dark gray) (no EZVI)	14-16	EZVI-SB204-16	SP	100	0.0
Brown medium sand, gray fine sand, brown med sand with trace shells, gray fine-med sand (no EZVI)	16-18	EZVI-SB204-18	SP	100	12.6
Fine gray sand, med-coarse sand with shells @19’, very fine sand (no EZVI)	18-20	EZVI-SB204-20	SP	90	146
Orange medium sand with trace shells, gray fine sand (no EZVI)	20-22	EZVI-SB204-22	SP-SM	80	17
Gray fine sand, EZVI band 4” long in med sand @~23’, gray silty fine sand (no EZVI)	22-24	EZVI-SB204-24	SP-Sm	100	9
Gray fine sand (no EZVI)	24-26	EZVI-SB204-26	SM	40	56
Gray silty fine sand (no EZVI)	26-28	EZVI-SB204-28	SM	100	190
Gray silty fine sand (no EZVI)	28-30	EZVI-SB204-30	SM	40	54

Logged by: M. Gaberell

Completion Date: 10/9/02

Construction Notes: EZVI-SB204-24-DUP,

LC34 Coring Logsheet

Date 10/9/02

Boring ID EZVI-SB204

Location EZVI Plot

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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty gray fine sand (no evidence of EZVI)	30-32	EZVI-SB204-32	SM	100	19

LC34 Coring Logsheet

Boring ID EZVI-SB207

Date 10/8/02

Location EZVI Plot

Battelle
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Boring Diameter	2 in	Total Depth	32 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine tan sand, no sample	0-6	---	SP	---	---
Med gray sand; dark brown med sand to orange-brown medium sand with trace shells	6-8	EZVI-SB207-8	SP	100	0.0
No recovery	8-10	---	---	0	---
Orange-brown medium sand, dark brown medium sand (2” thick), to gray fine sand *soil may have slid down sleeve	10-12	EZVI-SB207-12	SP	60	0.0
Brown coarse sand w/trace shells	12-14	EZVI-SB207-14	SP	50	0.0
Gray fine sand to medium gray sand, black EZVI 2” band @~15’ in medium gray sand	14-16	EZVI-SB207-16	SP	100	0.0
Brown medium coarse sand with trace shells to gray fine sand (no EZVI)	16-18	EZVI-SB207-18	SP	50	0.0
Fine gray sand to med sand with trace shells, EZVI black 2” band @18’ in med fine sand	18-20	EZVI-SB207-20	SP	100	0.0
Orange-brown coarse sand with trace shells (~3” thick) at 20 ft; gray medium sand to gray fine sand with trace shells; EZVI black band (2”thick) @21 ft in medium sand	20-22	EZVI-SB207-22	SP	100	191
Gray med-coarse sand with trace shells to gray sand, black EZVI band (3” thick) at 23.5 ft in med sand	22-24	EZVI-SB207-24	SP	100	22
Gray fine sand, trace silt (no EZVI)	24-26	EZVI-SB207-26	SM	40	914
Gray silty fine sand (no EZVI)	26-28	EZVI-SB207-28	SM	100	368
Gray silty fine sand (no EZVI)	28-30	EZVI-SB207-30	SM	70	282

Logged by: M. Gaberell

Completion Date: 10/8/02

Construction Notes: EZVI-SB207-24-DUP, EZVI-SB207-Rinseate at 11:58

LC34 Coring Logsheet

Boring ID EZVI-SB207

Date 10/8/02

Location EZVI Plot

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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty gray fine sand (no evidence of EZVI)	30-32	EZVI-SB207-32	SM	100	49.5

LC34 Coring Logsheet

Boring ID EZVI-SB208

Date 10/8/02

Location EZVI Plot

Battelle
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Boring Diameter 2 in

Casing Outer Diameter 2 in

Casing Inner Diameter --- in

Casing Material ---

Screen Type ---

Screen Slot ---

Screen Length --- ft

Screen Depth from --- to --- ft

Total Depth 32 ft

Sand Pack ---

Sand Pack Depth from --- to --- ft

Grout Material Portland

Grout Depth from 0 to Depth ft

Surface Completion Grout flush

Drilling Method Direct Push Vibra-core

Driller Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine tan sand, no sample	0-6	---	SP	---	---
Med light brown sand; orange brown med sand (1” thick), tan medium sand	6-8	EZVI-SB20-8	SP	NA	0.0
Brown medium sand to brown medium sand with trace shells	8-10	---	---	0	---
Brown medium sand with trace shells to gray medium sand (1.5” black EZVI band at 12’ in gray med sand)	10-12	EZVI-SB208-12	SP	NA	0.0
Brown med-fine sand with trace shells, gray fine sand, black EZVI band ½” thick at 14’	12-14	EZVI-SB208-14	SP	100	0.0
Gray fine sand, black EZVI band @15.5” in medium-fine gray sand	14-16	EZVI-SB208-16	SP	100	0.0
Tan medium sand with trace shells, gray medium sand to gray medium sand with trace shells, black EZVI band 1” thick at 17’	16-18	EZVI-SB208-18	SP	100	0.0
Fine gray sand, EZVI black 1” band @18’ in med sand	18-20	---	---	0	---
No recovery	20-22	---	---	0	---
Gray med-fine sand (no EZVI)	22-24	EZVI-SB208-24	SP	40	104
No recovery	24-26	---	---	0	---
Gray silty fine sand with trace shells (no EZVI)	26-28	EZVI-SB208-28	SM	100	26 238
No recovery	28-32	---	---	0	---

Logged by: M. Gaberell

Completion Date: 10/8/02

Construction Notes: EZVI-SB208-28-DUP

LC34 Coring Logsheet

Boring ID EZVI-SB209

Date 10/8/02

Location EZVI Plot

Battelle
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Boring Diameter	2 in	Total Depth	32 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Hand auger fine tan sand, no sample	0-6	---	SP	---	---
Lt to drk brown med sand, orange brown medium sand with trace shells	6-8	EZVI-SB209-8	SP	100	0.0
No recovery	8-10	---	---	0	---
Orange-brown medium-coarse sand with trace shells to gray medium-fine sand (2” black EZVI band at 12’)	10-12	EZVI-SB209-12	SP	100	0.0
Brown med-fine sand with trace shells, gray med-fine sand, some evidence of EZVI	12-14	EZVI-SB209-14	SP	90	0.0
Gray fine sand, 2” black EZVI band @15.5” in med-coarse sand	14-16	EZVI-SB209-16	SP	100	0.0
Brown medium sand with trace shells, gray fine sility sand, black EZVI band at 17.5-18’ in med-coarse sand’	16-18	EZVI-SB209-18	SP	100	0.0
Gray silty fine gray sand, med sand with trace shells (no EZVI)	18-20	EZVI-SB209-20	SP	100	165
Brown med sand with trace shells, gray fine silty sand, black EZVI band (1”) at 21 ft in med coarse gray sand	20-22	EZVI-SB209-22	SP	100	0.0
Gray silty fine sand, EZVI black band (2”) at 23” in med fine gray sand with trace shells	22-24	EZVI-SB209-24	SP-SM	100	63.5
Silty fine gray sand (no evidence of EZVI)	24-26	EZVI-SB209-26	SM	20	222
Silty fine gray sand, trace shells at 27’ (no evidence of EZVI)	26-28	EZVI-SB209-28	SM	100	572
Silty fine gray sand (no evidence of EZVI)	28-30	EZVI-SB209-30	SM	40	300

Logged by: M. Gaberell

Completion Date: 10/8/02

Construction Notes: EZVI-SB209-22-DUP

LC34 Coring Logsheet

Boring ID EZVI-SB209

Date 10/8/02

Location EZVI Plot

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Lithologic Description	Depth	Sample	USCS	Rec.	PID
Silty gray fine sand, very wet at 32’ (no evidence of EZVI)	30-32	X	SM	100	---

LC34 Coring Logsheet Boring ID EZVI-SB210

Date 10/9/02 Location EZVI Plot

Battelle . . . Putting Technology To Work

Boring Diameter	2 in	Total Depth	32 ft
Casing Outer Diameter	--- in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Portland
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Hand auger fine tan sand, no sample	0-8	---	SP	---	---
Orange brown med sand with trace shells	8-10	X	SP	20	0.0
Orange brown med sand with trace shells, 1” EZVI band at 12’ in med sand	10-12	X	SP	100	0.0
Orange-brown medium-coarse sand with trace shells (2” black EZVI band at 14’)	12-14	X	SP	60	0.0
Gray med sand with trace shells, gray fine sand, gray med sand with trace shells, gray fine sand (no EZVI)	14-16	X	SP	100	348
Orange brown sand with trace shells, gray med-fine sand, gray fine sand	16-18	X	SP	100	50
Dark gray med sand with trace shells, fine gray sand, dark gray med sand with trace shells, gray fine sand, odor at 17’ (no EZVI)	18-20	X	SP	100	1117
Brown medium coarse sand with trace shells, gray med sand, EZVI band 1” thick at 20.5’ in medium sand, (evidence of smearing below EZVI band)	20-22	X	SP	100	65
Gray fine sand, dark gray med sand with trace shells, gray fine sand, odor (no EZVI)	22-24	X	SP-SM	100	1416
Gray silty fine sand (no EZVI)	24-26	X	SM	90	352
Gray silty fine sand (no EZVI)	26-28	X	SM	100	345

Logged by: M. Gaberell

Construction Notes: for visual ID of EZVI beyond western edge of plot

LC34 Coring Logsheet

Boring ID EZVI-SB301

Date 11/21/02

Location EZVI Post

Battelle
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Boring Diameter 2 in
Casing Outer Diameter 2 in
Casing Inner Diameter --- in
Casing Material ---
Screen Type ---
Screen Slot ---
Screen Length --- ft
Screen Depth from --- to --- ft

Total Depth 46 ft
Sand Pack ---
Sand Pack Depth from --- to --- ft
Grout Material Med Bentonite Chips
Grout Depth from 0 to Depth ft
Surface Completion Grout flush
Drilling Method Direct Push Vibra-core
Driller Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine-med. tan sand	0-5	---	SP	---	---
Lt gray-white fine-med sand to brown fine-med sand	6-8	SB301-8	SP	75	0
Gray-brown fine-med sand with shell matter	8-10	SB301-10	SP	25	0
As above to gray fine-med sand with shell matter	10-12	SB301-12	SP	100	11.8
Gray-brown fine-med sand with shell matter	12-14	SB301-14	SP	75	1.5
As above to gray fine-med sand, EZVI band at 15' (shelly layer)	14-16	SB301-16	SP	100	1.7
Orange brown fine-med sand with shell matter to gray brown fine-med sand with shell matter	16-18	SB301-18	SP	100	0.9
Gray fine-med sand to gray fine sand, EZVI band at 18.5'	18-20	SB301-20	SP	100	0.1
Gray fine-med sand, bad odor	20-22	SB301-22	SP	25	0
Gray fine-med sand, trace shells, bad odor	22-24	SB301-24	SP	100	5.6
No recovery	24-26	---	---	0	---
Silty fine gray sand	26-28	SB301-28	SM	90	69
Silty fine gray sand, trace shells	28-30	SB301-30	SM	80	7.9

Logged by: L. Cumming

Completion Date: 11/21/02

Construction Notes: 4' Macro-core acetate sleeves, rinseate = EZVI-SB301 -Rinseate, Dup = EZVI-SB301-36DUP

LC34 Coring Logsheet

Date 11/21/02

Boring ID EZVI-SB301

Location EZVI Post

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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty fine gray sand, trace shells	30-32	SB301-32	SM	100	1.1
Silty fine gray sand	32-34	SB301-34	SM	80	3.9
Silty fine gray sand to gray silty fine-med sand with shell matter	34-36	SB301-36	SM	100	0.8
Silty fine gray sand	36-38	SB301-38	SM-SP	35	1.1
Silty fine-med gray sand and shell matter to silty fine-med sand	38-40	SB301-40	SM	100	20
Silty-clayey fine gray sand, trace shells, slightly clayey	40-42	SB301-42	SM-SP	35	0
As above	42-44	SB301-44	SM-SC	100	0
Gray silty fine-med sand and shells	44-46	SB301-46	SM-GM	100	0
End core at 46’					

LC34 Coring Logsheet

Boring ID EZVI-SB302

Date 11/18/02

Location EZVI Post

Battelle
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Boring Diameter	2 in	Total Depth	46 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Med Bentonite Chips
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine-med. tan sand	0-5	---	SP	---	---
Lt gray fine sand, some black bands to med sand to coarse sand with shell material	6-8	SB302-8	SP	100	1.3
No recovery	8-10	---	---	0	---
Brown fine-med to orange-brown sand and shell material, wet	10-12	SB302-12	SP	100	1.6
As above to gray fine-med sand with shell matter	12-14	SB302-14	SP	75	106
Gray fine-med sand with shell matter to light gray fine sand	14-16	SB302-16	SP	100	96
Orange brown fine-med sand with shell matter to very dark gray med sand, banding?	16-18	SB302-18	SP	100	30.5
Lt gray fine sand, trace shells to gray med sand to lt gray fine sand	18-20	SB302-20	SP	100	278
No recovery	20-22	---	---	0	---
Lt gray fine-med sand	22-24	SB302-24	SP	100	35
Gray fine sand to silty fine gray sand	24-26	SB302-26	SP	100	68
Silty fine gray sand	26-28	SB302-28	SP-SM	100	0
Silty fine gray sand	28-30	SB302-30	SM	100	72

Logged by: L. Cumming

Completion Date: 11/18/02

Construction Notes: 4' Macro-core acetate sleeves, rinseate = EZVI-SB302 -Rinseate, Dup = EZVI-SB302-18DUP

LC34 Coring Logsheet

Date 11/18/02

Boring ID EZVI-SB302

Location EZVI Post

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty fine gray sand	30-32	SB302-32	SM	100	40
No recovery	32-34	---	---	0	---
Silty fine gray sand to coarse sand with shell matter	34-36	SB302-36	SM	25	1.8
Coarse shells with sand to gray silty sand with shell material	36-38	SB302-38	GM-SM	100	32
Gray silty sand with shell material	38-40	SB302-40	SM	50	0
Gray silty fine sand, soupy, clayey	40-42	SB302-42	SM-SC	100	0
Gray silty fine-med sand	42-44	SB302-44	SM	100	0
Gray silty fine-med sand	44-46	SB302-46	SM	100	0
End core at 46’					

LC34 Coring Logsheet

Date 11/20/02

Boring ID EZVI-SB303

Location EZVI Post

Battelle
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Boring Diameter 2 in

Casing Outer Diameter 2 in

Casing Inner Diameter --- in

Casing Material ---

Screen Type ---

Screen Slot ---

Screen Length --- ft

Screen Depth from --- to --- ft

Total Depth 46 ft

Sand Pack ---

Sand Pack Depth from --- to --- ft

Grout Material Med Bentonite Chips

Grout Depth from 0 to Depth ft

Surface Completion Grout flush

Drilling Method Direct Push Vibra-core

Driller Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine-med. tan sand	0-5	---	SP	---	---
White-gray fine sand to orange-brown fine-med sand with shell material	6-8	SB303-8	SP	80	0.4
As above, more coarse, faint dark gray layer (EZVI?)	8-10	SB303-10	SP	20	0
Orange brown med sand with shell matter to light gray fine sand, black EZVI bands appear at 11-12' bgs	10-12	SB303-12	SP	100	2.8
Orange-brown med sand with shell matter to gray-orange brown med sand with shell matter, EZVI evidence	12-14	SB303-14	SP	90	35.1
Gray fine-med sand with shell matter, EZVI dark gray layers at bottom	14-16	SB303-16	SP	100	6.9
Orange brown med sand with shell matter to gray fine-med sand	16-18	SB303-18	SP	100	11.5
Gray fine-med sand, some dark gray layers	18-20	SB303-20	SP	100	> 2000
Orange-brown fine-med sand to gray fine-med sand	20-22	SB303-22	SP	100	138
Lt gray fine-med sand, more silty at bottom	22-24	SB303-24	SP-SM	100	> 2000
Gray silty fine sand	24-26	SB303-26	SM	35	4.5
Silty fine gray sand	26-28	SB303-28	SM	100	91
Silty fine gray sand, wet	28-30	SB303-30	SM	50	20.9

Logged by: L. Cumming

Completion Date: 11/20/02

Construction Notes: 4' Macro-core acetate sleeves, rinseate = EZVI-SB303 -Rinseate, Dup = EZVI-SB303-20DUP

LC34 Coring Logsheet

Date 11/20/02

Boring ID EZVI-SB303

Location EZVI Post

Battelle
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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty fine gray sand, wet	30-32	SB303-32	SM	100	34
Silty fine gray sand, wet	32-34	SB303-34	SM	50	35
Silty fine gray sand, trace shells, soupy at top	34-36	SB303-36	SM-SP	100	135
Gray silty fine sand, no sample	36-38	SB303-38	SP	5	5
Gray silty fine sand to silty-clayey sand to silty fine-med sand with shell material	38-40	SB303-40	SP-SM-SC	100	0
Gray silty fine sand with shells	40-42	SB303-42	SM	30	0.5
Gray silty fine sand with more shells	42-44	SB303-44	SM	100	3.4
Gray silty fine-med sand to silty shells and fine-med sand	44-46	SB303-46	SM-GM	100	0
End core at 46’					

LC34 Coring Logsheet

Date 11/19/02

Boring ID EZVI-SB304

Location EZVI Post

Battelle
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Boring Diameter	2 in	Total Depth	46 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Med Bentonite Chips
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine-med. tan sand	0-5	---	SP	---	---
Light gray-white fine sand to orange brown fine-medium sand	6-8	SB304-8	SP	75	14.1
Gray-brown fine-med sand	8-10	SB304-10	SP	25	0
Orange brown med sand with shell matter to gray fine-med sand	10-12	SB304-12	SP	100	0
Orange-brown fine-med sand with shell matter	12-14	SB304-14	SP	50	12.9
As above to gray fine-med sand, EZVI dark gray band at ~15.5’	14-16	SB304-16	SP	100	0
Orange brown fine-med sand with shell matter to gray fine-med sand	16-18	SB304-18	SP	100	36
Gray fine-med sand, some dark gray med sand layers, faint banding?	18-20	SB304-20	SP	100	0
Gray fine sand, bad odor	20-22	SB304-22	SP	25	0.6
Gray fine-med sand, bad odor	22-24	SB304-24	SP-SM	100	1.2
Gray fine sand, trace shell matter	24-26	SB304-26	SM	25	16
As above, more silty at bottom	26-28	SB304-28	SP-SM	100	7.3
Silty fine gray sand	28-30	SB304-30	SM	50	52

Logged by: L. Cumming

Completion Date: 11/19/02

Construction Notes: 4’ Macro-core acetate sleeves, rinseate = EZVI-SB304 -Rinseate, Dup = EZVI-SB304-32DUP

LC34 Coring Logsheet

Boring ID EZVI-SB304

Date 11/19/02

Location EZVI Post

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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty fine gray sand	30-32	SB304-32	SM	100	7.3
Silty fine gray sand	32-34	SB304-34	SM	100	52
Silty fine gray sand to gray fine-med sand	34-36	SB304-36	SM	100	2.8
Gray silty sand with shell matter to silty fine sand	36-38	SB304-38	SM	50	9.7
Gray silty fine sand to silty-clayey sand to fine to coarse sand	38-40	SB304-40	SM-SC	100	5.8
Gray silty fine sand, trace shells	40-42	SB304-42	SM	90	NR
Gray silty fine sand, trace shells	42-44	SB304-44	SM	100	NR
Gray silty fine sand with shell matter	44-46	SB304-46	SM	100	31.5
End core at 46’					

LC34 Coring Logsheet

Boring ID EZVI-SB307

Date 11/21/02

Location EZVI Post

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Boring Diameter	2 in	Total Depth	46 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Med Bentonite Chips
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	Depth	Sample	USCS	Rec.	PID
Hand auger fine-med. tan sand	0-5	---	SP	---	---
Light gray fine sand to orange brown fine-med sand	6-8	SB307-8	SP	75	0
No recovery	8-10	---	SP	0	---
Brown-orange fine-med sand with shells to gray fine-med sand	10-12	SB307-12	SP	100	30
Brown-gray fine-med sand to orange-brown fine-med sand with shell matter	12-14	SB307-14	SP	80	0
Gray fine-med sand with shell matter to gray fine sand, EZVI dark gray band at ~15.25’	14-16	SB307-16	SP	100	0
No recovery	16-18	---	---	0	---
Gray fine-med sand	18-20	SB307-20	SP	80	57.6
No recovery	20-22	---	---	0	---
Gray fine-med sand, EZVI band at middle (coarse layer)	22-24	SB307-24	SP-SM	100	15.8
Gray silty fine sand, trace shells	24-26	SB307-26	SM	40	429
As above	26-28	SB307-28	SM	100	232
No recovery	28-30	---	---	0	---

Logged by: L. Cumming

Completion Date: 11/21/02

Construction Notes: 4’ Macro-core acetate sleeves, rinseate = EZVI-SB307 -Rinseate, Dup = EZVI-SB307-26DUP

LC34 Coring Logsheet

Boring ID EZVI-SB307

Date 11/21/02

Location EZVI Post

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty fine gray sand, very strong TCE odor	30-32	SB307-32	SM	100	340
Silty fine gray sand, trace shells, soupy	32-34	SB307-34	SM	90	68
Silty fine gray sand, trace-little shells	34-36	SB307-36	SM	100	28
Gray silty fine sand with shell matter	36-38	SB307-38	SM-SP	75	14.1
As above to gray silty clayey sand	38-40	SB307-40	SM-SC	100	6.2
Gray silty-clayey sand to gray silty fine sand with shells	40-42	SB307-42	SC-SM	80	0
Gray silty fine sand	42-44	SB307-44	SM	100	0
Gray silty fine sand, trace large shells to silty fine sand	44-46	SB307-46	SM	100	49.3
End core at 46’					

LC34 Coring Logsheet

Date 11/22/02

Boring ID EZVI-SB308

Location EZVI Post

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Boring Diameter	2 in	Total Depth	46 ft
Casing Outer Diameter	2 in	Sand Pack	---
Casing Inner Diameter	--- in	Sand Pack Depth	from --- to --- ft
Casing Material	---	Grout Material	Med Bentonite Chips
Screen Type	---	Grout Depth	from 0 to Depth ft
Screen Slot	---	Surface Completion	Grout flush
Screen Length	--- ft	Drilling Method	Direct Push Vibra-core
Screen Depth	from --- to --- ft	Driller	Precision

Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Hand auger fine-med. tan sand	0-5	---	SP	---	---
Light gray to white fine sand	6-8	SB308-8	SP	30	0
As above to orange brown fine-medium sand	8-10	SB308-10	SP	100	0
Brown-orange fine-med sand with shell matter	10-12	SB308-12	SP	50	5.2
As above to gray fine-med sand	12-14	SB308-14	SP	100	5.8
No recovery	14-16	---	---	0	---
Brown-gray fine-med sand to gray fine-med sand	16-18	SB308-18	---	75	0.3
No recovery	18-20	---	---	0	---
Gray fine-med sand to gray fine sand, faint EZVI band 3” from bottom	20-22	SB308-22	---	100	100
Gray silty fine sand	22-24	SB308-24	SM	25	183
As above	24-26	SB308-26	SM	100	449
As above	26-28	None	---	<5	---
Gray silty fine sand, trace shells to gray silty fine sand, more clayey at bottom	28-30	SB308-30	SM-SC	100	182

Logged by: L. Cumming

Completion Date: 11/22/02

Construction Notes: 4’ Macro-core acetate sleeves, Dup = EZVI-SB308-42DUP

LC34 Coring Logsheet

Date 11/22/02

Boring ID EZVI-SB308

Location EZVI Post

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Lithologic Description	**Depth**	**Sample**	**USCS**	**Rec.**	**PID**
Silty fine gray sand	30-32	---	SM	<5	18
Silty fine gray sand, more clayey at bottom interval	32-34	SB308-34	SM	100	139
Silty fine gray sand to gray silty shells and sand	34-36	SB308-36	SM-GM	<5	0
Silty sand and shells to gray fine-med sand, clayey at bottom	36-38	SB308-38	GM-SM	100	0.2
Gray clayey-silty fine-med sand to silty sand and shells	38-40	SB308-40	SM-GM	50	4.2
Silty sand and shells to clayey fine sand to clayey-silty fine-med sand	40-42	SB308-42	SM-SC	100	4.4
Gray silty fine-med sand to silty sand and shells	42-44	SB308-44	SM-GM	90	0
Gray silty fine sand and shells to silty fine-med sand	44-46	SB308-46	SM-SC	100	36
End core at 46’					

Appendix C
CVOC Measurements

Table C-1. CVOC Results of Groundwater Samples for EZVI Demonstration

	TCE (µg/L)			***cis* -1,2-DCE (µg/L)**			***trans* -1,2-DCE (µg/L)**			**Vinyl chloride (µg/L)**		
Well ID	**Pre-Demo**	**Demo 1**	**Post-Demo**	**Pre-Demo**	**Demo 1**	**Post-Demo**	**Pre-Demo**	**Demo 1**	**Post-Demo**	**Pre-Demo**	**Demo 1**	**Post-Demo**
EZVI Plot Well												
PA-23	1,180,000	92,100	8,790	16,900	17,900	169,000	<1,000	68 J	245	<1,000	53 J	21,600
PA-23-DUP	1,130,000	84,600	9,010	17,300	14,600	132,000	<1,000	33 J	314	<1,000	<100	24,700
EZVI Perimeter Wells												
PA-24S	772,000	474,000	12,100	47,400	15,800	31,700	<1,000	<50	190 J	<1,000	<50	1,580
PA-24I	258,000	110,000	86,400	149,000	161,000	181,000	482	644	1,020	140 J	1,070	779
PA-24D	469,000	497,000	656,000	61,800	83,400	99,400	260 J	360 J	610	110 J	590	160 J
PA-25S	71,300	69,600	129,000	69,200	9,320	42,800	<1,000	46 J	381	<1,000	<100	75 J
PA-25I	534,000	784,000	944,000	116,000	104,000	90,900	320J	230	270 J	<500	<100	170 J
PA-25D	2,760	36,200	53,200	60,800	101,000	117,000	278	395	544	<50	142	354
Injection & Extraction Wells												
EIW-1	144,000	NA	7,820	38,300	NA	3,280	556	NA	24 J	638	NA	322
EEW-1	1,050,000	NA	471,000	67,100	NA	80,100	550J	NA	390 J	<1,000	NA	6,980

J: Estimated value, below reporting limit.
Pre-Demo: March 2002.
Demo 1 for EZVI: August 19th to 21st, 2002.
Post-Demo: EZVI-November 2002.

Table C-2. Summary of CVOC Results in Soil from EZVI Pre-Demonstration Monitoring

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-1-8	6	8	1/16/2002	194	93	89	121	0	<100	ND	<100	ND	<100	ND
EZVI-SB-1-8-DUP	6	8	1/16/2002	191	72	68	<100	ND	10J	0	<100	ND	<100	ND
EZVI-SB-1-10 (SS)	8	10	1/16/2002	193	147	125	459	1	488	1	<100	ND	<100	ND
EZVI-SB-1-12	10	12	1/16/2002	192	100	80	184	1	119	0	<100	ND	<100	ND
EZVI-SB-1-14	12	14	1/16/2002	192	149	126	1,300	3	1,920	4	34J	0	<100	ND
EZVI-SB-1-16	14	16	1/16/2002	191	88	74	1,760	6	1,600	6	34J	0	<100	ND
EZVI-SB-1-18	16	18	1/16/2002	190	124	103	34,100	87	6,200	16	60J	0	21J	0
EZVI-SB-1-20	18	20	1/16/2002	192	80	58	61,800	282	884	4	<100	ND	<100	ND
EZVI-SB-1-22	20	22	1/16/2002	192	106	93	75,400	208	1,000	3	<100	ND	<100	ND
EZVI-SB-1-24	22	24	1/16/2002	191	129	111	98,200	230	1,100	3	12J	0	<100	ND
EZVI-SB-1-26	24	26	1/16/2002	194	155	126	130,000	283	1,220	3	<100	ND	<100	ND
EZVI-SB-1-28	26	28	1/16/2002	191	135	106	103,000	263	1,590	4	<100	ND	<100	ND
EZVI-SB-1-30	28	30	1/16/2002	192	145	112	104,000	256	18,300	45	49J	0	20J	0
EZVI-SB-1-32	30	32	1/16/2002	190	190	148	3,060	6	53,000	101	140	0	<100	ND
EZVI-SB-1-34	32	34	1/16/2002	194	101	84	<100	ND	15,100	47	35J	0	<100	ND
EZVI-SB-1-36	34	36	1/16/2002	191	149	124	<100	ND	9,760	21	44J	0	<100	ND
EZVI-SB-1-38	36	38	1/16/2002	192	151	122	<100	ND	9,090	20	74J	0	<100	ND
EZVI-SB-1-40	38	40	1/16/2002	194	123	93	<100	ND	1,340	4	<100	ND	<100	ND
EZVI-SB-1-42	40	42	1/16/2002	194	126	90	<100	ND	3,110	10	44J	0	<100	ND
EZVI-SB-1-44	42	44	1/16/2002	194	146	122	140	0	3,520	8	<100	ND	<100	ND
EZVI-SB-1-46	44	46	1/16/2002	192	187	155	4,650	8	6,980	12	<100	ND	<100	ND
EZVI-SB-1-MB (SS)	Lab Blank		1/16/2002	192	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-1-RINSATE	EQ		1/16/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-2-8 (SS)	6	8	1/16/2002	192	101	100	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-2-10	8	10	1/16/2002	194	111	97	<100	ND	118	0	<100	ND	<100	ND
EZVI-SB-2-12	10	12	1/16/2002	193	113	99	<100	ND	113	0	<100	ND	<100	ND
EZVI-SB-2-14	12	14	1/16/2002	191	158	131	501	1	1,120	2	19J	0	<100	ND
EZVI-SB-2-16	14	16	1/16/2002	193	196	164	5,700	10	6,680	11	141	0	63J	0
EZVI-SB-2-18	16	18	1/16/2002	192	172	141	45,700	89	7,980	16	85J	0	38J	0
EZVI-SB-2-20	18	20	1/16/2002	191	152	130	89,800	182	4,440	9	<100	ND	<100	ND
EZVI-SB-2-22	20	22	1/16/2002	191	208	165	135,000	233	4,860	8	<100	ND	<100	ND
EZVI-SB-2-24	22	24	1/16/2002	191	97	83	67,200	207	913	3	<100	ND	<100	ND
EZVI-SB-2-24-DUP	22	24	1/16/2002	195	94	74	72,600	262	1,020	4	<100	ND	<100	ND
EZVI-SB-2-26	24	26	1/16/2002	191	90	75	75,600	259	4,440	15	<100	ND	<100	ND
EZVI-SB-2-28	26	28	1/16/2002	192	121	95	95,200	270	2,550	7	<100	ND	<100	ND
EZVI-SB-2-30	28	30	1/16/2002	194	104	85	63,000	196	10,100	31	<100	ND	<100	ND
EZVI-SB-2-32	30	32	1/16/2002	192	164	116	2,180	5	38,100	96	102	0	<100	ND
EZVI-SB-2-34	32	34	1/16/2002	191	189	157	376	1	27,500	48	79J	0	<100	ND

Table C-2. Summary of CVOC Results in Soil from EZVI Pre-Demonstration Monitoring (Continued)

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-2-36	34	36	1/16/2002	192	256	211	209	0	16,000	22	69J	0	<100	ND
EZVI-SB-2-38	36	38	1/16/2002	192	193	162	110	0	8,600	15	44J	0	<100	ND
EZVI-SB-2-40	38	40	1/16/2002	192	130	90	<100	ND	1,890	6	<100	ND	<100	ND
EZVI-SB-2-42	40	42	1/16/2002	194	192	150	<100	ND	668	1	<100	ND	<100	ND
EZVI-SB-2-44	42	44	1/16/2002	192	85	50	<100	ND	3,760	21	<100	ND	<100	ND
EZVI-SB-2-46	44	46	1/16/2002	192	211	178	<100	ND	3,180	5	<100	ND	<100	ND
EZVI-SB-2-MB (SS)	Lab Blank		1/16/2002	191	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-2-RINSATE	EQ		1/16/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-3-8 (SS)	6	8	1/17/2002	194	134	132	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-3-10	8	10	1/17/2002	191	157	140	120	0	156	0	<100	ND	<100	ND
EZVI-SB-3-12	10	12	1/17/2002	191	134	111	107	0	124	0	<100	ND	<100	ND
EZVI-SB-3-14	12	14	1/17/2002	191	171	146	544	1	1,320	2	24J	0	27J	0
EZVI-SB-3-16	14	16	1/17/2002	190	167	146	3,830	7	2,920	5	60J	0	<100	ND
EZVI-SB-3-18	16	18	1/17/2002	191	101	90	2,160,000	6,067	10,200	29	134	0	29J	0
EZVI-SB-3-20	18	20	1/17/2002	191	102	88	72,000	209	1,430	4	<100	ND	<100	ND
EZVI-SB-3-22	20	22	1/17/2002	191	109	95	72,500	195	906	2	<100	ND	<100	ND
EZVI-SB-3-24	22	24	1/17/2002	192	171	137	125,000	253	1,570	3	<100	ND	<100	ND
EZVI-SB-3-26	24	26	1/17/2002	191	144	114	114,000	272	1,180	3	<100	ND	<100	ND
EZVI-SB-3-28	26	28	1/17/2002	190	115	94	90,700	252	798	2	<100	ND	<100	ND
EZVI-SB-3-30	28	30	1/17/2002	192	114	92	118,000	340	6,040	17	12J	0	<100	ND
EZVI-SB-3-32	30	32	1/17/2002	190	127	94	72,400	211	26,400	77	62J	0	19J	0
EZVI-SB-3-34	32	34	1/17/2002	194	157	125	859	2	40,400	90	83J	0	<100	ND
EZVI-SB-3-36	34	36	1/17/2002	192	132	112	<100	ND	4,180	10	<100	ND	<100	ND
EZVI-SB-3-38	36	38	1/17/2002	192	139	118	212	0	7,220	16	17J	0	<100	ND
EZVI-SB-3-40	38	40	1/17/2002	193	142	111	241	1	347	1	<100	ND	<100	ND
EZVI-SB-3-40-DUP	38	40	1/17/2002	191	95	44	158	1	249	2	<100	ND	<100	ND
EZVI-SB-3-42	40	42	1/17/2002	192	145	116	192	0	371	1	<100	ND	<100	ND
EZVI-SB-3-44	42	44	1/17/2002	191	118	97	<100	ND	1,540	4	<100	ND	<100	ND
EZVI-SB-3-46	44	46	1/17/2002	190	152	127	15,700	33	5,150	11	<100	ND	<100	ND
EZVI-SB-3-MB (SS)	Lab Blank		1/17/2002	195	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-3-RINSATE	EQ		1/16/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-4-8 (SS)	6	8	1/17/2002	191	153	149	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-4-10	8	10	1/17/2002	193	215	188	139	0	154	0	<100	ND	<100	ND
EZVI-SB-4-12	10	12	1/17/2002	191	171	142	158	0	159	0	<100	ND	<100	ND
EZVI-SB-4-14	12	14	1/17/2002	190	148	130	2,770	6	1,890	4	39J	0	<100	ND
EZVI-SB-4-16	14	16	1/17/2002	190	129	110	2,520	6	2,840	7	52J	0	<100	ND
EZVI-SB-4-18	16	18	1/17/2002	190	119	102	17,700	45	4,570	12	67J	0	25J	0
EZVI-SB-4-20	18	20	1/17/2002	190	102	85	53,300	161	2,480	8	<100	ND	<100	ND

Table C-2. Summary of CVOC Results in Soil from EZVI Pre-Demonstration Monitoring (Continued)

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-4-22	20	22	1/17/2002	190	117	91	58,500	171	1,740	5	<200	ND	<200	ND
EZVI-SB-4-24	22	24	1/17/2002	192	147	118	108,000	249	1,840	4	<200	ND	<200	ND
EZVI-SB-4-26	24	26	1/17/2002	191	175	140	146,000	289	2,020	4	<200	ND	<200	ND
EZVI-SB-4-28	26	28	1/17/2002	192	120	98	94,300	255	5,620	15	<200	ND	<200	ND
EZVI-SB-4-30	28	30	1/17/2002	191	139	108	93,500	236	17,900	45	43J	0	23J	0
EZVI-SB-4-32	30	32	1/18/2002	191	281	220	10,100	14	52,500	72	122	0	<100	ND
EZVI-SB-4-34	32	34	1/18/2002	192	152	110	23,300	60	42,200	109	100	0	<100	ND
EZVI-SB-4-36	34	36	1/18/2002	191	230	181	514	1	16,600	27	45J	0	<100	ND
EZVI-SB-4-38	36	38	1/18/2002	192	165	140	<100	ND	3,680	7	<100	ND	<100	ND
EZVI-SB-4-40	38	40	1/18/2002	191	167	107	512	1	111	0	<100	ND	<100	ND
EZVI-SB-4-40-DUP	38	40	1/18/2002	190	145	116	217	1	88J	0	<100	ND	<100	ND
EZVI-SB-4-42	40	42	1/18/2002	192	104	87	366	1	226	1	<100	ND	<100	ND
EZVI-SB-4-44	42	44	1/18/2002	191	174	144	<100	ND	2,600	5	13J	0	<100	ND
EZVI-SB-4-46	44	46	1/18/2002	192	181	151	17,500	32	5,650	10	<100	ND	<100	ND
EZVI-SB-4-MB (SS)	Lab Blank		1/17/2002	192	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-4-RINSATE	EQ		1/17/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-5-8 (SS)	6	8	1/31/2002	193	96	93	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-5-10	8	10	1/31/2002	192	119	103	105	0	78J	0	<100	ND	<100	ND
EZVI-SB-5-12	10	12	1/31/2002	192	119	104	<100	ND	128	0	<100	ND	<100	ND
EZVI-SB-5-14	12	14	1/31/2002	191	116	92	329	1	509	1	<100	ND	<100	ND
EZVI-SB-5-16	14	16	1/31/2002	192	121	114	3,510	8	2,320	5	27J	0	<100	ND
EZVI-SB-5-18	16	18	1/31/2002	191	156	136	35,200	68	7,120	14	23J	0	<100	ND
EZVI-SB-5-20	18	20	1/31/2002	192	120	105	46,800	115	3,630	9	<100	ND	<100	ND
EZVI-SB-5-22	20	22	1/31/2002	191	103	88	37,900	111	2,700	8	<100	ND	<100	ND
EZVI-SB-5-24	22	24	1/31/2002	191	122	100	67,400	178	2,700	7	<100	ND	<100	ND
EZVI-SB-5-26	24	26	1/31/2002	191	110	93	56,600	157	2,290	6	<100	ND	<100	ND
EZVI-SB-5-28	26	28	1/31/2002	191	120	102	85,000	216	2,540	6	<100	ND	<100	ND
EZVI-SB-5-30	28	30	1/31/2002	191	102	82	77,500	247	3,240	10	<100	ND	<100	ND
EZVI-SB-5-32	30	32	1/31/2002	191	104	83	44,900	142	15,300	48	31J	0	<100	ND
EZVI-SB-5-34	32	34	1/31/2002	191	96	87	15,600	45	17,500	50	36J	0	<1,00	ND
EZVI-SB-5-36	34	36	1/31/2002	189	128	107	362	1	21,800	53	53J	0	<100	ND
EZVI-SB-5-38	36	38	1/31/2002	190	100	90	4,050	11	12,800	36	28J	0	<100	ND
EZVI-SB-5-38-DUP	36	38	1/31/2002	191	92	81	245	1	11,600	36	26J	0	<100	ND
EZVI-SB-5-40	38	40	1/31/2002	192	110	77	<100	ND	10,600	38	46J	0	<100	ND
EZVI-SB-5-42	40	42	1/31/2002	192	156	126	<100	ND	8,410	18	38J	0	<100	ND
EZVI-SB-5-MB (SS)	Lab Blank		1/31/2002	191	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-5-RINSATE	EQ		1/31/2002	NA	NA	NA	<1	ND	<1	ND	<1	ND	<1	ND
EZVI-SB-6-8 (SS)	6	8	2/1/2002	191	93	94	<100	ND	<100	ND	<100	ND	<100	ND

Table C-2. Summary of CVOC Results in Soil from EZVI Pre-Demonstration Monitoring (Continued)

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-6-10	8	10	2/1/2002	192	106	93	<100	ND	59J	0	<100	ND	<100	ND
EZVI-SB-6-12	10	12	2/1/2002	191	142	124	122	0	212	0	<100	ND	<100	ND
EZVI-SB-6-14	12	14	2/1/2002	192	107	96	266	1	539	1	<100	ND	<100	ND
EZVI-SB-6-16	14	16	2/1/2002	192	103	90	4,020	11	3,660	10	61J	0	<100	ND
EZVI-SB-6-18	16	18	2/1/2002	192	127	109	18,300	44	6,320	15	29J	0	<100	ND
EZVI-SB-6-20	18	20	2/1/2002	193	139	115	51,300	120	3,360	8	<100	ND	<100	ND
EZVI-SB-6-22	20	22	2/1/2002	191	141	123	58,900	124	2,200	5	<100	ND	<100	ND
EZVI-SB-6-24	22	24	2/1/2002	193	129	113	81,000	187	1,230	3	<100	ND	<100	ND
EZVI-SB-6-26	24	26	2/1/2002	193	132	110	80,500	195	1,010	2	<100	ND	<100	ND
EZVI-SB-6-28	26	28	2/1/2002	194	170	141	144,000	280	1,020	2	<100	ND	<100	ND
EZVI-SB-6-30	28	30	2/1/2002	195	98	77	93,200	324	1,940	7	<100	ND	<100	ND
EZVI-SB-6-32	30	32	2/1/2002	192	121	88	82,600	259	11,000	35	27J	0	<100	ND
EZVI-SB-6-32-DUP	30	32	2/1/2002	193	94	76	67,600	233	7,390	26	16J	0	<100	ND
EZVI-SB-6-34	32	34	2/1/2002	192	125	109	11,600	28	23,800	57	62J	0	<100	ND
EZVI-SB-6-36	34	36	2/1/2002	190	103	91	169	0	24,700	69	56J	0	<100	ND
EZVI-SB-6-38	36	38	2/1/2002	193	168	133	195	0	22,800	48	70J	0	<100	ND
EZVI-SB-6-40	38	40	2/1/2002	195	132	94	10,900	33	33,100	100	90J	0	<100	ND
EZVI-SB-6-42	40	42	2/1/2002	191	154	120	727	2	26,300 S	60	71J	0	<100	ND
EZVI-SB-6-MB (SS)	Lab Blank		2/1/2002	192	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-6-RINSATE	EQ		2/1/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-7-8 (SS)	6	8	2/7/2002	193	84	84	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-7-10	8	10	2/7/2002	190	135	135	153 SR	0	<100	ND	<100	ND	<100	ND
EZVI-SB-7-12	10	12	2/7/2002	191	102	92	137	0	55J	0	<100	ND	<100	ND
EZVI-SB-7-14	12	14	2/7/2002	192	133	114	698	2	1,010	2	<100	ND	<100	ND
EZVI-SB-7-16	14	16	2/7/2002	193	99	85	23,000	70	2,370	7	<100	ND	189	1
EZVI-SB-7-18	16	18	2/7/2002	192	139	121	541,000	1,167	11,200	24	95J	0	615	1
EZVI-SB-7-20	18	20	2/7/2002	192	139	118	92,500	207	1,740	4	<100	ND	422	1
EZVI-SB-7-22	20	22	2/7/2002	192	157	133	87,100	175	1,180	2	<100	ND	317	1
EZVI-SB-7-24	22	24	2/7/2002	193	146	127	97,600	202	1,270	3	<100	ND	390	1
EZVI-SB-7-26	24	26	2/7/2002	193	160	133	109,000	222	1,980	4	<100	ND	<100	ND
EZVI-SB-7-28	26	28	2/7/2002	191	124	97	96,600	268	4,140	11	<100	ND	<100	ND
EZVI-SB-7-30	28	30	2/7/2002	195	141	118	109,000	249	12,200	28	<100	ND	<100	ND
EZVI-SB-7-32	30	32	2/7/2002	192	133	110	305	1	17,400	42	25J	0	<100	ND
EZVI-SB-7-34	32	34	2/7/2002	192	198	152	26,900	51	56,500	107	97J	0	<100	ND
EZVI-SB-7-36	34	36	2/7/2002	192	150	128	<100	ND	12,500	26	<100	ND	<100	ND
EZVI-SB-7-38	36	38	2/7/2002	191	141	120	<100	ND	2,380	5	<100	ND	<100	ND

Table C-2. Summary of CVOC Results in Soil from EZVI Pre-Demonstration Monitoring (Continued)

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-7-40	38	40	2/7/2002	192	145	111	182	0	10,600	26	37J	0	<100	ND
EZVI-SB-7-42	40	42	2/7/2002	192	154	125	<100	ND	5,720	12	<100	ND	<100	ND
EZVI-SB-7-44	42	44	2/7/2002	192	132	112	<100	ND	444	1	<100	ND	<100	ND
EZVI-SB-7-44-DUP	42	44	2/7/2002	192	133	112	161	0	430	1	<100	ND	<100	ND
EZVI-SB-7-46	44	46	2/7/2002	191	141	120	<100	ND	741	2	<100	ND	<100	ND
EZVI-SB-7-MB (SS)	Lab Blank		2/7/2002	192	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-7-RINSATE	EQ		2/7/2002	NA	NA	NA	2.88	0	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-8-8 (SS)	6	8	3/20/2002	193	87	88	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-8-10	8	10	3/20/2002	194	119	107	1,180	3	505	1	<100	ND	<100	ND
EZVI-SB-8-12	10	12	3/20/2002	193	121	87	503	2	274	1	<100	ND	<100	ND
EZVI-SB-8-14	12	14	3/20/2002	195	125	111	714	2	1,040	2	22J	0	18J	0
EZVI-SB-8-16	14	16	3/20/2002	194	103	90	7,170	21	2,210	6	46J	0	11J	0
EZVI-SB-8-18	16	18	3/20/2002	194	104	90	43,900	127	2,270	7	19J	0	<100	ND
EZVI-SB-8-20	18	20	3/20/2002	193	113	106	57,300	136	2,430	6	20J	0	<100	ND
EZVI-SB-8-22	20	22	3/20/2002	193	100	87	53,000	157	837	2	<100	ND	<100	ND
EZVI-SB-8-24	22	24	3/20/2002	192	98	93	60,600	162	802	2	<100	ND	<100	ND
EZVI-SB-8-26	24	26	3/20/2002	196	111	91	71,800	212	1,090	3	<100	ND	<100	ND
EZVI-SB-8-28	26	28	3/20/2002	195	106	88	78,800	237	1,120	3	<100	ND	<100	ND
EZVI-SB-8-30	28	30	3/20/2002	192	104	90	79,000	226	5,880	17	18J	0	<100	ND
EZVI-SB-8-32	30	32	3/20/2002	193	143	114	19,600	47	33,300	80	65J	0	<100	ND
EZVI-SB-8-34	32	34	3/20/2002	192	126	110	160	0	16,800	40	41J	0	<100	ND
EZVI-SB-8-34-DUP	32	34	3/20/2002	192	124	104	219	1	16,700	42	38J	0	<100	ND
EZVI-SB-8-36	34	36	3/20/2002	195	169	144	136	0	6,950	13	24J	0	<100	ND
EZVI-SB-8-MeOH(SS)	Lab Blank		3/20/2002	193	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-8-RINSATE	EQ		3/20/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND

NA: Not available.
ND: Not detected.
DUP: Duplicate sample.
MB: Method blank.
SS: Surrogate spiked.
J: Result was estimated but below the reporting limit.
S: Spike Recovery outside accepted recovery limits due to the high concentration present in the sample.
R: RPD for MS/MSD outside accepted receovery limits.

Table C-3. Summary of CVOC Results in Soil from EZVI Intermediate Monitoring

Coring after the EZVI Injection	Sample Depth (ft)				Wet Soil	Dry Soil	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
Sample ID	Top Depth	Bottom Depth	Sample Date	MeOH (g)	Weight (g)	Weight (g)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-203-8 (SS)	6	8	10/9/2002	194	137	129	387	1	165	0	<100	ND	<100	ND
EZVI-SB-203-10	8	10	10/9/2002	193	No Recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-203-12	10	12	10/9/2002	192	154	136	290	1	324	1	<100	ND	<100	ND
EZVI-SB-203-14	12	14	10/9/2002	191	122	114	324	1	198	0	<100	ND	<100	ND
EZVI-SB-203-16	14	16	10/9/2002	190	217	188	8,990	13	1,020	1	<100	ND	<100	ND
EZVI-SB-203-18	16	18	10/9/2002	191	232	201	538	1	142	0	<100	ND	<100	ND
EZVI-SB-203-18-DUP	16	18	10/9/2002	191	168	146	426	1	124	0	<100	ND	<100	ND
EZVI-SB-203-20	18	20	10/9/2002	193	158	133	505,000	1,023	16,700	34	70 J	0	<500	ND
EZVI-SB-203-22	20	22	10/9/2002	192	200	169	492,000	798	7,840	13	95 J	0	75 J	0
EZVI-SB-203-24	22	24	10/9/2002	194	126	107	200,000	495	5,800	14	33 J	0	257	1
EZVI-SB-203-26	24	26	10/9/2002	192	104	85	518	2	153	0	<100	ND	19 J	0
EZVI-SB-203-28	26	28	10/9/2002	192	123	99	433	1	191	1	<100	ND	38 J	0
EZVI-SB-203-30	28	30	10/9/2002	192	70	57	60,300	271	2,220	10	14 J	0	<100	ND
EZVI-SB-203-MeOH	Lab Blank		10/9/2002	NA	NA	NA	254	NA	54 J	NA	<100	ND	<100	ND
EZVI-SB-203-RINSATE	EQ		10/9/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-204-8 (SS)	6	8	10/9/2002	191	106	98	<100	ND	148	0	16 J	0	<100	ND
EZVI-SB-204-10	8	10	10/9/2002	190	No Recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-204-12	10	12	10/9/2002	196	186	162	143	0	112	0	<100	ND	<100	ND
EZVI-SB-204-14	12	14	10/9/2002	194	81	71	148	1	58 J	0	<100	ND	<100	ND
EZVI-SB-204-16	14	16	10/9/2002	192	198	171	391	1	36 J	0	<100	ND	<100	ND
EZVI-SB-204-18	16	18	10/9/2002	193	191	163	436	1	95 J	0	<100	ND	<100	ND
EZVI-SB-204-20	18	20	10/9/2002	191	135	120	2,990	6	2,780	6	<100	ND	174	0
EZVI-SB-204-22	20	22	10/9/2002	195	174	159	1,580	3	897	1	<100	ND	17 J	0
EZVI-SB-204-24	22	24	10/9/2002	194	164	138	17,800	35	11,100	22	17 J	0	1,370	3
EZVI-SB-204-24-DUP	22	24	10/9/2002	192	144	119	5,570	13	9,260	21	13 J	0	1,490	3
EZVI-SB-204-26	24	26	10/9/2002	194	102	82	56,400	183	8,440	27	13 J	0	13 J	0
EZVI-SB-204-28	26	28	10/9/2002	192	156	128	12,800	27	2,700	6	<100	ND	38 J	0
EZVI-SB-204-30	28	30	10/9/2002	193	106	84	42,000	133	22,200	70	29 J	0	<100	ND
EZVI-SB-204-MeOH	Lab Blank		10/9/2002				200		36 J		<100	ND	<100	ND
EZVI-SB-207-8 (SS)	6	8	10/8/2002	193	157	149	535	1	161	0	<100	ND	<100	ND
EZVI-SB-207-10	8	10	10/8/2002	192	No Recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-207-12	10	12	10/8/2002	193	148	128	246	1	90 J	0	<100	ND	<100	ND
EZVI-SB-207-14	12	14	10/8/2002	191	155	138	<100	ND	68 J	0	<100	ND	<100	ND
EZVI-SB-207-16	14	16	10/8/2002	195	224	196	<100	ND	2,030	3	<100	ND	132	0
EZVI-SB-207-18	16	18	10/8/2002	193	145	132	114	0	218	0	<100	ND	14 J	0
EZVI-SB-207-20	18	20	10/8/2002	196	230	196	37,400	54	10,600	15	22 J	0	428	1
EZVI-SB-207-22	20	22	10/8/2002	194	154	139	<100	ND	711	1	<100	ND	87 J	0
EZVI-SB-207-24	22	24	10/8/2002	197	184	161	506,000	856	13,400	23	<500	ND	1,120	2

Table C-3. Summary of CVOC Results in Soil from EZVI Intermediate Monitoring (Continued)

Coring after the EZVI Injection	Sample Depth (ft)				Wet Soil	Dry Soil	TCE		*cis*-1,2-DCE		*trans*-1,2-DCE		Vinyl Chloride	
Sample ID	Top Depth	Bottom Depth	Sample Date	MeOH (g)	Weight (g)	Weight (g)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-207-24-DUP	22	24	10/8/2002	194	162	145	148,000	268	10,200	18	<500	ND	715	1
EZVI-SB-207-26	24	26	10/8/2002	193	118	101	68,400	177	1,460	4	13 J	0	14 J	0
EZVI-SB-207-28	26	28	10/8/2002	196	230	188	163,000	252	3,740	6	28 J	0	21 J	0
EZVI-SB-207-30	28	30	10/8/2002	192	114	91	84,900	248	4,570	13	41 J	0	20 J	0
EZVI-SB-207-MeOH	Lab Blank		10/8/2002				193		37 J		<100	ND	<100	ND
EZVI-SB-207-RINSATE	EQ		10/8/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-208-8 (SS)	6	8	10/8/2002	192	148	145	<100	ND	163	0	<100	ND	<100	ND
EZVI-SB-208-10	8	10	10/8/2002	193	98	90	<100	ND	201	1	<100	ND	<100	ND
EZVI-SB-208-12	10	12	10/8/2002	191	126	119	<100	ND	33 J	0	<100	ND	<100	ND
EZVI-SB-208-14	12	14	10/8/2002	192	130	114	<100	ND	109	0	<100	ND	<100	ND
EZVI-SB-208-16	14	16	10/8/2002	193	110	97	<100	ND	152	0	<100	ND	37 J	0
EZVI-SB-208-18	16	18	10/8/2002	191	136	97	<100	ND	295	1	<100	ND	11 J	0
EZVI-SB-208-20	18	20	10/8/2002	190	154	130	<100	ND	927	2	<100	ND	129	0
EZVI-SB-208-22	20	22	10/8/2002	192	No Recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-208-24	22	24	10/8/2002	191	154	131	70,800	143	2,250	5	12 J	0	32 J	0
EZVI-SB-208-26	24	26	10/8/2002	192	No Recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-208-28	26	28	10/8/2002	192	172	138	134,000	269	6,830	14	25 J	0	18 J	0
EZVI-SB-208-28-DUP	26	28	10/8/2002	190	134	109	83,900	204	5,300	13	20 J	0	12 J	0
EZVI-SB-208-30	28	30	10/8/2002	191	No Recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-208-MeOH	Lab Blank		10/8/2002				160		33 J		<100	ND	<100	ND
EZVI-SB-209-8 (SS)	6	8	10/8/2002	191	165	155	156	0	138	0	<100	ND	<100	ND
EZVI-SB-209-10	8	10	10/8/2002	190	No Recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-209-12	10	12	10/8/2002	190	157	139	1,120	2	184	0	<100	ND	20 J	0
EZVI-SB-209-14	12	14	10/8/2002	194	145	130	<100	ND	174	0	<100	ND	31 J	0
EZVI-SB-209-16	14	16	10/8/2002	192	209	171	<100	ND	1,300	2	<100	ND	46 J	0
EZVI-SB-209-18	16	18	10/8/2002	192	192	168	1,170	2	1,990	3	<100	ND	238	0
EZVI-SB-209-20	18	20	10/8/2002	191	171	149	22,800	40	10,100	18	14 J	0	847	1
EZVI-SB-209-22	20	22	10/8/2002	190	178	160	311	1	1,240	2	<100	ND	335	1
EZVI-SB-209-22-DUP	20	22	10/8/2002	189	151	120	166	0	828	2	<100	ND	140	0
EZVI-SB-209-24	22	24	10/8/2002	192	146	133	10,200	20	3,520	7	14 J	0	554	1
EZVI-SB-209-26	24	26	10/8/2002	192	87	71	78,800	287	1,020	4	14 J	0	10 J	0
EZVI-SB-209-28	26	28	10/8/2002	190	186	146	154,000	296	1,570	3	33 J	0	15 J	0
EZVI-SB-209-30	28	30	10/8/2002	192	101	81	76,000	247	1,480	5	10 J	0	<100	ND
EZVI-SB-209-MeOH	Lab Blank		10/8/2002				313		60 J		<100	ND	<100	ND

NA: Not available.
ND: Not detected.
DUP: Duplicate sample.

Table C-3. Summary of CVOC Results in Soil from EZVI Intermediate Monitoring (Continued)

Coring after the EZVI Injection Sample ID	Sample Depth (ft) Top Depth	Bottom Depth	Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE Results in MeOH (µg/L)	TCE Results in Dry Soil (mg/Kg)	*cis* -1,2-DCE Results in MeOH (µg/L)	*cis* -1,2-DCE Results in Dry Soil (mg/Kg)	*trans* -1,2-DCE Results in MeOH (µg/L)	*trans* -1,2-DCE Results in Dry Soil (mg/Kg)	Vinyl Chloride Results in MeOH (µg/L)	Vinyl Chloride Results in Dry Soil (mg/Kg)

MB: Method blank.
SS: Surrogate spiked.
J: Result was estimated but below the reporting limit.
S: Spike Recovery outside accepted recovery limits due to the high concentration present in the sample.
R: RPD for MS/MSD outside accepted receovery limits.

Table C-4. Summary of CVOC Results in Soil from Post-Demonstration Monitoring in EZVI Plot

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-301-8 (SS)	6	8	11/21/2002	194	122	117	119	0	33J	0	<100	ND	<100	ND
EZVI-SB-301-10	8	10	11/21/2002	194	122	110	476	1	506	1	<100	ND	<100	ND
EZVI-SB-301-12	10	12	11/21/2002	195	129	111	626	1	4,580	11	<100	ND	<100	ND
EZVI-SB-301-14	12	14	11/21/2002	194	130	110	1,680	4	2,430	6	<100	ND	<100	ND
EZVI-SB-301-16	14	16	11/21/2002	194	170	152	670	1	5,560	10	<100	ND	175	0
EZVI-SB-301-18	16	18	11/21/2002	194	165	144	329	1	5,520	10	<100	ND	43J	0
EZVI-SB-301-20	18	20	11/21/2002	194	195	172	7,500	12	7,850	12	16J	0	748	1
EZVI-SB-301-22	20	22	11/21/2002	195	170	142	3,970	8	4,250	8	20J	0	2,300	4
EZVI-SB-301-24	22	24	11/21/2002	195	149	129	136	0	752	2	21J	0	4,410	9
EZVI-SB-301-26	24	26	11/21/2002	194	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-301-28	26	28	11/21/2002	193	183	150	64,100	119	5,860	11	16J	0	864	2
EZVI-SB-301-30	28	30	11/21/2002	193	164	131	4,450	9	2,050	4	<100	ND	52J	0
EZVI-SB-301-32	30	32	11/21/2002	194	147	115	24,200	58	13,300	32	38J	0	11J	0
EZVI-SB-301-34	32	34	11/21/2002	194	162	128	16,400	36	21,200	46	88J	0	11J	0
EZVI-SB-301-36	34	36	11/21/2002	193	132	111	118	0	15,900	38	40J	0	<100	ND
EZVI-SB-301-36-DUP	34	36	11/21/2002	193	137	119	1,090	2	24,800	55	61J	0	<100	ND
EZVI-SB-301-38	36	38	11/21/2002	195	171	142	<100	ND	8,220	16	30J	0	<100	ND
EZVI-SB-301-40	38	40	11/21/2002	193	165	120	123	0	5,020	12	26J	0	<100	ND
EZVI-SB-301-42	40	42	11/21/2002	193	201	153	168	0	1,470	3	28J	0	<100	ND
EZVI-SB-301-44	42	44	11/21/2002	193	162	131	112	0	860	2	<100	ND	<100	ND
EZVI-SB-301-46	44	46	11/21/2002	194	317	261	574	1	7,000	8	29J	0	<100	ND
EZVI-SB-301-MB (SS)	Lab Blank		11/21/2002	194	NA	NA	130	NA	16J	NA	<100	ND	<100	ND
EZVI-SB-301-RINSATE	EQ		11/21/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-302-8 (SS)	6	8	11/18/002	194	151	147	192	0	65J	0	<100	ND	<100	ND
EZVI-SB-302-10	8	10	11/18/002	195	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-302-12	10	12	11/18/002	195	192	168	354	1	262	0	<100	ND	<100	ND
EZVI-SB-302-14	12	14	11/18/002	195	177	158	596	1	1,400	2	<100	ND	<100	ND
EZVI-SB-302-16	14	16	11/18/002	195	154	140	5,870	11	3,210	6	<100	ND	<100	ND
EZVI-SB-302-18	16	18	11/18/002	197	135	121	2,330	5	2,890	6	<100	ND	26J	0
EZVI-SB-302-18-DUP	16	18	11/18/002	196	154	135	3,180	6	3,110	6	<100	ND	18J	0
EZVI-SB-302-20	18	20	11/18/002	195	203	175	36,100	57	5,410	8	23J	0	358	1
EZVI-SB-302-22	20	22	11/18/002	196	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-302-24	22	24	11/18/002	196	209	178	11,400	18	2,940	5	23J	0	129	0
EZVI-SB-302-26	24	26	11/18/002	197	155	134	3,680	7	974	2	<100	ND	<100	ND

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Table C-4. Summary of CVOC Results in Soil from Post-Demonstration Monitoring in EZVI Plot (Continued)

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-302-28	26	28	11/18/002	195	188	155	4,360	8	1,160	2	10J	0	54J	0
EZVI-SB-302-30	28	30	11/18/002	195	144	115	60,000	144	13,600	33	34J	0	10J	0
EZVI-SB-302-32	30	32	11/18/002	196	230	181	17,000	28	43,500	71	95J	0	<100	ND
EZVI-SB-302-34	32	34	11/18/002	193	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-302-36	34	36	11/18/002	192	189	158	124	0	21,700	38	56J	0	<100	ND
EZVI-SB-302-38	36	38	11/18/002	194	166	146	211	0	9,780	18	40J	0	<100	ND
EZVI-SB-302-40	38	40	11/18/002	194	145	117	212	0	7,660	18	36J	0	<100	ND
EZVI-SB-302-42	40	42	11/18/002	193	175	127	196	0	2,310	5	25J	0	<100	ND
EZVI-SB-302-44	42	44	11/18/002	195	188	151	222	0	2,040	4	25J	0	<100	ND
EZVI-SB-302-46	44	46	11/18/002	192	250	202	3,300	5	5,970	9	29J	0	<100	ND
EZVI-SB-302-MB (SS)	Lab Blank		11/18/002	195	NA	NA	121	NA	19J	NA	<100	ND	<100	ND
EZVI-SB-302-RINSATE	EQ		11/18/003	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-303-8 (SS)	6	8	11/20/2002	196	132	126	164	0	44J	0	<100	ND	<100	ND
EZVI-SB-303-10	8	10	11/20/2002	194	131	121	194	0	83J	0	<100	ND	<100	ND
EZVI-SB-303-12	10	12	11/20/2002	196	240	209	567	1	4,580	6	<100	ND	75J	0
EZVI-SB-303-14	12	14	11/20/2002	194	101	96	364	1	5,120	13	<100	ND	16J	0
EZVI-SB-303-16	14	16	11/20/2002	195	265	227	3,290	4	6,790	9	13J	0	197	0
EZVI-SB-303-18	16	18	11/20/2002	194	171	151	784	1	8,250	15	15J	0	54J	0
EZVI-SB-303-20	18	20	11/20/2002	193	165	141	237,000	451	9,880	19	37J	0	355	1
EZVI-SB-303-20-DUP	18	20	11/20/2002	195	156	132	195,000	400	11,900	24	29J	0	483	1
EZVI-SB-303-22	20	22	11/20/2002	193	173	156	4,110	7	8,160	14	19J	0	120	0
EZVI-SB-303-24	22	24	11/20/2002	194	241	209	3,390,000	4,502	36,600	49	193	0	1,020	1
EZVI-SB-303-26	24	26	11/20/2002	193	122	101	6,410	17	1,260	3	22J	0	25J	0
EZVI-SB-303-28	26	28	11/20/2002	193	166	133	21,400	45	3,070	6	36J	0	51J	0
EZVI-SB-303-30	28	30	11/20/2002	193	132	106	115,000	293	4,160	11	20J	0	14J	0
EZVI-SB-303-32	30	32	11/20/2002	193	161	122	95,100	221	17,200	40	57J	0	17J	0
EZVI-SB-303-34	32	34	11/20/2002	194	207	163	9,880	18	48,000	85	122	0	<100	ND
EZVI-SB-303-36	34	36	11/20/2002	194	144	127	<100	ND	21,900	45	69J	0	<100	ND
EZVI-SB-303-38	36	38	11/20/2002	194	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-303-40	38	40	11/20/2002	195	199	163	<100	ND	5,170	9	38J	0	<100	ND
EZVI-SB-303-42	40	42	11/20/2002	193	138	115	168	0	590	1	<100	ND	<100	ND
EZVI-SB-303-44	42	44	11/20/2002	195	189	156	290	1	627	1	13J	0	<100	ND
EZVI-SB-303-46	44	46	11/20/2002	194	206	169	242	0	3,030	5	14J	0	<100	ND
EZVI-SB-303-MB (SS)	Lab Blank		11/20/2002	194	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND

Table C-4. Summary of CVOC Results in Soil from Post-Demonstration Monitoring in EZVI Plot (Continued)

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-303-RINSATE	EQ		11/20/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-304-8 (SS)	6	8	11/19/2002	194	151	147	105	0	25J	0	<100	ND	<100	ND
EZVI-SB-304-10	8	10	11/19/2002	194	102	98	102	0	39J	0	<100	ND	<100	ND
EZVI-SB-304-12	10	12	11/19/2002	195	102	91	120	0	1,830	5	<100	ND	<100	ND
EZVI-SB-304-14	12	14	11/19/2002	195	153	134	209	0	1,740	3	<100	ND	<100	ND
EZVI-SB-304-16	14	16	11/19/2002	194	170	152	<100	ND	1,960	3	<100	ND	15J	0
EZVI-SB-304-18	16	18	11/19/2002	195	143	130	<100	ND	2,260	5	<100	ND	45J	0
EZVI-SB-304-20	18	20	11/19/2002	196	147	130	965	2	3,190	7	<100	ND	308	1
EZVI-SB-304-22	20	22	11/19/2002	196	116	98	439	1	8,540	23	<100	ND	2,300	6
EZVI-SB-304-24	22	24	11/19/2002	196	199	168	152	0	723	1	<100	ND	1,350	2
EZVI-SB-304-26	24	26	11/19/2002	194	136	116	150	0	84J	0	<100	ND	280	1
EZVI-SB-304-28	26	28	11/19/2002	194	154	122	12,200	28	1,100	3	<100	ND	25J	0
EZVI-SB-304-30	28	30	11/19/2002	195	116	94	67,400	193	13,700	39	34J	0	13J	0
EZVI-SB-304-32	30	32	11/19/2002	195	133	103	27,700	74	29,800	80	67J	0	82J	0
EZVI-SB-304-32-DUP	30	32	11/19/2002	195	147	115	25,900	63	30,500	74	72J	0	68J	0
EZVI-SB-304-34	32	34	11/19/2002	193	186	136	139	0	33,100	72	75J	0	14J	0
EZVI-SB-304-36	34	36	11/19/2002	194	179	149	<100	ND	12,800	24	36J	0	22J	0
EZVI-SB-304-38	36	38	11/19/2002	195	141	119	<100	ND	2,030	5	15J	0	<100	ND
EZVI-SB-304-40	38	40	11/19/2002	195	145	134	221	0	1,340	3	10J	0	<100	ND
EZVI-SB-304-42	40	42	11/19/2002	194	155	120	256	1	970	2	10J	0	<100	ND
EZVI-SB-304-44	42	44	11/19/2002	195	153	122	<100	ND	81J	0	<100	ND	<100	ND
EZVI-SB-304-46	44	46	11/19/2002	194	174	148	1,850	3	4,920	9	15J	0	<100	ND
EZVI-SB-304-MB (SS)	Lab Blank		11/19/2002	192	NA	NA	<100	ND	10J	NA	<100	ND	<100	ND
EZVI-SB-304-RINSATE	EQ		11/19/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND
EZVI-SB-307-8 (SS)	6	8	11/21/2002	195	108	109	151	0	31J	0	<100	ND	<100	ND
EZVI-SB-307-10	8	10	11/21/2002	194	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-307-12	10	12	11/21/2002	193	166	145	979	2	4,270	8	<100	ND	<100	ND
EZVI-SB-307-14	12	14	11/21/2002	195	174	149	760	1	4,560	8	<100	ND	17J	0
EZVI-SB-307-16	14	16	11/21/2002	192	202	184	250	0	4,210	6	<100	ND	62J	0
EZVI-SB-307-18	16	18	11/21/2002	193	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-307-20	18	20	11/21/2002	193	177	152	12,700	23	3,870	7	31J	0	1,650	3
EZVI-SB-307-22	20	22	11/21/2002	194	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-307-24	22	24	11/21/2002	194	236	195	13,200	19	3,900	6	31J	0	1,660	2
EZVI-SB-307-26	24	26	11/21/2002	194	164	135	55,800	113	1,430	3	15J	0	<100	ND

Table C-4. Summary of CVOC Results in Soil from Post-Demonstration Monitoring in EZVI Plot (Continued)

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-307-26-DUP	24	26	11/21/2002	194	166	135	72,500	149	1,350	3	12J	0	11J	0
EZVI-SB-307-28	26	28	11/21/2002	193	134	112	73,400	175	1,340	3	15J	0	11J	0
EZVI-SB-307-30	28	30	11/21/2002	193	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-307-32	30	32	11/21/2002	194	221	171	136,000	235	21,100	36	54J	0	23J	0
EZVI-SB-307-34	32	34	11/21/2002	193	219	163	51,900	96	55,200	102	118	0	16J	0
EZVI-SB-307-36	34	36	11/21/2002	194	190	155	12,700	23	50,300	91	112	0	<100	ND
EZVI-SB-307-38	36	38	11/21/2002	193	174	144	242	0	7,200	14	19J	0	<100	ND
EZVI-SB-307-40	38	40	11/21/2002	194	187	150	172	0	3,970	7	25J	0	<100	ND
EZVI-SB-307-42	40	42	11/21/2002	193	155	112	165	0	328	1	<100	ND	<100	ND
EZVI-SB-307-44	42	44	11/21/2002	193	199	156	172	0	480	1	<100	ND	<100	ND
EZVI-SB-307-46	44	46	11/21/2002	193	128	100	8,790	24	4,570	12	<100	ND	<100	ND
EZVI-SB-307-MB (SS)	Lab Blank		11/21/2002	194	NA	NA	129	NA	11J	NA	<100	ND	<100	ND
EZVI-SB-307-RINSATE	EQ		11/21/2002	NA	NA	NA	<1.0	ND	0.26J	NA	<1.0	ND	<1.0	ND
EZVI-SB-308-8 (SS)	6	8	11/22/2002	194	92	92	<100	ND	13J	0	<100	ND	<100	ND
EZVI-SB-308-10	8	10	11/22/2002	193	136	125	186	0	47J	0	<100	ND	<100	ND
EZVI-SB-308-12	10	12	11/22/2002	194	205	178	605	1	1,990	3	<100	ND	<100	ND
EZVI-SB-308-14	12	14	11/22/2002	194	157	138	131	0	999	2	<100	ND	<100	ND
EZVI-SB-308-16	14	16	11/22/2002	194	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-308-18	16	18	11/22/2002	193	197	173	159	0	1,200	2	<100	ND	144	0
EZVI-SB-308-20	18	20	11/22/2002	193	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-308-22	20	22	11/22/2002	194	180	152	98,300	177	24,400	44	31J	0	1,400	3
EZVI-SB-308-24	22	24	11/22/2002	193	130	109	53,500	130	2,990	7	11J	0	169	0
EZVI-SB-308-26	24	26	11/22/2002	192	161	131	60,000	125	2,210	5	<100	ND	56J	0
EZVI-SB-308-28	26	28	11/22/2002	194	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-308-30	28	30	11/22/2002	193	185	146	128,000	248	5,680	11	26J	0	17J	0
EZVI-SB-308-32	30	32	11/22/2002	194	no recovery		NA	NA	NA	NA	NA	NA	NA	NA
EZVI-SB-308-34	32	34	11/22/2002	194	140	111	17,800	44	27,100	67	62J	0	<100	ND
EZVI-SB-308-36	34	36	11/22/2002	195	192	162	134	0	12,000	21	30J	0	<100	ND
EZVI-SB-308-38	36	38	11/22/2002	193	167	136	<100	ND	5,060	10	16J	0	<100	ND
EZVI-SB-308-40	38	40	11/22/2002	193	194	150	<100	ND	5,430	10	31J	0	<100	ND
EZVI-SB-308-42	40	42	11/22/2002	194	140	110	<100	ND	5,320	13	30J	0	<100	ND
EZVI-SB-308-42-DUP	40	42	11/22/2002	192	152	118	<100	ND	5,210	12	30J	0	<100	ND
EZVI-SB-308-44	42	44	11/22/2002	194	148	123	<100	ND	692	2	<100	ND	<100	ND
EZVI-SB-308-46	44	46	11/22/2002	194	215	171	16,000	27	5200	9	17J	0	<100	ND

Table C-4. Summary of CVOC Results in Soil from Post-Demonstration Monitoring in EZVI Plot (Continued)

Sample ID	Sample Depth (ft)		Sample Date	MeOH (g)	Wet Soil Weight (g)	Dry Soil Weight (g)	TCE		*cis* -1,2-DCE		*trans* -1,2-DCE		Vinyl Chloride	
	Top Depth	Bottom Depth					Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)	Results in MeOH (µg/L)	Results in Dry Soil (mg/Kg)
EZVI-SB-308-MB (SS)	Lab Blank		11/22/2002	193	NA	NA	<100	ND	<100	ND	<100	ND	<100	ND
EZVI-SB-308-RINSATE	EQ		11/22/2002	NA	NA	NA	<1.0	ND	<1.0	ND	<1.0	ND	<1.0	ND

NA: Not available.
ND: Not detected.
DUP: Duplicate sample.
MB: Method blank.
SS: Surrogate spiked.
J: Result was estimated but below the reporting limit.

C-5. Long-Term Groundwater Sampling

In December 2003 and March 2004, groundwater samples were collected from various monitoring wells associated with the EZVI demonstration and analyzed for CVOCs. The purpose of these two individual sampling events was to collect observational data on the concentrations of CVOCs in groundwater after a significant amount of time had passed since the initial injection of EZVI. The results were not intended to use in assessing the performance of the technology. Because the results were not used for performance assessment, they are not included in the main text of the report but are presented here in Appendix C-5.

In November 2002, Battelle performed the post-demonstration soil and groundwater characterization for performance assessment of the EZVI technology. In December 2003, GeoSyntec collected a round of groundwater samples from the multilevel wells along the plot edges (EML-1 through EML-4, see Figure 3-3). The results are presented in Table C-5. In addition, the pre- and post-demonstration CVOC concentrations in the multilevel wells and other nearby wells have been reprinted from Table 5-4 for reference. TCE concentrations decreased substantially in all four monitoring wells, from 23,000-76,000 µg/L during post-demonstration monitoring to <100-2,700 µg/L one year later. Decreases in cis-1,2-DCE also were observed in all four monitoring wells. With respect to vinyl chloride, concentrations increased in two monitoring wells, from 29,000 µg/L to 33,500 µg/L in EML-1 and from 500 µg/L to 1,830 µg/L in EML-3. Vinyl chloride concentrations decreased substantially in EML-2, from 20,000 µg/L to 4,950 µg/L, while concentrations remained relatively stable in EML-4 one year later. The continued decreases in TCE and *cis*-1,2-DCE concentrations one year after post-demonstration groundwater characterization suggests that the EZVI technology had a prolonged impact on the treatment area. The continued increase in VC concentrations indicates that biologically driven reductive dechlorination of the CVOCs is continuing.

In March 2004, approximately 16 months after the post-demonstration characterization, a single groundwater sampling event was conducted in several of the shallow monitoring wells in and around the test plot. The results are presented in Table C-6. In addition, the pre- and post-demonstration CVOC concentrations in the wells have been reprinted from Table 5-8 for reference. The CVOC concentrations in monitoring well PA-23 are plotted in Figure C-1. Figure C-2 contains TCE and ethene concentrations to reflect the significant difference in concentration scales between the two compounds. Although the data were collected for observational purposes, the results suggest that the EZVI treatment had a long-lasting effect on CVOCs in the subsurface. In PA-23, TCE concentrations decreased from 8,790 µg/L during post-demonstration sampling to 2 µg/L. Concentrations of the degradation byproducts *cis*-1,2 DCE, *trans*-1,2-DCE, and vinyl chloride also decreased substantially in monitoring PA-23 in the center of the test plot after post-demonstration characterization. Decreases in TCE were also seen in shallow monitoring wells PA-24S and PA-25S around the perimeter of the test plot, as well as in the injection and extraction wells EIW-1 and EEW-1. Increased concentrations of degradation daughter products *cis*-1,2-DCE, *trans*-1,2-DCE, and vinyl chloride were observed in PA-24S and PA-25S. Ethene concentrations increased substantially in PA-23 after the post-demonstration characterization event. This could suggest that the remaining EZVI in the treatment area still promotes dechlorination of TCE in and around the test area.

These groundwater samples were collected when the recirculation system in the test plot had been turned off for over one year, and natural groundwater flow patterns were likely reestablished. The results of this sampling event suggest that the CVOCs in the test plot continued to degrade by biotic and abiotic means for more than a year after injection of EZVI.

Table C-5. CVOC Groundwater Concentrations in the Multilevel Wells One Year after Post-Demonstration Characterization

Well ID	TCE (µg/L) Pre-Demo	TCE (µg/L) Post-Demo	TCE (µg/L) Long-Term	*cis*-1,2-DCE (µg/L) Pre-Demo	*cis*-1,2-DCE (µg/L) Post-Demo	*cis*-1,2-DCE (µg/L) Long-Term	Vinyl Chloride (µg/L) Pre-Demo	Vinyl Chloride (µg/L) Post-Demo	Vinyl Chloride (µg/L) Long-Term
PA-23	1,180,000	8,790	NA	16,900	169,000	NA	<1,000	21,600	NA
EEW-1	1,050,000	471,000	NA	67,100	80,100	NA	<1,000	6,980	NA
EML-1	450,000	76,000	2,700	11,000	96,000	77,900	<500	29,000	33,500
EML-2	350,000	23,000	1,000	21,000	130,000	5,320	<500	20,000	4,950
EML-3	1,300	74,000	740	<100	41,000	2,630	<100	500	1,830
EML-4	1,600	24,000	<100	130	42,000	1,150	<20	1,500	1,460
PA-24S	772,000	12,100	NA	47,400	31,700	NA	<1,000	1,580	NA
PA-25S	71,300	129,000	NA	69,200	42,800	NA	<1,000	75J	NA

NA = not analyzed
Pre-demonstration: March 2002; Post-demonstration: November 2002; Long-Term: December 2003.

Table C-6. CVOC and Ethene Concentrations in Groundwater in Shallow Wells, March 2004

Well ID	Pre-Demo	During	Post-Demo	Long-Term	Pre-Demo	During	Post-Demo	Long-Term
	TCE (µg/L)				***cis*-1,2-DCE (µg/L)**			
EZVI Plot Well								
PA-23	1,180,000	92,100	8,790	2 J	16,900	17,900	169,000	870
EZVI Perimeter Wells								
PA-24S	772,000	474,000	12,100	501	47,400	15,800	31,700	63,100
PA-25S	71,300	69,600	129,000	<5	69,200	9,320	42,800	<5
Injection and Extraction Wells								
EIW-1	144,000	NA	7,820	108	38,300	NA	3,280	8,650
EEW-1	1,050,000	NA	471,000	4.5	67,100	NA	80,100	10.6
	***trans*-1,2-DCE (µg/L)**				**Vinyl Chloride (µg/L)**			
EZVI Plot Well								
PA-23	<1,000	68 J	245	71	<1,000	53 J	21,600	3,620
EZVI Perimeter Wells								
PA-24S	<1,000	<50	190 J	1,140	<1,000	<50	1,580	54,600
PA-25S	<1,000	46 J	381	83.8	<1,000	<100	75 J	8.75
Injection and Extraction Wells								
EIW-1	556	NA	24 J	148	638	NA	322	4,890
EEW-1	550 J	NA	390 J	10.5	<1,000	NA	6,980	34.9
	Ethene (µg/L)							
EZVI Plot Well								
PA-23	79.3	10	1,680	9,280				

Well IDs: S = shallow well (Upper Sand Unit)
EIW-1 = injection well; EEW-1 = extraction well.
Pre-demonstration = March 2002; during the demonstration = August 2002; post-demonstration = November 2002; Long-term = March 2004
J = Estimated value, below reporting limit.

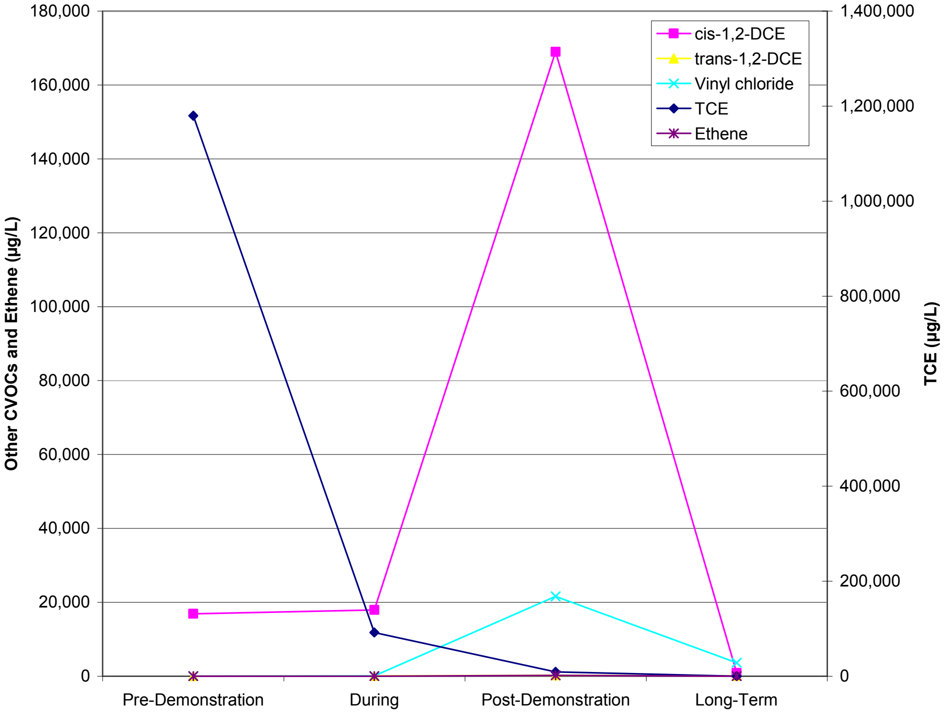

Figure C-1. CVOC Concentrations and Ethene in PA-23 After EZVI Treatment

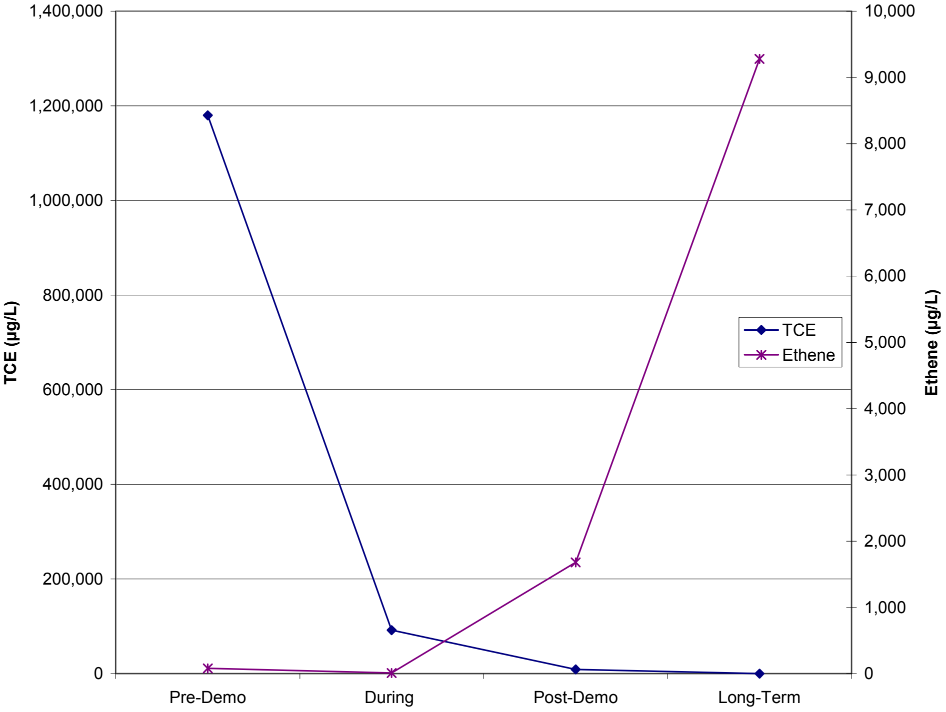

Figure C-2. TCE and Ethene Concentrations in Groundwater in PA-23 after EZVI Treatment

Appendix D

Inorganic and Other Aquifer Parameters

Table D-1. Groundwater Field Parameters

	Temperature (°C)			DO (mg/L)			pH			ORP (mV)			Conductivity (mS/cm)		
Well ID	**Pre-Demo**	**Aug 2002**	**Post-Demo**	**Pre-Demo**	**Aug 2002**	**Post-Demo**	**Pre-Demo**	**Aug 2002**	**Post-Demo**	**Pre-Demo**	**Aug 2002**	**Post-Demo**	**Pre-Demo**	**Aug 2002**	**Post-Demo**
EZVI Plot Well															
PA-23	26.2	29.62	27.88	0.39	0.1	0.00	6.49	7.23	6.41	31	-143	-17	0.18	1.81	0.24
EZVI Perimeter Wells															
PA-24S	25.9	29.4	27.72	1.03	0.1	0.00	6.40	7.07	6.6	42	-97	32	0.15	1.82	0.2
PA-24I	25.6	28	27.02	0.59	0.1	0.00	6.81	7.5	7.16	33	-128	55	0.22	2.73	0.28
PA-24D	25.4	27.99	26.54	0.94	0.3	0.00	6.78	7.16	6.93	15	-107	40	0.16	2.42	0.28
PA-25S	26.2	29.75	29.42	0.98	0.2	0.00	6.58	7.22	7.1	148	-125	11	0.22	1.78	0.12
PA-25I	25.7	28.93	27.53	0.90	0.2	0.00	6.83	7.56	7.12	83	-121	11	0.21	1.99	0.19
PA-25D	25.4	28.11	26.9	0.97	0.3	0.00	6.77	7.49	6.97	71	-195	3	0.33	3.1	0.3
Injection and Extraction Wells															
EIW-1	29.1	NA	26.98	0.83	NA	0.00	6.62	NA	6.6	15	NA	17	0.16	NA	0.19
EEW-1	25.4	NA	28.09	0.31	NA	0.00	6.47	NA	6.48	55	NA	106	0.16	NA	0.19

Pre-Demo: March 2002
Post-Demo: EZVI-November 2002.

Table D-2. Inorganic Results of Groundwater from the EZVI Demonstration

	Dissolved Iron (mg/L)			Total Iron (mg/L)			Manganese (mg/L)			Calcium (mg/L)			Magnesium (mg/L)			Potassium (mg/L)			Sodium (mg/L)		
Well ID	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo
EZVI Plot Well																					
PA-23	15.7	3.65	3.03	14.8	4.07	2.73	0.12	0.0498	0.121	159	111	224	19.9	34.7	51	231	122	147	36.8	72.4	67.2
PA-23-DUP	15.4	3.56	2.99	13	4.11	2.52	0.119	0.0492	0.12	157	122	240	19.2	40.9	57.7	232	133	161	34.4	80.4	66.5
EZVI Perimeter Wells																					
PA-24S	27.4	2.58	16.2	21.8	2.8	17.3	0.2	0.067	0.0701	184	160	154	26.6	40.7	41.9	116	98.9	87.1	38	64.2	65.8
PA-24I	5.54	0.751	2.56	6.05	0.811	2.62	0.148	0.0473	0.0568	935	68.3	59.1	65.3	78.2	59.4	55.6	36.2	28.6	280	323	312
PA-24D	2.36	1.74	3.12	3.07	2.04	4.2	0.0893	0.0567	0.035	104	105	87.4	53.2	61.8	59.4	50.1	53.9	46	174	218	257
PA-25S	12	2.27	2.97	13.2	2.51	3.23	0.0985	0.0318	0.0188	138	138	72	21.3	38	16.8	299	75.6	68	39.7	81.4	62.3
PA-25I	2.68	0.255	1.82	1.54	0.448	1.84	0.0461	0.0163	0.026	66.5	51.1	49.3	65.2	83	66.2	51.9	30.3	27.2	232	213	195
PA-25D	1.12	0.784	0.906	1.21	1.08	1.02	0.0391	0.0182	0.024	59.9	59.2	59.2	72.3	74.5	66.4	17.2	20.9	19.7	443	405	374
Injection and Extraction Wells																					
EIW-1	7.23	NA	6.16	7.33	NA	5.54	0.21	NA	0.653	156	NA	201	15	NA	32.7	161	NA	134	99.1	NA	65.6
EEW-1	13.4	NA	6.45	12.9	NA	6.76	0.154	NA	0.208	178	NA	160	15.9	NA	30.5	195	NA	170	37.1	NA	73.4

	Chloride (mg/L)			Phosphate (mg/L)			Bromide (mg/L)			Sulfate (mg/L)			Nitrate (NO_3-NO_2 as N)			Alkalinity (mg/L)		
Well ID	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo	Pre-Demo	Demo 1	Post-Demo
EZVI Plot Well																		
PA-23	200	175	294	<0.5	<3.0	<0.5	<1.0	<2.0	2.65	103.0	147	12.7	NA	<0.5	<0.5	475	384	669
PA-23-DUP	200	175	209	<0.5	<3.0	<0.5	<1.0	<2.0	2.6	103.0	147	12.9	NA	<0.5	<0.5	470	391	616
EZVI Perimeter Wells																		
PA-24S	191	183	201	<3.0	<3.0	<0.5	<2.0	<2.0	0.41 J	90.7	139	118	NA	<0.5	<0.5	392	416	461
PA-24I	463	521	581	<6.0	<3.0	<0.5	<4.0	<2.0	1.06	100.0	105	77.5	NA	<0.5	<0.5	342	364	341
PA-24D	353	487	572	<3.0	<3.0	<0.5	<2.0	<2.0	5.47	89.6	132	73.9	NA	<0.5	<0.5	320	326	316
PA-25S	244	170	128	<3.0	<3.0	<0.5	<2.0	6.2	2.61	132.0	237	112	NA	<0.5	<0.5	537	367	208
PA-25I	359	313	277	<3.0	<3.0	<0.5	<2.0	<2.0	0.36 J	136.0	112	112	NA	<0.5	<0.5	363	405	391
PA-25D	848	760	722	<3.0	<3.0	<0.5	22.9	<2.0	1.44	58.0	64.4	61.6	NA	<0.5	<0.5	222	249	267
Injection and Extraction Wells																		
EIW-1	199	NA	196	<3.0	NA	<0.5	<2.0	NA	2.66	164.0	NA	1.4 J	NA	NA	<0.5	320	NA	623
EEW-1	177	NA	195	<0.5	NA	<0.5	<1.0	NA	3.84	107.0	NA	113	NA	NA	0.842	453	NA	479

NA: Not analyzed.
S: Spike recovery outside control limits.
Pre-Demo: March 2002.
Post-Demo: EZVI-November 2002.

Table D-3. Other Parameter Results of Groundwater from the EZVI Demonstration

Well ID	TDS (mg/L)			TOC (mg/L)		BOD (mg/L)		Dissolved Silica (mg/L)		
	Pre-Demo	August 2002	Post-Demo	Pre-Demo	Post-Demo	Pre-Demo	Post-Demo	Pre-Demo	August 2002	Post-Demo
EZVI Plot Well										
PA-23	1,090	969	1,470	150	77	3.0	30	32.1	40.6	85.7
PA-23-DUP	1,080	972	1,160	154	85	3.0	148	32.1	33.5	92.2
EZVI Perimeter Wells										
PA-24S	947	1,020	1,070	108	45	<6.0	39	32.1	46.6	65.4
PA-24I	1,290	1,390	1,460	54	19	6.0	<3.0	38.4	54.2	65.8
PA-24D	1,100	1,400	1,450	66	21	6.0	4	37.8	NA	61.2
PA-25S	1,230	1,120	663	114	21	7.0	5	31.7	NA	44.1
PA-25I	1,120	1,100	1,040	87	28	10.0	5	54.6	NA	87.1
PA-25D	1,670	1,680	1,600	18	19	<6.0	<3.0	53.5	NA	76.4
Injection and Extraction Wells										
EIW-1	993	NA	1,180	55	66	<3.0	141	20.1	NA	88.0
EEW-1	989	NA	1,200	144	76	<3.0	136	24.3	NA	49.4

Pre-Demo: March 2002.

Post-Demo: EZVI-November 2002.

Table D-4. Results of Chloride Using Waterloo Profiler®

Sample ID	Chloride mg/L	Sample ID	Chloride mg/L
EZVI Plot			
EZVI-WP1-15	64.8	EZVI-WP201-15	175
EZVI-WP1-20	170	EZVI-WP201-24	227
EZVI-WP1-30	349	EZVI-WP201-30	388
EZVI-WP1-38	783	EZVI-WP201-38	993
EZVI-WP1-40	743	EZVI-WP201-40	990
EZVI-WP2-15	88.8	EZVI-WP202-15	157
EZVI-WP2-20	188	EZVI-WP202-24	188
EZVI-WP2-30	347	EZVI-WP202-30	672
EZVI-WP2-36	763	EZVI-WP202-38	902
EZVI-WP2-38	798	EZVI-WP202-40	927

Table D-5. Results of Dissolved Gases in Groundwater from the EZVI Demonstration

Well ID	Ethane (mg/L) Pre-Demo	Ethane (mg/L) August 2002	Ethane (mg/L) Post-Demo	Ethylene (mg/L) Pre-Demo	Ethylene (mg/L) August 2002	Ethylene (mg/L) Post-Demo	Methane (mg/L) Pre-Demo	Methane (mg/L) August 2002	Methane (mg/L) Post-Demo
EZVI Plot Well									
PA-23	0.00205	0.0022	0.0231	0.0757	0.010	1.68	0.0125	0.0432	0.547
PA-23-DUP	0.00328	0.0021	0.0214	0.0793	0.01	1.56	0.0141	0.0399	0.502
EZVI Perimeter Wells									
PA-24S	0.0376	NA	0.0047	0.274	NA	0.105	0.0218	NA	0.140
PA-24I	0.0203	NA	0.0065	0.278	NA	0.031	0.0174	NA	0.047
PA-24D	0.0388	NA	0.0089	0.475	NA	0.069	0.0127	NA	0.034
PA-25S	0.00613 R	NA	<0.002	0.207	NA	0.007	0.00734	NA	0.012
PA-25I	0.00829	NA	0.0035	0.305	NA	0.062	0.0204	NA	0.061
PA-25D	0.00909	NA	0.0048	0.051	NA	0.018	0.00524	NA	0.016
Injection and Extraction Wells									
EIW-1	<0.002	NA	<0.002	0.0234	NA	0.137	0.0145	NA	0.611
EEW-1	0.0035	NA	0.0551	0.0512	NA	0.978	0.0162	NA	0.978

R: RPD outside accepted recovery limits.

Pre-Demo: March 2002.

Post-Demo: EZVI-November 2002.

Table D-6. Results of TOC in Soil Samples Prior to the EZVI Demonstration

Sample ID	TOC Results (wt%-dry)
EZVI-SB4-12	0.10
EZVI-SB4-14	0.06
EZVI-SB4-32	0.14
EZVI-SB4-34	0.15
EZVI-SB4-40	0.32
EZVI-SB4-42	0.26

Table D-7. Mass Flux Measurements of Groundwater from the EZVI Demonstration Provided by GeoSyntec Consultants

Extraction Transect	**TCE (µmoles/L)**			**cis-1,2-DCE (µmoles/L)**			**VC (µmoles/L)**			**Ethene (µmoles/L)**			**Total Ethenes (µmoles/L)**		
Depth (ft bgs)	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**
16	49	2	**-47**	23	7	**-15**	0	320	**320**	0	128	**128**	72	458	**385**
18.5	2967	1223	**-1744**	61	1288	**1227**	0	451	**451**	0	318	**318**	3028	3280	**252**
21	6086	1278	**-4808**	330	1669	**1339**	0	622	**622**	0	402	**402**	6415	3971	**-2444**
23.5	10498	3880	**-6618**	330	1772	**1442**	0	413	**413**	0	134	**134**	10827	6198	**-4629**
26	9357	6466	**-2891**	564	2215	**1650**	0	462	**462**	0	109	**109**	9921	9252	**-669**
Sum of All Depths	28956	12849	**-16107**	1307	6950	**5643**	0	2268	**2268**	0	1091	**1091**	30263	23159	**-7105**
Injection Transect															
Depth (ft bgs)	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**
16	18	68	**50**	4	447	**443**	0	179	**179**	0	561	**561**	22	1255	**1233**
18.5	14	18	**4**	4	19	**15**	0	2	**2**	0	90	**90**	18	129	**111**
21	22	33	**11**	1	33	**32**	0	8	**8**	0	138	**138**	23	212	**188**
23.5	47	26	**-21**	3	27	**23**	0	7	**7**	0	152	**152**	50	212	**162**
26	124	31	**-93**	17	26	**9**	0	6	**6**	0	148	**148**	141	210	**69**
Sum of All Depths	225	175	**-49**	30	551	**521**	0	202	**202**	0	1089	**1089**	255	2018	**1763**
PA-23	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**	**Pre**	**Post**	**▲**
	723	1	**-722**	42	12	**-30**	0	45	**45**	0	145	**145**	765	202	**-563**

Table D-7. Mass Flux Measurements of Groundwater from the EZVI Demonstration (Continued)
Provided by GeoSyntec Consultants

Sample Location	TCE (µmoles/L)			cis-1,2-DCE (µmoles/L)			VC (µmoles/L)			Ethene (µmoles/L)			Total Ethenes (µmoles/L)		
	Pre	**Post**	**Change**	**Pre**	**Post**	**Change**	**Pre**	**Post**	**Change**	**Pre**	**Post**	**Change**	**Pre**	**Post**	**Change**
E-ML1-1	20	0	**-20**	0	0	**0**	0	1	**1**	0	5	**5**	20	6	**-14**
E-ML1-2	2815	1217	**-1597**	49	834	**785**	0	319	**319**	0	169	**169**	2864	2540	**-324**
E-ML1-3	3423	700	**-2723**	113	783	**670**	0	319	**319**	0	236	**236**	3536	2038	**-1498**
E-ML1-4	5173	1597	**-3575**	134	948	**814**	0	319	**319**	0	92	**92**	5307	2956	**-2351**
E-ML1-5	4564	989	**-3575**	101	1957	**1856**	0	462	**462**	0	109	**109**	4665	3518	**-1147**
E-ML2-1	30	2	**-27**	23	7	**-16**	0	319	**319**	0	124	**124**	52	452	**399**
E-ML2-2	152	6	**-146**	11	453	**442**	0	132	**132**	0	148	**148**	163	740	**576**
E-ML2-3	2662	578	**-2084**	216	886	**670**	0	303	**303**	0	166	**166**	2879	1933	**-946**
E-ML2-4	5325	2282	**-3043**	196	824	**628**	0	94	**94**	0	42	**42**	5521	3243	**-2278**
E-ML2-5	4792	5477	**685**	464	258	**-206**	0	0	**0**	0	0	**0**	5256	5735	**479**
E-ML3-1	13	67	**54**	3	443	**440**	0	175	**175**	0	494	**494**	16	1179	**1163**
E-ML3-2	9	17	**8**	3	16	**13**	0	0	**0**	0	74	**74**	12	107	**95**
E-ML3-3	10	28	**18**	0	20	**20**	0	3	**3**	0	78	**78**	10	128	**118**
E-ML3-4	21	21	**0**	2	11	**10**	0	3	**3**	0	74	**74**	22	109	**87**
E-ML3-5	33	26	**-7**	6	16	**11**	0	3	**3**	0	81	**81**	38	127	**88**
E-ML4-1	5	1	**-4**	1	4	**3**	0	4	**4**	0	67	**67**	7	76	**70**
E-ML4-2	4	1	**-3**	1	3	**2**	0	2	**2**	0	16	**16**	5	22	**16**
E-ML4-3	12	4	**-8**	1	13	**12**	0	6	**6**	0	60	**60**	14	84	**70**
E-ML4-4	27	6	**-21**	2	15	**14**	0	4	**4**	0	78	**78**	28	103	**75**
E-ML4-5	91	5	**-86**	11	9	**-2**	0	3	**3**	0	67	**67**	103	84	**-19**
PA-23	723	1	**-722**	42	12	**-30**	0	45	**45**	0	145	**145**	765	202	**-563**

Table D-8. Genetrac Analysis of Groundwater Samples from the EZVI Demonstration Provided by GeoSyntec Consultants

Well ID	Sample ID	Sample Date	Non-*Dehalococcides* Bacterial DNA	**Dehalococcides* Test, Intensity (% of Positive Control)	**Intensity Score	Test Results: *Dehalococcoides* DNA
E-ML3-2	E-ML3-2-DB	10-Jul-02	Detected	80%	+++	Detected (3 of 3 primer sets)
	E-ML3-2-RS	6-Jan-03	Not Determined	0%	-	Not Detected
PA-23	PA-23-DB	10-Jul-02	Detected	105%	++++	Detected (3 of 3 primer sets)
	PA-23-RS	6-Jan-03	Detected	151%	++++	Detected (3 of 3 primer sets)

Notes:

The above results refer only to that portion of the sample tested with the Gene-Trac™ assay. The test is based on a polymerase chain reaction (PCR) test with 3 primer sets specific to DNA sequences in the 16S rRNA gene of *Dehalococcoides* organisms. A positive (+ to ++++) result indicates that genetic material (DNA) from a member of the *Dehalococcoides* group was detected. *Dehalococcoides* organisms are the only microorganisms proven to possess the necessary enzymes for the complete dechlorination of PCE or TCE to ethene. The presence of *Dehalococcoides* genetic material has been positively correlated to complete dechlorination of chlorinated ethenes at contaminated sites.

*"Dehalococcoides Test Intensity" = quantitative assessment of electrophoresis band intensity of PCR product as a percentage of the corresponding positive control reaction. This value provides a semi-quantitative assessment of the amount of *Dehalococcoides* genetic material present in the sample. While band intensity might reflect actual concentration of the target organism, Gene-Trac™ is a semi-quantitative method and is only recommended to determine the presence or absence of *Dehalococcoides* genetic material in the sample.

**"Intensity Score", categorizes PCR product quantity based on the "intensity (% of positive control)":

++++ = Very high band intensity (greater than 100% of positive control), +++ = high band intensity (67-100%),

++ moderate band intensity (34-66%) + = low band intensity (10-33%), -/+ = inconclusive (1-9%), - = no detectable band (0%)

Appendix E

Quality Assurance/Quality Control Information

Table E-1. Results of the Extraction Procedure Performed on PA-4 Soil Samples

Extraction Procedure Conditions	Combined
Total Weight of Wet Soil (g) = 2,124.2	1,587.8 g dry soil from PA-4 boring
Concentration (mg TCE/g soil) = 3.3	529.3 g deionized water
Moisture Content of Soil (%) = 24.9	5 mL TCE

Laboratory Extraction Sample ID	TCE Concentration in MeOH (mg/L)	TCE Mass in MeOH (mg)	TCE Concentration in Spiked Soil (mg/kg)	Theoretical TCE Mass Expected in MeOH (mg)	Percentage Recovery of Spiked TCE (%)
1st Extraction procedure on same set of samples					
SEP-1-1	1800.0	547.1	3252.5	744.11	73.53
SEP-1-2	1650.0	501.8	3164.9	701.26	71.55
SEP-1-3	1950.0	592.2	3782.3	692.62	85.51
SEP-1-4	1840.0	558.1	3340.2	739.13	75.51
SEP-1-5	1860.0	564.0	3533.9	705.91	79.89
SEP-1-6 (Control)	78.3	19.4	-	25.00	77.65
				Average % Recovery =	77.20
2nd Extraction procedure on same set of samples					
SEP-2-1	568.0	172.7	861.1	887.28	19.47
SEP-2-2	315.0	95.5	500.5	843.77	11.31
SEP-2-3	170.0	51.3	268.2	846.42	6.06
SEP-2-4	329.0	99.8	498.4	885.29	11.27
SEP-2-5	312.0	94.8	476.3	880.31	10.77
SEP-2-6 (Control)	82.6	20.4	-	25.00	81.79
				Average % Recovery =	11.78
3rd Extraction procedure on same set of samples					
SEP-3-1	55.8	17.0	84.6	885.96	1.91
SEP-3-2	59.0	17.9	94.2	841.77	2.13
SEP-3-3	56.8	17.2	90.1	846.42	2.04
SEP-3-4	63.0	19.1	95.2	888.61	2.15
SEP-3-5	52.2	15.8	80.0	875.99	1.81
SEP-3-6 (Control)	84.3	20.9	-	25.00	83.55
				Average % Recovery =	2.01

Table E-2. 1,1,1-TCA Surrogate Spike Recovery Values for Soil Samples Collected During the EZVI Demonstration Characterization

EZVI Treatment Plot 1,1,1 TCA-Spiked Soil Samples QA/QC Target Level RPD < 30.0 %					Total Number of Soil Samples Collected = 328 [Pre-(157); Post-(171)] Total Number of Spiked Samples Analyzed = 8 (Pre-) 6 (Post-)				
Sample ID	**Sample Date**	**1,1,1-TCA Result (ug/L)**	**RPD (%)**	**Met QA/QC Criteria?**	**Sample ID**	**Sample Date**	**1,1,1-TCA Result (ug/L)**	**RPD (%)**	**Met QA/QC Criteria?**
Pre-Demonstration					***Post-Demonstration***				
EZVI-SB1-10(SS)	01/16/02	5,270	23.89	Yes	EZVI-SB302-8(SS)	11/18/02	6,560	14.55	Yes
EZVI-SB1-MB(SS)		6,700			EZVI-SB302- MB(SS)		5,670		
EZVI-SB2-8(SS)	01/16/02	5,840	19.14	Yes	EZVI-SB304-8(SS)	11/19/02	4,230	27.52	Yes
EZVI-SB2- MB(SS)		4,820			EZVI-SB304- MB(SS)		5,580		
EZVI-SB3-8(SS)	01/17/02	6,100	2.43	Yes	EZVI-SB303-8(SS)	11/20/02	5,790	32.05	No
EZVI-SB3- MB(SS)		6,250			EZVI-SB303- MB(SS)		8,000		
EZVI-SB4-8(SS)	01/18/02	5,190	19.48	Yes	EZVI-SB301-8(SS)	11/21/02	5,140	4.17	Yes
EZVI-SB4- MB(SS)		6,310			EZVI-SB301- MB(SS)		4,930		
EZVI-SB5-8(SS)	01/31/02	4,750	8.66	No	EZVI-SB307-8(SS)	11/21/02	5,300	14.52	Yes
EZVI-SB5- MB(SS)		5,180			EZVI-SB307- MB(SS)		6,130		
EZVI-SB6-8 (SS)	02/01/02	6,190	0.96	Yes	EZVI-SB308-8(SS)	11/22/02	5,200	5.06	Yes
EZVI-SB6- MB(SS)		6,250			EZVI-SB308- MB(SS)		5,470		
EZVI-SB7-8 (SS)	02/07/02	5,070	8.86	Yes					
EZVI-SB7- MB(SS)		4,640							
EZVI-SB8-8 (SS)	03/20/02	6,230	9.41	Yes					
EZVI-SB8-MeOH(SS)(a)		5,670							

(a) Sample was labeled with –MeOH rather than the traditional –MB.

Table E-3. Results and Precision of the Field Duplicate Samples Collected During the Pre- and Post-Demonstration Soil Sampling

EZVI Treatment Plot Field Duplicate Soil Samples QA/QC Target Level RPD < 30.0 %					**Total Number of Soil Samples Collected = 328 [Pre-(157); Post-(171)] Total Number of Field Duplicate Samples Analyzed = 8 (Pre-) 11 (Post-)**				
Sample ID	**Sample Date**	**TCE Result (mg/kg)**	**RPD (%)**	**Met QA/QC Criteria?**	**Sample ID**	**Sample Date**	**TCE Result (mg/kg)**	**RPD (%)**	**Met QA/QC Criteria?**
Pre-Demonstration					***Post-Demonstration***				
EZVI-SB1-8	01/16/02	Trace	0.0	Yes	EZVI-SB208-8	10/08/02	269	27.48	Yes
EZVI-SB1-8 DUP		Trace			EZVI-SB208-8 DUP		204		
EZVI-SB2-24	01/16/02	207	23.45	Yes	EZVI-SB207-24	10/08/02	856	104(b)	No
EZVI-SB2-24 DUP		262			EZVI-SB207-24 DUP		268		
EZVI-SB3-40	01/17/02	1	0.0	Yes	EZVI-SB209-22	10/08/02	1.0	0.0	Yes
EZVI-SB3-40 DUP		1			EZVI-SB209-22 DUP		Trace		
EZVI-SB4-40	01/18/02	1	0.0	Yes	EZVI-SB203-18	10/09/02	1.1	9.52	Yes
EZVI-SB4-40 DUP		1			EZVI-SB203-18 DUP		1.0		
EZVI-SB5-38	01/31/02	11	167(a)	No	EZVI-SB204-24	10/09/02	35	91.67(a)	No
EZVI-SB5-38 DUP		1			EZVI-SB204-24 DUP		13		
EZVI-SB6-32	02/01/02	259	2.34	Yes	EZVI-SB302-18	11/18/02	5.2	15.93	Yes
EZVI-SB6-32 DUP		233			EZVI-SB302-18 DUP		6.1		
EZVI-SB7-44	02/07/02	Trace	0.0	Yes	EZVI-SB304-32	11/19/02	74	16.06	Yes
EZVI-SB7-44 DUP		Trace			EZVI-SB304-32 DUP		63		
EZVI-SB8-34	03/20/02	Trace	0.0	Yes	EZVI-SB303-20	11/20/02	451	11.98	Yes
EZVI-SB8-34 DUP		1			EZVI-SB303-20 DUP		400		
					EZVI-SB301-36	11/21/02	Trace	200(a)	No
					EZVI-SB301-36 DUP		2.0		
					EZVI-SB307-26	11/21/02	113	27.48	Yes
					EZVI-SB307-26 DUP		149		
					EZVI-SB308-42	11/22/02	Trace	0.0	Yes
					EZVI-SB308-42 DUP		Trace		

(a) High RPD value due to the effect of low (or below detect) concentrations of TCE, which drastically affected the RPD calculation.

(b) High RPD value may be due to high levels of DNAPL distributed heterogeneously through the soil core sample.

Table E-4. Results of the Rinsate Blank Samples Collected During the Pre- and Post-Demonstration Soil Sampling

EZVI Rinsate Blank Soil Extraction QA/QC Samples QA/QC Target Level TCE < 1.0 ug/L				**Total Number of Soil Samples Collected = 328 [Pre-(157); Post-(171)] Total Number of Field Samples Analyzed = 15**			
Sample ID	**Sample Date**	**TCE Result (ug/L)**	**Met QA/QC Criteria?**	**Sample ID**	**Sample Date**	**TCE Result (ug/L)**	**Met QA/QC Criteria?**
Pre-Demonstration Rinsate Blank Samples				***Post-Demonstration Rinsate Blank Samples***			
EZVI-SB1-RINSATE	01/16/02	<1.0	Yes	EZVI-SB207-RINSATE	10/08/02	<1.0	Yes
EZVI-SB2-RINSATE	01/16/02	<1.0	Yes	EZVI-SB203-RINSATE	10/09/02	<1.0	Yes
EZVI-SB3-RINSATE	01/17/02	<1.0	Yes	EZVI-SB304-RINSATE	11/19/02	<1.0	Yes
EZVI-SB4-RINSATE	01/18/02	<1.0	Yes	EZVI-SB302-RINSATE	11/18/02	<1.0	Yes
EZVI-SB6-RINSATE	02/01/02	<1.0	Yes	EZVI-SB303-RINSATE	11/20/02	<1.0	Yes
EZVI-SB7-RINSATE	02/07/02	2.88	No	EZVI-SB301-RINSATE	11/21/02	<1.0	Yes
EZVI-SB8-RINSATE	03/20/02	<1.0	Yes	EZVI-SB307-RINSATE	11/21/02	<1.0	Yes
				EZVI-SB308-RINSATE	11/22/02	<1.0	Yes

Table E-5. Results of the Methanol Blank Samples Collected During the Pre- and Post-Demonstration Soil Sampling

EZVI Methanol Blank Soil Extraction QA/QC Samples **QA/QC Target Level < 100 ug/L**				**Total Number of Soil Samples Collected = 328 [Pre-(157); Post-(171)]** **Total Number of Methanol Blank Samples Analyzed = 19**			
Sample ID	**Sample Date**	**TCE Result (ug/L)**	**Met QA/QC Criteria?**	**Sample ID**	**Sample Date**	**TCE Result (ug/L)**	**Met QA/QC Criteria?**
Pre-Demonstration Methanol Blank Samples				***Post-Demonstration Methanol Blank Samples***			
EZVI-SB1-MEOH	01/16/02	<100	Yes	EZVI-SB208-MEOH	10/08/02	160	No
EZVI-SB2-MEOH	01/16/02	<100	Yes	EZVI-SB207-MEOH	10/08/02	193	No
EZVI-SB3-MEOH	01/17/02	<100	Yes	EZVI-SB209-MEOH	10/08/02	313	No
EZVI-SB4-MEOH	01/18/02	<100	Yes	EZVI-SB203-MEOH	10/09/02	254	No
EZVI-SB5-MEOH	01/31/02	<100	Yes	EZVI-SB204-MEOH	10/09/02	200	No
EZVI-SB6-MEOH	02/01/02	<100	Yes	EZVI-SB302-MEOH	11/18/02	<100	Yes
EZVI-SB7-MEOH	02/07/02	<100	Yes	EZVI-SB304-MEOH	11/19/02	<100	Yes
EZVI-SB8-MB(a)	03/20/02	<100	Yes	EZVI-SB303-MEOH	11/20/02	<100	Yes
				EZVI-SB301-MEOH	11/21/02	117	No
				EZVI-SB307-MEOH	11/21/02	140	No
				EZVI-SB308-MEOH	11/22/02	<100	Yes

(a) Sample was labeled with –MB rather than the traditional –MEOH.

Table E-6. Results and Precision of the Field Duplicate Samples Collected During the EZVI Demonstration Groundwater Sampling Events

EZVI Treatment Plot Groundwater QA/QC QA/QC Target Level RPD < 30.0 %		**Total Number of Groundwater Samples Collected = 28 [Pre- (10); During (8); Post- (10)] Total Number of Field Duplicate Samples Analyzed = 3**		
Sample ID	**Sample Date**	**TCE Result (ug/L)**	**RPD (%)**	**Met QA/QC Criteria?**
EZVI Pre-Demonstration Field Duplicate Samples				
PA-23	03/26/02	1,180,000	4.33	Yes
PA-23DUP	03/26/02	1,130,000		
During the EZVI Demonstration				
PA-23	08/20/02	92,100	8.49	Yes
PA-23DUP	08/20/02	84,600		
EZVI Post-Demonstration Field Duplicate Samples				
PA-23	11/25/02	8,790	2.47	Yes
PA-23DUP	11/25/02	9,010		

Table E-7. Results of the Rinsate Blank Samples Collected During the EZVI Demonstration Groundwater Sampling Events

EZVI Groundwater QA/QC Samples QA/QC Target Level TCE < 3.0 ug/L	**Total Number of Samples Collected = 28 [Pre- (10); During- (8); Post- (10)] Total Number of Rinsate Blank Samples Analyzed = 3**		
Sampling Event	**Analysis Date**	**TCE Concentration (ug/L)**	**Met QA/QC Criteria?**
Pre-Demonstration	03/26/02	<1.0	Yes
During the Demonstration	08/20/02	1.05	Yes
Post-Demonstration	11/25/02	<1.0	Yes

Table E-8. Results of the Trip Blank Samples Analyzed During the EZVI Demonstration Soil and Groundwater Sampling

EZVI Trip Blank QA/QC Samples **QA/QC Target Level TCE < 3.0 ug/L**				**Total Number of Samples Collected = 328 (Soil) 28 (Groundwater)** **Total Number of Field Samples Analyzed = 19**			
Sample ID	**Sample Date**	**TCE Result (ug/L)**	**Met QA/QC Criteria?**	**Sample ID**	**Sample Date**	**Result (ug/L)**	**Met QA/QC Criteria?**
EZVI Demonstration Trip Blanks							
EZVI-TB-1	01/16/02	<1.0	Yes	EZVI-TB-11	10/09/02	12.4	No
EZVI-TB-2	01/21/02	<1.0	Yes	EZVI-TB-12	11/19/02	<1.0	Yes
EZVI-TB-3	02/01/02	<1.0	Yes	EZVI-TB-13	11/18/02	<1.0	Yes
EZVI-TB-4	02/04/02	<1.0	Yes	EZVI-TB-14	11/20/02	<1.0	Yes
EZVI-TB-5	02/07/02	<1.0	Yes	EZVI-TB-15	11/21/02	<1.0	Yes
EZVI-TB-6	02/08/02	<1.0	Yes	EZVI-TB-16	11/21/02	<1.0	Yes
EZVI-TB-7	03/20/02	1.09	Yes	EZVI-TB-17	11/22/02	<1.0	Yes
EZVI-TB-8	03/26/02	<1.0	Yes	EZVI-TB-18	11/25/02	<1.0	Yes
EZVI-TB-9	03/27/02	<1.0	Yes	EZVI-TB-19	11/25/02	<1.0	Yes
EZVI-TB-10	10/08/02	14.5	No				

Table E-9. Matrix Spike Sample Analysis for the EZVI Pre-Demonstration Soil Sampling Events

EZVI Demonstration Soil MS/MSD Samples **QA/QC Target Level Recovery % = 70 – 130 %** **QA/QC Target Level RPD < 30.0 %**						**Total Number of Samples Collected = 328 [Pre- (157); Post- (171)]** **Total Number of Matrix Spike Samples Analyzed = 18** **Total Number of Matrix Spike Duplicate Samples Analyzed = 18**					
Sample ID	**Sample Date**	**TCE Recovery (%)**	**Met QA/QC Criteria?**	**RPD (%)**	**Met QA/QC Criteria?**	**Sample ID**	**Sample Date**	**TCE Recovery (%)**	**Met QA/QC Criteria?**	**RPD (%)**	**Met QA/QC Criteria?**
EZVI Pre-Demonstration Matrix Spike Samples											
0201067-03A MS	01/18/02	103	Yes	0.054	Yes	0201104-04A MS	01/29/02	110	Yes	2.46	Yes
0201067-03A MSD		103	Yes			0201104-04A MSD		113	Yes		
0201067-26A MS	01/19/02	101	Yes	1.97	Yes	0201104-50A MS	01/29/03	109	Yes	4.77	Yes
0201067-26A MSD		103	Yes			0201104-50A MSD	01/30/03	103	Yes		
0201067-49A MS	01/21/02	121	Yes	0.446	Yes	0202007-04A MS	02/04/02	108	Yes	2.52	Yes
0201067-49A MSD		121	Yes			0202007-04A MSD		105	Yes		
0201067-60A MS	01/22/02	103	Yes	5.47	Yes	0202007-27A MS	02/04/02	108	Yes	0.918	Yes
0201067-60A MSD		90	Yes			0202007-27A MSD		108	Yes		
0201067-15A MS(a)	01/22/02	-52.4	No	0.712	Yes	0202007-21A MS	02/05/02	112	Yes	2.18	Yes
0201067-15A MSD(a)		-53.2	No			0202007-21A MSD		110	Yes		
0201087-04A MS	01/23/02	102	Yes	0.269	Yes	0202014-11A MS	02/06/02	108	Yes	0.799	Yes
0201087-04A MSD		102	Yes			0202014-11A MSD		109	Yes		
0201087-27A MS	01/23/02	105	Yes	0.381	Yes	0202037-10A MS	02/12/02	121	Yes	0.909	Yes
0201087-27A MSD		104	Yes			0202037-10A MSD		120	Yes		
0201087-17A MS	01/25/02	110	Yes	0.039	Yes	0202037-09A MS	02/13/02	130	Yes	21.5	Yes
0201087-17A MSD		110	Yes			0202037-09A MSD		162	No		
0201105-01A MS(a)	01/26/02	33.9	No	0.556	Yes	0203105-03A MS	03/24/02	101	Yes	1.34	Yes
0201105-01A MSD(a)		26.5	No			0203105-03A MSD		99.7	Yes		

(a) Spike recovery was outside of the control limits due to the high concentration of TCE present in the reference sample. No further corrective actions were required and no sample results were adversely affected.

Table E-10. Matrix Spike Sample Analysis for the EZVI Post-Demonstration Soil Sampling Events

EZVI Demonstration Soil MS/MSD Samples **QA/QC Target Level Recovery % = 70 – 130 %** **QA/QC Target Level RPD < 30.0 %**	**Total Number of Samples Collected = 328 [Pre- (157); Post- (171)]** **Total Number of Matrix Spike Samples Analyzed = 16** **Total Number of Matrix Spike Duplicate Samples Analyzed = 16**

Sample ID	**Sample Date**	**TCE Recovery (%)**	**Met QA/QC Criteria?**	**RPD (%)**	**Met QA/QC Criteria?**	**Sample ID**	**Sample Date**	**TCE Recovery (%)**	**Met QA/QC Criteria?**	**RPD (%)**	**Met QA/QC Criteria?**
EZVI Post-Demonstration Matrix Spike Samples											
0210032-02A MS	10/10/02	101	Yes	5.08	Yes	0211098-18A MS[(a)]	11/26/02	136	No	2.45	Yes
0210032-02A MSD		96.2	Yes			0211098-18A MSD[(a)]		139	No		
0210032-13A MS	10/10/02	107	Yes	24.9	Yes	0211079-03A MS	11/20/02	110	Yes	5.44	Yes
0210032-13A MSD[(a)]		139	No			0211079-03A MSD		103	Yes		
0210037-28A MS	10/11/02	104	Yes	2.44	Yes	0211108-08A MS	11/26/02	93.5	Yes	4.51	Yes
0210037-28A MSD		102	Yes			0211108-08A MSD		98.3	Yes		
0210037-27A MS	10/14/02	89	Yes	2.20	Yes	0211108-24A MS	11/27/02	108	Yes	8.13	Yes
0210037-27A MSD		87.1	Yes			0211108-24A MSD		99.6	Yes		
0210037-05A MS	10/12/02	116	Yes	0.274	Yes	0211120-17A MS	12/02/02	111	Yes	7.24	Yes
0210037-05A MSD		117	Yes			0211120-17A MSD		103	Yes		
0210037-15A MS	10/15/02	99.7	Yes	6.94	Yes	0211142-10A MS[(a)]	12/05/02	-294	No	4.59	Yes
0210037-15A MSD		92.6	Yes			0211142-10A MSD[(a)]		-402	No		
0211089-03A MS	11/21/02	107	Yes	2.44	Yes	0211120-02A MS	12/05/02	110	Yes	4.04	Yes
0211089-03A MSD		110	Yes			0211120-02A MSD		106	Yes		
0211089-20A MS	11/22/02	111	Yes	0.649	Yes	0211121-18A MS	11/27/02	92.6	Yes	8.17	Yes
0211089-20A MSD		110	Yes			0211121-18A MSD		85.3	Yes		

(b) Spike recovery was outside of the control limits due to the high concentration of TCE present in the reference sample. No further corrective actions were required and no sample results were adversely affected.

Table E-11. Laboratory Control Spike Sample Analysis During the EZVI Pre-and Post Demonstration Soil Sampling Events

EZVI Demonstration Soil LCS Samples **QA/QC Target Level TCE Recovery % = 70 – 130 %**				**Total Number of Samples Collected = 328 [Pre- (157); Post- (171)]** **Total Number of Laboratory Control Spike Samples Analyzed = 41**			
Sample ID	**Sample Date**	**TCE Recovery (%)**	**Met QA/QC Criteria?**	**Sample ID**	**Sample Date**	**TCE Recovery (%)**	**Met QA/QC Criteria?**
EZVI Pre-Demonstration Laboratory Control Spike Samples							
LCS-9593	01/18/02	95.5	Yes	LCS-9649	01/25/02	110	Yes
LCS-9598	01/19/02	101	Yes	LCS-9650	01/27/02	103	Yes
LCS-9604	01/21/02	116	Yes	LCS-9662	01/28/02	90.2	Yes
LCS-9608	01/22/02	90.6	Yes	LCS-9665	01/29/02	112	Yes
LCS-9620	01/23/02	95.6	Yes	LCS-9668	01/29/02	113	Yes
LCS-9634	01/22/02	101	Yes	LCS-9706	02/04/02	107	Yes
LCS-9635	01/23/02	94.5	Yes	LCS-9711	02/04/02	106	Yes
LCS-9621	01/23/02	100	Yes	LCS-9712	02/05/02	107	Yes
LCS-9629	01/23/02	101	Yes	LCS-9726	02/05/02	107	Yes
LCS-9635	01/23/02	94.5	Yes	LCS-9772	02/11/02	121	Yes
LCS-9637	01/24/02	95.5	Yes	LCS-9788	02/13/02	123	Yes
LCS-9646	01/25/02	110	Yes	LCS-10147	03/24/02	97.6	Yes
LCS-9647	01/25/02	92	Yes				
EZVI Post-Demonstration Laboratory Control Spike Samples							
LCS-11576	10/09/02	99.5	Yes	LCS-11873	11/25/02	117	Yes
LCS-11583	10/10/02	102	Yes	LCS-11841	11/20/02	103	Yes
LCS-11595	10/11/02	103	Yes	LCS-11879	11/26/02	89	Yes
LCS-11601	10/14/02	103	Yes	LCS-11887	11/27/02	105	Yes
LCS-11593	10/11/02	102	Yes	LCS-11897	11/27/02	85.1	Yes
LCS-11600	10/14/02	108	Yes	LCS-11907	12/02/02	107	Yes
LCS-11850	11/21/02	105	Yes	LCS-11933	12/04/02	109	Yes
LCS-11857	11/22/02	103	Yes	LCS-11940	12/05/02	110	Yes

Table E-12. Method Blank Sample Analysis during the EZVI Pre- and Post-Demonstration Soil Sampling Events

EZVI Demonstration Soil QA/QC Samples QA/QC Target Level TCE < 3.0 ug/L				Total Number of Samples Collected = 328 [Pre- (157); Post- (171)] Total Number of Method Blank Samples Analyzed = 41			
Sample ID	**Sample Date**	**TCE Recovery (ug/L)**	**Met QA/QC Criteria?**	**Sample ID**	**Sample Date**	**TCE Recovery (ug/L)**	**Met QA/QC Criteria?**
EZVI Pre-Demonstration Method Blank Samples							
MB-9593	01/18/02	<1.0	Yes	MB-9649	01/25/02	<1.0	Yes
MB-9598	01/19/02	<1.0	Yes	MB-9650	01/27/02	<1.0	Yes
MB-9604	01/21/02	<1.0	Yes	MB-9662	01/28/02	<1.0	Yes
MB-9608	01/22/02	<1.0	Yes	MB-9665	01/29/02	<1.0	Yes
MB-9620	01/23/02	<1.0	Yes	MB-9668	01/29/02	<1.0	Yes
MB-9634	01/22/02	<1.0	Yes	MB-9706	02/04/02	<1.0	Yes
MB-9635	01/23/02	<1.0	Yes	MB-9711	02/04/02	<1.0	Yes
MB-9621(a)	01/23/02	<100	Unknown	MB-9712	02/05/02	<1.0	Yes
MB-9629	01/23/02	<1.0	Yes	MB-9726	02/05/02	<1.0	Yes
MB-9635	01/23/02	<1.0	Yes	MB-9772	02/11/02	<1.0	Yes
MB-9637	01/24/02	<1.0	Yes	MB-9788	02/13/02	<1.0	Yes
MB-9646	01/25/02	<1.0	Yes	MB-10147	03/24/02	<1.0	Yes
MB-9647	01/25/02	<1.0	Yes				
EZVI Post-Demonstration Method Blank Samples							
MB-11576	10/09/02	<1.0	Yes	MB-11873	11/25/02	<1.0	Yes
MB-11583	10/10/02	<1.0	Yes	MB-11841	11/20/02	<1.0	Yes
MB-11595	10/11/02	<1.0	Yes	MB-11879	11/26/02	<1.0	Yes
MB-11601	10/14/02	<1.0	Yes	MB-11887	11/27/02	<1.0	Yes
MB-11593	10/11/02	<1.0	Yes	MB-11897	11/27/02	<1.0	Yes
MB-11600	10/14/02	<1.0	Yes	MB-11907	12/02/02	<1.0	Yes
MB-11850	11/21/02	<1.0	Yes	MB-11933	12/04/02	<1.0	Yes
MB-11857	11/22/02	<1.0	Yes	MB-11940	12/05/02	<1.0	Yes

(a) Reporting limit was 100 ug/L TCE for this sample.

Table E-13. Matrix Spike Sample Analysis During the EZVI Demonstration Groundwater Sampling Events

EZVI Demonstration Groundwater QA/QC
QA/QC Target Level TCE Recovery % = 75 – 125 %
QA/QC Target Level RPD < 20.0 %

Total Number of Samples Collected = 28
[Pre- (10); During (8); Post- (10)]
Total Number of Matrix Spike Samples Analyzed = 6
Total Number of Matrix Spike Duplicate Samples Analyzed = 6

Sample ID	Sample Date	TCE Recovery (%)	Met QA/QC Criteria?	RPD (%)	Met QA/QC Criteria?
EZVI Pre-Demonstration Matrix Spike Samples					
0203129-04A MS	03/28/02	90.7	Yes	0.913	Yes
0203129-04A MSD		88.4	Yes		
0203133-20A MS	03/29/02	99.1	Yes	0.995	Yes
0203133-20A MSD		100	Yes		
During the EZVI Demonstration					
0208106-03A MS	08/27/02	125	Yes	7.76	Yes
0208106-03A MSD		115	Yes		
0208115-04A MS(a)	08/29/02	353	No	0.421	Yes
0208115-04A MSD(a)		347	No		
EZVI Post-Demonstration Matrix Spike Samples					
0211142-10A MS(a)	12/05/02	-294	No	4.59	Yes
0211142-10A MSD(a)		-402	No		
0211120-02A MS	12/05/02	110	Yes	4.04	Yes
0211120-02A MSD		106	Yes		

(a) Matrix spike (MS) and matrix spike duplicate (MSD) were outside of the control limits due to the high concentration of TCE present in the reference sample. No further corrective actions were required and no sample results were adversely affected.

Table E-14. Laboratory Control Spike Sample Analysis During the EZVI Demonstration Groundwater Sampling Events

EZVI Demonstration Groundwater QA/QC **QA/QC Target Level TCE Recovery % = 75 – 125 %**		**Total Number of Samples Collected = 28** **[Pre- (10); During (8); Post- (10)]** **Total Number of Matrix Spike Samples Analyzed = 6**	
Sample ID	**Sample Date**	**TCE Recovery (%)**	**Met QA/QC Criteria?**
EZVI Pre-Demonstration Laboratory Control Spike Samples			
LCS-10179	03/28/02	102	Yes
LCS-10187	03/29/02	105	Yes
During the EZVI Demonstration			
LCS-11251	08/27/02	111	Yes
LCS-11273	08/28/02	100	Yes
EZVI Post-Demonstration Laboratory Control Spike Samples			
LCS-11933	12/04/02	109	Yes
LCS-11940	12/05/02	110	Yes

Table E-15. Method Blank Sample Analysis During the EZVI Demonstration Groundwater Sampling Events

EZVI Demonstration Groundwater QA/QC **QA/QC Target Level TCE < 3.0 ug/L**		**Total Number of Samples Collected = 28** **[Pre- (10); During (8); Post- (10)]** **Total Number of Method Blank Samples Analyzed = 6**	
Sample ID	**Sample Date**	**TCE Recovery (ug/L)**	**Met QA/QC Criteria?**
EZVI Pre-Demonstration Method Blank Samples			
MB-10179	03/28/02	<1.0	Yes
MB-10187	03/29/02	<1.0	Yes
During the EZVI Demonstration			
MB-11251	08/27/02	<1.0	Yes
MB-11273	08/29/02	<1.0	Yes
EZVI Post-Demonstration Method Blank Samples			
MB-11933	12/04/02	<1.0	Yes
MB-11940	12/05/02	<1.0	Yes

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ADDITIONAL REPORT COPIES TO: EDD FORMAT

DATE: 2/7/02 PAGE 2 OF 3
PO #: 169646 DHL WORK ORDER #: 0202037
PROJECT LOCATION OR NAME: CCAS 2
CLIENT PROJECT #: G482010 COLLECTOR: ED

Authorize 5% surcharge for TRRP report?
☐ Yes ☐ No

S=SOIL W=WATER A=AIR P=PAINT SL=SLUDGE OT=OTHER
↑ MeOH

ANALYSES
BTEX ☐ MTBE ☐
TRPH 418.1 ☐ TPH 1005 ☐ TPH 1006 ☐
GASOLINE MOD 8015 ☐
DIESEL - MOD 8015 ☐
VOC 8260 ☐
SVOC 8270 ☐ PAH 8270 ☐
8081 PESTICIDES ☐ 8151 HERBICIDES ☐
8082 PCBS ☐
TCLP - METALS (RCRA) ☐ TCLP VOC ☐
TCLP - PEST ☐ HERB ☐ Semi-VOC ☐
TOTAL METALS (RCRA) ☐ OTHER LIST ☐
LEAD - TOTAL ☐ D.W. 200.8 ☐ TCLP ☐
RCI ☐ TOX ☐ FLASHPOINT ☐
TDS ☐ TSS ☐ % MOISTURE ☐
pH ☐ HEXAVALENT CHROMIUM ☐
EXPLOSIVES ☐ PECHLORATE ☐
CHLORIDE ☐ ANIONS ☐ ALKALINITY ☐
VOCs (TCE, VC, cis/trans DCE)

Field Sample I.D.	DHL Lab #	Date	Time	Matrix	Container Type	# of Containers	PRESERVATION: HCl	HNO$_3$	H$_2$SO$_4$ ☐ NaOH ☐	ICE	UNPRESERVED	FIELD NOTES
EZVI-SB7-24	16	2/7/02	12:00	W	20mL VOA	1					X	
EZVI-SB7-26	17	↓	↓	W	↓	1					X	
EZVI-SB7-28	18			W		1					X	
EZVI-SB7-30	19			W		1					X	
EZVI-SB7-32	20			W		1					X	
EZVI-SB7-34	21			W		1					X	
EZVI-SB7-36	22			W		1					X	
EZVI-SB7-38	23			W		1					X	
EZVI-SB7-40	24			W		1					X	
EZVI-SB7-42	25			W		1					X	
EZVI-SB7-44	26			W		1					X	
EZVI-SB7-44 DUP	27			W		1					X	
EZVI-SB7-46	28			W		1					X	
EZVI-SB7-RINSATE	29		9:00	W	40mL VOA	3	X					
TRIP BLANK	30		15:00	W	20mL VOA	1					X	

TOTAL 17

RELINQUISHED BY: (Signature) DATE/TIME 2/7/02 18:00 RECEIVED BY: (Signature) FX
RELINQUISHED BY: (Signature) FX DATE/TIME 2-8-2 830 RECEIVED BY: (Signature)
RELINQUISHED BY: (Signature) DATE/TIME RECEIVED BY: (Signature)

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Appendix F

Economic Analysis Information

Appendix F

Economic Analysis Information

This appendix details the cost assessment for the application of the pump-and-treat (P&T) system for containment of a DNAPL source at Launch Complex 34, for a source zone that is the same size as the EZVI plot. Because the groundwater flow in this area is generally to the northeast, the DNAPL source could be contained by installing one or more extraction wells on the northeast side of the resistive heating plot. The life cycle cost of a pump-and-treat system can be compared to the cost of DNAPL source removal by EZVI injection, as described in Section 7 of the main report.

Experience at previous sites indicates that the most efficient long-term P&T system is one that is operated at the minimum rate necessary to contain a plume or source zone (Cherry et al., 1996). Table F-1 shows a preliminary size determination for the P&T system. The P&T system should be capable of capturing the groundwater flowing through a cross-section that is approximately 50 ft wide (width of a realistic contamination for the EZVI plot) and 30 ft deep (thickness of the EZVI target depth). Because capture with P&T systems is somewhat inefficient in that cleaner water from surrounding parts of the aquifer may also be drawn in, an additional safety factor of 100% was applied to ensure that any uncertainties in aquifer capture zone or DNAPL source characterization are accounted for. An extraction rate of 2 gallon per minute (gpm) is found to be sufficient to contain the source.

One advantage of low groundwater extraction rates is that the air effluent from stripping often does not have to be treated, as the rate of VOC discharge to the ambient air is often within regulatory limits. The longer period of operation required (at a low withdrawal rate) is more than offset by higher efficiency (lower influx of clean water from outside the plume), lower initial capital investment (smaller treatment system), and lower annual O&M requirements. Another advantage of a containment type P&T system is that, unlike source removal technologies, it does not require very extensive DNAPL zone characterization.

F.1 Capital Investment for the P&T System

The P&T system designed for this application consists of the components shown in Table F-2. Pneumatically driven pulse pumps, which are used in each well, are safer than electrical pumps in the presence of TCE vapors in the wells. This type of pump can sustain low flowrates during continuous operation. Stainless steel and Teflon™ construction ensure compatibility with the high concentrations (up to 1,100 mg/L TCE) of dissolved solvent and any free-phase DNAPL that may be expected. Extraction wells are assumed to be 30 ft deep, 2 inches in diameter, and have stainless steel screens with PVC risers.

The aboveground treatment system consists of a DNAPL separator and air stripper. Very little free-phase solvent is expected and the separator may be disconnected after the first year of operation, if desired. The air stripper used is a low-profile tray-type air stripper. As opposed to conventional packed towers, low-profile strippers have a smaller footprint, much smaller height, and can handle large air:water ratios (higher mass transfer rate of contaminants) without generating significant pressure losses. Because of their small size and easy installation, they are more often used in groundwater remediation. The capacity of the air stripper selected is much higher than 2 gpm, so that additional flow (or additional extraction wells) can be handled if required.

The high air:water ratio ensures that TCE (and other minor volatile components) are removed to the desired levels. The treated water effluent from the air stripper is discharged to the sewer. The air effluent is treated with a catalytic oxidation unit before discharge.

The piping from the wells to the air stripper is run through a 1-ft-deep covered trench. The air stripper and other associated equipment are housed on a 20-ft-x-20-ft concrete pad, covered by a basic shelter. The base will provide a power drop (through a pole transformer) and a licensed electrician will be used for the power hookups. Meters and control valves are strategically placed to control water and air flow through the system.

The existing monitoring system at the site will have to be supplemented with seven long-screen (10-foot screen) monitoring wells. The objective of these wells is to ensure that the desired containment is being achieved.

F.2 Annual Cost of the P&T System

The annual costs of P&T are shown in Table F-3 and include annual O&M. Annual O&M costs include the labor, materials, energy, and waste disposal cost of operating the system and routine maintenance (including scheduled replacement of seals, gaskets, and O-rings). Routine monitoring of the stripper influent and effluent is done through ports on the feed and effluent lines on a monthly basis. Groundwater monitoring is conducted on a quarterly basis through seven monitoring wells. All water samples are analyzed for PCE and other CVOC by-products.

F.3 Periodic Maintenance Cost

In addition to the routine maintenance described above, periodic maintenance will be required, as shown in Table F-3, to replace worn-out equipment. Based on manufacturers' recommendations for the respective equipment, replacement is done once in 5 or 10 years. In general, all equipment involving moving parts is assumed will be replaced once every 5 years, whereas other equipment is changed every 10 years.

F.4 Present Value (PV) Cost of P&T

Because a P&T system is operated for the long term, a 30-year period of operation is assumed for estimating cost. Because capital investment, annual costs, and periodic maintenance costs occur at different points in time, a life cycle analysis or present value analysis is conducted to estimate the long-term cost of P&T in today's dollars. This life cycle analysis approach is recommended for long-term remediation applications by the guidance provided in the Federal Technologies Roundtable's *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* (United States Environmental Protection Agency [U.S. EPA], 1998). The PV cost can then be compared with the cost of faster (DNAPL source reduction) remedies.

$$PV_{\text{P\&T costs}} = \sum \frac{\text{Annual Cost in Year t}}{(1 + r)^t} \qquad \text{Equation (F-1)}$$

$$PV_{\text{P\&T costs}} = \text{Capital Investment} + \frac{\text{Annual cost in Year 1}}{(1 + r)^1} + \ldots + \frac{\text{Annual cost in Year n}}{(1 + r)^n}$$

Equation (F-2)

Table F-3 shows the PV calculation for P&T based on Equation F-1. In Equation F-1, each year's cost is divided by a discount factor that reflects the rate of return that is foregone by incurring the cost. As seen in Equation F-2, at time t = 0, which is in the present, the cost incurred is the initial capital investment in equipment and labor to design, procure, and build the P&T system. Every year after that, a cost is incurred to operate and maintain the P&T system. A real rate of return (or discount rate), r, of 2.9% is used in the analysis as per recent U.S. EPA guidance on discount rates (U.S. EPA, 1999). The total PV cost of purchasing, installing, and operating a 2-gpm P&T source containment system for 30 years is estimated to be **$1,360,000** (rounded to the nearest thousand).

Long-term remediation costs are typically estimated for 30-year periods as mentioned above. Although the DNAPL source may persist for a much longer time, the contribution of costs incurred in later years to the PV cost of the P&T system is not very significant and the total 30-year cost is indicative of the total cost incurred for this application. This can be seen from the fact that in Years 28, 29, and 30, the differences in cumulative PV cost are not as significant as the difference in, say, Years 2, 3, and 4. The implication is that, due to the effect of discounting, costs that can be postponed to later years have a lower impact than costs that are incurred in the present.

As an illustration of a DNAPL source that may last much longer than the 30-year period of calculation, Figure F-1 shows a graphic representation of PV costs assuming that the same P&T system is operated for 100 years instead of 30 years. The PV cost curve flattens with each passing year. The total PV cost after 100 years (in Table F-4) is estimated at $2,126,000.

Table F-1. Pump-and-Treat (P&T) System Design Basis

Item	Value	Units	Item	Value	Units
Width of DNAPL zone, w	50	ft	Hyd. conductivity, K	40	ft/d
Depth of DNAPL zone, d	30	ft	Hyd. gradient, I	0.0007	ft/ft
Crossectional area of DNAPL zone, a	1500	sq ft	Porosity, n	0.3	
Capture zone required	140	cu ft/d	Gw velocity, v	0.093333	ft/d
Safety factor, 100%	2				
Required capture zone	280	cu ft/d	GPM =	1.5	gpm
Design pumping rate	2	gpm	Number of wells to achieve capture	1	
Pumping rate per well	2	gpm			
TCE conc. in water near DNAPL zone	100	mg/L	TCE allowed in discharge water	1	mg/L
Air stripper removal efficiency required	99.00%				
TCE in air effluent from stripper	2.4	lbs/day	TCE allowed in air effluent	6	lbs/day

Table F-2. Capital Investment for a P&T System at Launch Complex 34, Cape Canaveral

Item	# units		Unit Price	Cost	Basis
Design/Procurement					
Engineer	120	hrs	$ 85	$10,200	
Drafter	80	hrs	$ 40	$3,200	
Hydrologist	120	hrs	$ 85	$10,200	
Contingency	1	ea	$ 10,000	$10,000	10% of total capital
TOTAL				$23,600	
Pumping system					
Extraction wells	1	ea	$ 5,000	$5,000	2-inch, 30 ft deep, 30-foot SS screen; PVC; includes installation
Pulse pumps	1	ea	$ 595	$595	2.1 gpm max., 1.66"OD for 2-inch wells; handles solvent contact; pneumatic; with chec valves
Controllers	1	ea	$ 1,115	$1,115	Solar powered or 110 V; with pilot valve
Air compressor	1	ea	$ 645	$645	100 psi (125 psi max), 4.3 cfm continuous duty, oil-less; 1 hp
Miscellaneous fittings	1	ea	$ 5,000	$5,000	Estimate
Tubing	150	ft	$ 3	$509	1/2-inch OD, chemical resistant; well to surface manifold
TOTAL				$12,864	
Treatment System					
Piping	150	ft	$ 3	$509	chemical resistant
Trench	1	day	$ 320	$320	ground surface
DNAPL separarator tank	1	ea	$ 120	$120	125 gal; high grade steel with epoxy lining; conical bottom with discharge
Air stripper feed pump	1	ea	$ 460	$460	0.5 hp; up to 15 gpm
Piping	50	ft	$ 3	$170	0.5 inch, chemical resistant; feed pump to stripper
Water flow meter	1	ea	$ 160	$160	Low flow; with read out
Low-profile air stripper with control panel	1	ea	$ 9,400	$9,400	1-25 gpm, 4 tray; SS shell and trays
Pressure gauge	1	ea	$ 50	$50	SS; 0-30 psi
Blower	1	ea	$ 1,650	$1,650	5 hp
Air flow meter	1	ea	$ 175	$175	Orifice type; 0-50 cfm
Stack	10	ft	$ 2	$20	2 inch, PVC, lead out of housing
Catalytic Oxidizer	1	ea	$ 65,000	$65,000	
Carbon	2	ea	$ 1,000	$2,000	
Stripper sump pump	1	ea	$ 130	$130	To sewer
Misc. fittings, switches	1	ea	$ 5,000	$5,000	Estimate (sample ports, valves, etc.)
TOTAL				$85,163	
Site Preparation					
Conctrete pad	400	sq ft	$ 3	$1,200	20 ft x 20 ft with berm; for air stripper and associated equipment
Berm	80	ft	$ 7	$539	
Power drop	1	ea	$ 5,838	$5,838	240 V, 50 Amps; pole transformer and licensed electrician
Monitoring wells	5	wells	$ 2,149	$10,745	Verify source containment; 2-inch PVC with SS screens
Sewer connection fee	1	ea	$ 2,150	$2,150	
Sewer pipe	300	ft	$ 10	$3,102	
Housing	1	ea	$ 2,280	$2,280	20 ft x 20 ft; shelter for air stripper and associated equipment
TOTAL				$25,854	
Installation/Start Up of Treatment System					
Engineer	60	hrs	$ 85	$5,100	Labor
Technician	200	hrs	$ 40	$8,000	Labor
TOTAL				$13,100	
TOTAL CAPITAL INVESTMENT				**$160,581**	

Table F-2. Capital Investment for a P&T System at Launch Complex 34, Cape Canaveral (Continued)

O&M Cost for P&T Sytem					
Annual Operation & Maintenance					
Engineer	80	hrs	$ 85	$6,800	Oversight
Technician	500	hrs	$ 40	$20,000	Routine operation; annual cleaning of air stripper trays, routine replacement of parts; any waste disposal
Replacement materials	1	ea	$ 2,000	$2,000	Seals, o-rings, tubing, etc.
Electricity	52,560	kW-hrs	$ 0	$5,256	8 hp (~6 kW) over 1 year of operation
Fuel (catalytic oxidizer	2,200	10E6 Btu	$ 6	$13,200	
Sewer disposal fee	525,600	gal/yr	$ 0	$799	
Carbon disposal	2		$ 1,000	$2,000	
Waste disposal	1	drum	$ 80	$200	30 gal drum; DNAPL, if any; haul to incinerator
TOTAL				$50,255	
Annual Monitoring					
Air stripper influent	12	smpls	$ 120	$1,440	Verify air stripper loading; monthly
Air stripper effluent	14	smpls	$ 120	$1,680	Discharge quality confirmation; monthly; CVOC analysis; MS, MSD
Monitoring wells	20	smpls	$ 120	$2,400	5 wells; quarterly; MS, MSD
Sampling materials	1	ea	$ 500	$500	Miscellaneous
Technician	64	hrs	$ 40	$2,560	Quarterly monitoring labor (from wells) only; weekly monitoring (from sample ports) included in O&M cost
Engineer	40	hrs	$ 85	$3,400	Oversight; quarterly report
TOTAL				$5,520	
TOTAL ANNUAL COST				**$55,775**	
Periodic Maintenance, Every 5 years					
Pulse pumps	4	ea	$ 595	$2,380	As above
Air compressor	1	ea	$ 645	$645	As above
Air stripper feed pump	1	ea	$ 460	$460	As above
Blower	1	ea	$ 1,650	$1,650	As above
Catalyst replacement	1	ea	$ 5,000	$5,000	
Stripper sump pump	1	ea	$ 130	$130	As above
Miscellaneous materials	1	ea	$ 1,000	$1,000	Estimate
Technician	40	hrs	$ 40	$1,600	Labor
TOTAL				**$12,865**	
				$68,640	
Periodic Maintenance, Every 10 years					
Air stripper	1	ea	$ 9,400	$9,400	As above
Catalytic oxidizer	1	ea	$ 16,000	$16,000	Major overhaul
Water flow meters	1	ea	$ 160	$160	As above
Air flow meter	1	ea	$ 175	$175	As above
Technician	40	hrs	$ 40	$1,600	Labor
Miscellaneous materials	1	ea	$ 1,000	$1,000	Estimate
TOTAL				**$28,335**	
TOTAL PERIODIC MAINTENANCE COSTS				**$96,975**	

Table F-3. Present Value of P&T System Costs for 30 Years of Operation

	P&T		
Year	Annual Cost *	PV of Annual Cost	Cumulative PV of Annual Cost
0	**$160,581**	$160,581	$160,581
1	$55,775	$54,203	$214,784
2	$55,775	$52,676	$267,460
3	$55,775	$51,191	$318,651
4	$55,775	$49,748	$368,399
5	**$68,640**	$59,498	$427,897
6	$55,775	$46,984	$474,880
7	$55,775	$45,660	$520,540
8	$55,775	$44,373	$564,913
9	$55,775	$43,122	$608,035
10	**$96,975**	$72,863	$680,898
11	$55,775	$40,726	$721,624
12	$55,775	$39,578	$761,202
13	$55,775	$38,463	$799,664
14	$55,775	$37,379	$837,043
15	**$68,640**	$44,704	$881,747
16	$55,775	$35,302	$917,049
17	$55,775	$34,307	$951,355
18	$55,775	$33,340	$984,695
19	$55,775	$32,400	$1,017,095
20	**$96,975**	$54,746	$1,071,841
21	$55,775	$30,600	$1,102,441
22	$55,775	$29,737	$1,132,178
23	$55,775	$28,899	$1,161,077
24	$55,775	$28,085	$1,189,162
25	**$68,640**	$33,589	$1,222,751
26	$55,775	$26,524	$1,249,275
27	$55,775	$25,777	$1,275,051
28	$55,775	$25,050	$1,300,102
29	$55,775	$24,344	$1,324,446
30	**$96,975**	$41,134	$1,365,579

* Annual cost in Year zero is equal to the capital investment.
Annual cost in other years is annual O&M cost plus annual monitoring cost
Annual costs in Years 10, 20, and 30 include annual
O&M, annual monitoring, and periodic maintenance

Table F-4. Present Value of P&T System Costs for 100 Years of Operation

	P&T		
Year	Annual Cost *	PV of Annual Cost	Cumulative PV of Annual Cost
0	**$160,581**	$160,581	$160,581
1	$55,775	$54,203	$214,784
2	$55,775	$52,676	$267,460
3	$55,775	$51,191	$318,651
4	$55,775	$49,748	$368,399
5	**$68,640**	$59,498	$427,897
6	$55,775	$46,984	$474,880
7	$55,775	$45,660	$520,540
8	$55,775	$44,373	$564,913
9	$55,775	$43,122	$608,035
10	**$96,975**	$72,863	$680,898
11	$55,775	$40,726	$721,624
12	$55,775	$39,578	$761,202
13	$55,775	$38,463	$799,664
14	$55,775	$37,379	$837,043
15	**$68,640**	$44,704	$881,747
16	$55,775	$35,302	$917,049
17	$55,775	$34,307	$951,355
18	$55,775	$33,340	$984,695
19	$55,775	$32,400	$1,017,095
20	**$96,975**	$54,746	$1,071,841
21	$55,775	$30,600	$1,102,441
22	$55,775	$29,737	$1,132,178
23	$55,775	$28,899	$1,161,077
24	$55,775	$28,085	$1,189,162
25	**$68,640**	$33,589	$1,222,751
26	$55,775	$26,524	$1,249,275
27	$55,775	$25,777	$1,275,051
28	$55,775	$25,050	$1,300,102
29	$55,775	$24,344	$1,324,446
30	**$96,975**	$41,134	$1,365,579
31	$55,775	$22,991	$1,388,571
32	$55,775	$22,343	$1,410,914
33	$55,775	$21,714	$1,432,628
34	$55,775	$21,102	$1,453,729
35	**$68,640**	$25,237	$1,478,966
36	$55,775	$19,929	$1,498,895
37	$55,775	$19,367	$1,518,263
38	$55,775	$18,822	$1,537,084
39	$55,775	$18,291	$1,555,375
40	**$96,975**	$30,906	$1,586,282
41	$55,775	$17,275	$1,603,556
42	$55,775	$16,788	$1,620,344
43	$55,775	$16,315	$1,636,659
44	$55,775	$15,855	$1,652,514
45	**$68,640**	$18,962	$1,671,476
46	$55,775	$14,974	$1,686,449
47	$55,775	$14,552	$1,701,001
48	$55,775	$14,142	$1,715,143
49	$55,775	$13,743	$1,728,886
50	**$68,640**	$16,436	$1,745,323
51	$55,775	$12,979	$1,758,302
52	$55,775	$12,614	$1,770,916
53	$55,775	$12,258	$1,783,174
54	$55,775	$11,913	$1,795,086
55	**$68,640**	$14,247	$1,809,334
56	$55,775	$11,251	$1,820,584
57	$55,775	$10,934	$1,831,518
58	$55,775	$10,625	$1,842,143
59	$55,775	$10,326	$1,852,469
60	**$96,975**	$17,448	$1,869,917
61	$55,775	$9,752	$1,879,669
62	$55,775	$9,477	$1,889,147
63	$55,775	$9,210	$1,898,357
64	$55,775	$8,951	$1,907,308
65	**$68,640**	$10,705	$1,918,012
66	$55,775	$8,453	$1,926,466
67	$55,775	$8,215	$1,934,681
68	$55,775	$7,984	$1,942,664
69	$55,775	$7,759	$1,950,423
70	**$96,975**	$13,109	$1,963,532
71	$55,775	$7,327	$1,970,859
72	$55,775	$7,121	$1,977,980
73	$55,775	$6,920	$1,984,901
74	$55,775	$6,725	$1,991,626
75	**$68,640**	$8,043	$1,999,669
76	$55,775	$6,351	$2,006,020
77	$55,775	$6,172	$2,012,193
78	$55,775	$5,998	$2,018,191
79	$55,775	$5,829	$2,024,021
80	**$96,975**	$9,850	$2,033,870
81	$55,775	$5,505	$2,039,376
82	$55,775	$5,350	$2,044,726
83	$55,775	$5,200	$2,049,926
84	$55,775	$5,053	$2,054,979
85	**$68,640**	$6,043	$2,061,022
86	$55,775	$4,772	$2,065,794
87	$55,775	$4,638	$2,070,432
88	$55,775	$4,507	$2,074,939
89	$55,775	$4,380	$2,079,319
90	**$96,975**	$7,401	$2,086,720
91	$55,775	$4,137	$2,090,856
92	$55,775	$4,020	$2,094,876
93	$55,775	$3,907	$2,098,783
94	$55,775	$3,797	$2,102,579
95	**$68,640**	$4,541	$2,107,120
96	$55,775	$3,586	$2,110,706
97	$55,775	$3,485	$2,114,190
98	$55,775	$3,386	$2,117,577
99	$55,775	$3,291	$2,120,867
100	**$96,975**	$5,561	$2,126,428

Figure F-1. P&T System Costs - 100 years