FINAL REPORT

Edible Oil Barriers for Treatment of Chlorinated Solvent Contaminated Groundwater

ESTCP Project ER-0221

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LIST OF ABBREVIATIONS USED IN THIS DOCUMENT

AFB	Air Force Base
AFCEE	Air Force Center for Engineering and the Environment (formerly Air Force Center for Environmental Excellence)
amsl	Above Mean Sea Level
BOD	Biochemical Oxygen Demand
CAH	Chlorinated Aliphatic Hydrocarbon
CF	Chloroform
Cl#	Chlorine Number
CO	Carbon Monoxide
CT	Carbon Tetrachloride
CVOC	Chlorinated Volatile Organic Compound
1,2-DCA	1,2-Dichloroethane
cis-DCE	*cis*-1,2-Dichloroethene
trans-DCE	*trans*-1,2-Dichloroethene
DHB	*Dehalobacter spp*.
DHC	*Dehalococcoides spp*.
DNAPL	Dense Non-Aqueous Phase Liquid
DO	Dissolved Oxygen
DoD	Department of Defense
DoE	Department of Energy
DSM	*Desulfuromonas spp.*
ECD	Electron Capture Detector
EISOPQAM	Environmental Investigation Standard Operating Procedure and Quality Assurance Manual
EOS®	Emulsified Oil Substrate
ESTCP	Environmental Security Technology Certification Program
FID	Flame Ionization Detector
ft bgs	Feet Below Ground Surface
GRAS	Generally Recognized As Safe
HCl	Hydrochloric Acid
HRC®	Hydrogen Release Compound
IDW	Investigation-Derived Waste
ISCO	*In Situ* Chemical Oxidation
LEL	Lower Explosive Limit

MCL	Maximum Contamination Limits
MIP	Membrane Interface Probe
NFESC	Naval Facilities Engineering Service Center
NWS	Naval Weapons Station
NPV	Net Present Value
OC	On-center
O&M	Operation and Maintenance
ORP	Oxidation-Reduction Potential
PCE	Tetrachloroethene
PI	Principal Investigator
PID	Photoionization Detector
PFM	Passive Flux Meter
PRB	Permeable Reactive Barrier
PVC	Polyvinyl Chloride
RTDF	Remediation Technologies Development Forum
SCDHEC	South Carolina Department of Health & Environmental Control
SERDP	Strategic Environmental Research and Development Program
SOUTHDIV	Naval Facilities Command, Southern Division
SRG	Soil Remediation Goal
SU	Standard Unit
SWMU	Solid Waste Management Unit
1,1,1-TCA	1,1,1-Trichloroethane
1,1,2-TCA	1,1,2-Trichloroethane
TCE	Trichloroethene
TIC	Total Inorganic Carbon
TOC	Total Organic Carbon
VC	Vinyl Chloride
VFA	Volatile Fatty Acid
VOC	Volatile Organic Compound
ZVI	Zero Valent Iron

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EXECUTIVE SUMMARY

The emulsified oil technology can be an effective approach to quickly stimulate biodegradation of recalcitrant organic compounds, particularly chlorinated ethenes and ethanes, and perchlorate in groundwater to less toxic forms. The technology involves the introduction of a long-lasting, natural, time-released organic substrate composed principally of emulsified edible oil, sometimes supplemented with nutrients and/or additives, into a contaminated aquifer to enhance reductive dechlorination of these solvents or bioconversion of other contaminants susceptible to anaerobic microbial metabolic processes.

This evaluation of the emulsified oil technology was funded by the Environmental Security Technology Certification Program (ESTCP Project No. ER-0221). The project was designed as a pilot test to monitor and describe the effectiveness of a commercially available emulsified oil substrate (EOS®) for enhancing the biodegradation of chlorinated volatile organic compounds (CVOCs) in contaminated groundwater and aquifer material in a treatment cell. The project was conducted at a small area within Solid Waste Management Unit (SWMU) 17 at the Charleston Naval Weapons Station, Charleston, SC.

The cell selected for the test was characterized by elevated concentrations of trichloroethene (TCE) in soil (up to 16,000 µg/kg) and groundwater (over 20,000 µg/L). The pilot test design utilized a 20 foot (ft) by 20 ft grid to represent cleanup of a "typical" source cell. The saturated zone containing contaminated groundwater was silty clayey sand extending generally between 8 and 18 feet below ground surface (ft bgs). The groundwater gradient was low and tidally influenced, resulting in fluctuating groundwater flow directions. Based on aquifer characterization tests, groundwater flow velocity was estimated to be less than 10 ft/yr. The volume of contaminated aquifer material within the pilot test cell was 4,000 ft^3 (148 yd^3). The pilot test results were evaluated for the substrate's deployment, distribution, contact time and longevity in the aquifer, changes in aquifer chemistry, and effect on the target contaminants.

The project was conducted in two phases. Phase I was performed as prescribed in the original Technology Demonstration Plan and included site characterization, baseline sampling, injection of emulsified oil substrate and performance monitoring for 28 months. Solutions-IES and ESTCP expanded the project to include Phase II after the performance monitoring results from Phase I indicated that low pH was limiting further biodegradation of the target chlorinated VOCs. Phase II included a bench-scale treatability study, development and injection of a newly formulated pH-buffered substrate to overcome the pH problem, and an additional 11 months of performance monitoring to measure the effect of the second substrate on enhanced reductive dechlorination.

In Phase I, 165 gallons (~1,260 lbs) of concentrated emulsified oil substrate (EOS® supplied by EOS Remediation, LLC, Raleigh, NC) were diluted with 519 gallons of water and injected into the aquifer via eight pairs of temporary injection wells installed in a 20 ft by 20 ft grid formation (5 ft on-center). Distribution of substrate away from the injection wells was encouraged by recirculating groundwater for several additional days; the length of time was due to the low permeability of the aquifer. Water table mounding was noted but quickly dissipated. Immediate

increases in total organic carbon (TOC) were recorded in three monitor wells located throughout the pilot test cell attesting to the successful transport of EOS® and smearing of the substrate throughout the treatment zone.

In Phase II, a bench-scale treatability study was first performed to evaluate the impact of various alkaline materials on increasing the pH of acidic site matrix soil and groundwater collected from the pilot test treatment cell. The study was begun approximately 18 months after the EOS® was initially injected and the pH in the aquifer had generally declined to between pH 4 and 6. Magnesium hydroxide [$Mg(OH)_2$] was determined the best alkaline material for raising the pH to the optimal range (i.e., pH >6.0) for dehalorespiring bacteria to metabolize the chlorinated VOCs. Further testing showed that raising the pH to above 6.0 could stimulate TCE biodegradation, and bioaugmentation with a dehalogenating microbial inoculum (e.g., SDC-9 from Shaw Environmental) at the neutral pH could more effectively result in complete biodegradation of TCE to ethene.

Solutions-IES worked with EOS Remediation to formulate a buffered-EOS® product for Phase II field testing. Approximately 28 months after beginning Phase I, 326 gallons (3,030 lbs) of buffered EOS® were injected into the treatment grid. The substrate was directly emplaced in the aquifer via a specially designed Geoprobe® injection tool. As in Phase I, some groundwater mounding occurred but soon dissipated. Immediate changes in TOC and pH in monitoring wells showed that the buffered substrate could quickly impact areas away from the injection points.

The data evaluation during Phase I showed that changes to groundwater geochemistry occurred within the first few months after injection of EOS® producing conditions conducive to enhanced reductive dechlorination. These included elevated TOC, reduced dissolved oxygen (DO), lowered oxidation-reduction potential (ORP), absence of nitrate and a decrease in sulfate. Other changes reflected bioactivity associated with the formation of anaerobic conditions in a carbon-rich environment including increases in dissolved iron and manganese and methanogensesis. Initial evidence of TCE biodegradation to *cis*-1,2-dichloroethene (*cis*-DCE) in groundwater was noted after 3 to 6 months. Similar transformation was noted in soil 9 months after injection. However, TCE degradation appeared to slow after several months and little degradation of *cis*-DCE to vinyl chloride (VC) or ethene was observed.

The absence of further biodegradation was hypothesized to be a result of a drop in pH and/or absence of appropriate microorganisms in the aquifer. The pH change was attributable to fermentation of the emulsified oil to short chain fatty acids and carbonic acid, followed by breakdown of TCE releasing *cis*-DCE and additional H^+. The H^+ ions are then available to react with chloride ions forming hydrochloric acid (HCl). *Dehalococcoides spp*. is needed to biodegrade *cis*-DCE to VC and ethene, but even if they are present, they are less effective at the low pH that was created.

Addition of buffered EOS® in Phase II effectively raised the pH and alkalinity of the aquifer. This allowed the native dehalorespiring populations to re-initiate their metabolism of TCE and DCE. In Phase II, TCE was effectively biodegraded throughout the pilot study test cell. Over the entire 41-month monitoring period in Phases I and II, the total chlorinated VOC concentration (i.e., sum of PCE, TCE, *cis*-DCE and VC) decreased from 198 µM to 17 µM, a

decline of 91%. Most of this final biodegradation occurred in the 13 months of Phase II after the pH was adjusted back toward neutrality.

The increase in pH achieved in Phase II after buffered EOS® addition resulted in relatively rapid conversion of TCE and *cis*-DCE to VC. However, further conversion of VC to ethene was slow. At the end of Phase II, the DHC population density was 4 to 5 orders-of-magnitude greater in the treated soil and groundwater compared to the untreated background matrices. However, no organisms were detected with the enzymes BAV1 VC R-dase or VC R-dase that are known to be capable of rapid reduction of VC to ethene. The slow conversion of VC to ethene is believed to be due to absence of organisms capable of rapid VC degradation. The rate of VC degradation would likely be enhanced by bioaugmentation with cultures capable of rapid conversion of VC to ethene.

Overall, the ESTCP-funded pilot test of the emulsified oil substrate technology was successful in evaluating the performance of this technology. Strengths and limitations are as follows:

- Substrate can be effectively introduced and distributed into the aquifer using a variety of injection approaches. The injection approach is limited more by the aquifer permeability than by the equipment used. Substrate can spread away from the injection points.
- The technology quickly changed the aquifer geochemistry making it conducive to anaerobic reductive dechlorination.
- There is some reduction of aquifer permeability as a result of injection of substrate, but this effect appears to have little impact on performance of the enhanced reductive dechlorination process.
- Over the course of the 28-months in Phase I, the average concentration of TCE in groundwater was reduced by 86 to 99% in the treatment zone. Chlorine number (Cl#) calculations supported the observation that most of the conversion of TCE stopped at *cis*-DCE.
- Complete biodegradation (i.e., final decline in the total concentration of chlorinated VOCs) occurred in the 13 months of Phase II after the pH was adjusted back toward neutrality. Chlorine #s approaching ~ Cl# 1 or below were calculated in the treatment cell compared to ~ Cl# 3 in areas surrounding the cell, confirming that by the end of Phase II, biodegradation was progressing toward completion
- The approach effectively reduced the mass of TCE in the treatment zone by over 96%. After treatment, many of the areas in the treatment cell met regulatory limits for TCE in soil.
- After 28 months, emulsified oil substrate injected in Phase I was still available to microbial activity. The final longevity of the initial application was not tested. In Phase II, additional EOS® was added along with the buffer. The impact of this fresh substrate was only monitored for 13 months, and the TOC from this material was still abundant at that time.

The cost of treatment of the 20 ft by 20 ft pilot test cell was $65,000 for substrate injection and distribution using a network of direct push wells with re-circulation (Phase I). Based on 4,000 ft^3 of contaminated material, the unit cost to employ this technology was $16/$ft^3$. Site characterization, design, project management and baseline/performance monitoring costs are not

included as these are site-specific. Based on the data obtained from the study, the amount of EOS® injected would be expected to last at least 3 years without replenishment.

The cost to perform a direct injection of buffered EOS® into this same pilot test cell (Phase II) was $48,100. The unit cost to employ this technology is $12/ft^3. Based on the data obtained from the injection of EOS® in Phase I, the buffered EOS® would also be expected to last at least 3 years without replenishment. However, the actual long-term effectiveness of the buffering agent for maintaining the optimal pH range was not determined by this pilot study.

The overall cost to perform the 4-year pilot test was higher than might be expected from a typical pilot test. This is due to additional site selection and site characterization steps, work plan development, laboratory treatability testing, extended and specialized monitoring, and technology transfer activities associated with the level of in-depth evaluation on ESTCP-funded projects. The specific costs to perform Phase I and II of the pilot test are also slightly higher than might be expected from full-scale *in situ* bioremediation applications. Nonetheless, the unit costs still compare favorably with unit costs for other technologies uses to treat chlorinated solvents in groundwater.

1.0 Introduction

This Technical Report documents and demonstrates the use of emulsified oil substrate (EOS®) for groundwater remediation of chlorinated solvents in a source cell. The project was funded by the Environmental Security Technology Certification Program (ESTCP) as Environmental Restoration Project No. ER-0221. The purpose of the demonstration was to evaluate the effectiveness of emulsified oil substrate for cell treatment of soil and groundwater contaminated with trichloroethene (TCE). The demonstration was performed between 2003 and 2007 at Solid Waste Management Unit (SWMU) 17 at the Charleston Naval Weapons Station (NWS) in Goose Creek, South Carolina.

A second demonstration was performed simultaneously as part of this project to demonstrate and evaluate the use of emulsified oils for remediation of perchlorate. The perchorate demonstration was conducted at a rocket manufacturing site in Elkton, Maryland and was reported separately (ESTCP, 2006b; ESTCP, 2008). A document titled "Protocol for Enhanced *In Situ* Bioremediation Using Emulsified Edible Oil" was prepared by Solutions-IES in January 2006 for ESTCP as part of the same project (ESTCP, 2006a).

1.1 Background

Chlorinated solvents in groundwater are a frequently encountered problem at Department of Defense (DoD) facilities. In recent years, anaerobic reductive dechlorination has been shown to be an efficient microbial means of transforming more highly chlorinated species to less chlorinated species. Chlorinated solvents amenable to *in situ* anaerobic bioremediation include tetrachloroethene (PCE), TCE, *cis*-1,2-dichloroethene (*cis*-DCE), vinyl chloride (VC), 1,1,1-trichloroethane (1,1,1-TCA), 1,1,2-trichloroethane (1,1,2-TCA), 1,2-dichloroethane (1,2-DCA), carbon tetrachloride (CT), and chloroform (CF). For example, by the following series of reactions, chlorinated ethenes, such as PCE and TCE, can be biologically degraded into non-toxic end products. The typical biodegradation sequence for reductive dechlorination of these compounds is shown below:

$$\text{PCE} \rightarrow \text{TCE} \rightarrow \textit{cis}\text{-DCE} \rightarrow \text{VC} \rightarrow C_2H_4 \text{ (ethene)} \rightarrow CO_2 + H_2O$$

To enhance *in situ* biodegradation, the chlorinated solvents must be brought into contact with a biodegradable organic substrate. The substrate serves as a carbon source for cell growth and as an electron donor for energy generation. Several groups, including ESTCP, the Air Force Center for Environmental Excellence (now Air Force Center for Engineering and the Environment; AFCEE) and the Remediation Technology Development Forum (RTDF) have completed large-scale pilot studies of enhanced anaerobic bioremediation of chlorinated solvents. In these projects, readily biodegradable soluble substrates have been injected into the aquifer and flushed through the contaminated zone (sometimes with a bioaugmentation culture) to stimulate anaerobic biodegradation. While several of these projects have been successful, they have also shown that continuously delivering a soluble, readily biodegradable substrate to the contaminated interval can be difficult and labor intensive.

When an easily biodegradable, dissolved substrate is injected into a formation, the contaminants surrounding the injection point will be removed by both flushing and enhanced biodegradation. Over time, this results in a 'clean' zone surrounding the injection point. To be effective, the substrate has to pass through this clean zone to reach the contaminants. If the substrate is fermented to methane in this zone, it will be wasted and will not enhance contaminant degradation. Excessive biological growth may also cause clogging of the injection zone, potentially reducing injection rates.

Continuously feeding a soluble, easily biodegradable substrate can be expensive. There is a significant capital cost for the required tanks, pumps, mixers, injection and pumping wells, and related process controls. In addition, operation and maintenance (O&M) costs are high because of problems associated clogging of mechanical equipment, injection wells and infiltration galleries. Thus, although the substrate may be relatively inexpensive, the overall long-term cost of the project often becomes more expensive.

In response to these operational and cost concerns, technologies using more slowly soluble substrates have been developed. Initially, neat vegetable oil was injected into contaminated zones to provide a low-cost slow-release substrate (Boulicault et al., 2000; Parsons, 2002). Neat vegetable oil can be useful for sequestering chlorinated solvents, retarding further contaminant migration and promoting anaerobic reductive dechlorination. Neat vegetable oil is relatively inexpensive, but is difficult to distribute away from the immediate injection zone (AFCEE et al., 2004). Consequently, more substrate and more injection points may be required to achieve adequate coverage of the treatment zone.

This project was developed to evaluate an innovative, low-cost approach for distributing and immobilizing biodegradable organic substrates in contaminated aquifers that employs the best features of the other technologies to promote reductive dechlorination of chlorinated solvents. The approach was designed to promote good contact between the oil and the contaminants over a wider radius of influence by placing and distributing a naturally long-lasting substrate in the ground. Instead of using a rapidly exhausted soluble substrate (e.g., molasses or lactate), the technology involves a one-time injection of low solubility, slowly biodegradable, edible oil emulsion.

Early in the development of this process, edible oil emulsions were prepared in the field immediately prior to injection. Typically, food-grade edible oils, surfactants and, in some cases, nutrients were shipped to the project site where field personnel blended the materials to form a coarse emulsion just prior to injection into the aquifer (AFCEE et al., 2004; AFCEE, 2007). The oil droplets present in these emulsions ranged in size from 1 to over 30 micrometers (μm) in diameter (Borden, 2007a, b). Continued research on emulsified oils demonstrated that emulsions with small, uniform, negatively charged droplets are most easily distributed with minimal permeability loss (Coulibaly and Borden, 2004; Coulibaly et al., 2006; Borden, 2007b). As a result, the majority of contractors have shifted over to use of premixed emulsions that are manufactured off-site under controlled conditions. These premixed emulsions typically have much smaller and more uniform droplets than emulsions prepared in the field. The premixed emulsions are shipped to the site as a concentrate and diluted with water on site prior to injection. At the first demonstration site (Elkton, MD) used for this project, a commercially available

emulsified oil substrate (EOS®)[1] was used to create a permeable reactive barrier (PRB) for treating contaminated groundwater (Borden, 2007c). At the second project site, located at the Charleston NWS, Solutions-IES tested the effectiveness of EOS®, when applied in a small grid design, for cell treatment of soil and groundwater contaminated with TCE. The results of the Charleston NWS pilot study are the subject of this Technical Report.

1.2 Objectives of the Demonstration

The overall objective of this project was to evaluate the performance of Emulsified Oil Substrate (EOS®) to treat perchlorate and chlorinated solvents in groundwater at DoD facilities. The technology demonstration at the Elkton, MD site evaluated the effectiveness of EOS® as a PRB for intercepting contaminant migration and biodegrading perchlorate (ESTCP 2006b, 2008). Elevated concentrations of 1,1,1-TCA and TCE were co-contaminants in the aquifer and offered an opportunity to simultaneously evaluate the PRB design for remediating these compounds.

The technology demonstration conducted at the Charleston NWS described in this Technical Report evaluates the effectiveness of the emulsified oil process for source area treatment of TCE. The pilot study was performed in two phases. In Phase I, the demonstration involved conducting a source area treatment using emulsified oil substrate and monitoring the performance for 28 months. Phase II was implemented based on data acquired during Phase I that identified pH as a significant problem limiting biodegradation in the treated cell. ESTCP provided supplemental funding to implement Phase II to measure the ability to inject and distribute a pH-buffered oil emulsion substrate into the aquifer and overcome the limitations encountered during the first part of the project. Phase II was monitored for almost 13 additional months. Specific objectives for Phase I and Phase II are discussed in Section 3.0.

1.3 Regulatory Drivers

The Federal government has established Maximum Contaminant Levels (MCLs) for PCE, TCE, and their daughter products in drinking water to protect human health. These MCLs are often used as default remediation goals for contaminants in groundwater. In addition, many states have developed their own standards for contaminants in groundwater. The South Carolina Department of Health & Environmental Control (SCDHEC) groundwater standards and soil remediation goals (SRGs) that are applicable for the NWS site are summarized in **Table 1-1** for the primary constituents of concern.

[1] EOS® is a patented emulsified oil process for groundwater bioremediation (US Patent RE 40, 448; EU Patent 1 315 675, International Patents Pending).

Table 1-1
SCDHEC Cleanup Standards for Groundwater and Soil

Compound	Groundwater Concentration[a] (µg/L)	Soil Concentration[b] (µg/kg)
Tetrachloroethene (PCE)	5	1,500
Trichloroethene (TCE)	5	53
cis-1,2-Dichloroethene (*cis*-DCE)	70	43,000
trans-1,2-Dichloroethene (*trans*-DCE)	100	69,000
Vinyl chloride (VC)	2	79

a. Class GB Groundwater, South Carolina Department of Health and Environmental Control Primary Drinking Water Regulations, Chapter R.61-68, April 25, 2008
b. USEPA Region 9 Soil Remediation Goals.
µg/L = micrograms per liter; µg/kg = micrograms per kilogram

1.4 Stakeholder/End-User Issues

There are a number of methods available for treatment of soil and groundwater contaminated with chlorinated solvents including pump-and-treat systems, *in situ* chemical oxidation (ISCO), zero-valent iron, thermal treatment, and enhanced anaerobic bioremediation using soluble substrates. Pump-and-treat technologies are well understood and can be effective for controlling chlorinated solvent migration in groundwater. However, capital costs are relatively high and many pump-and-treat systems have been in operation for decades with little improvement in groundwater quality. ISCO treatment can be very effective in rapidly reducing contaminant concentrations. However, contaminant concentrations often rebound following ISCO treatment as contaminants slowly diffuse out of lower permeability zones that were untreated (McGuire et al., 2006). Thermal treatment can be very effective in treating chlorinated solvent source areas (McGuire et al., 2006). However, capital costs for thermal treatment maybe higher than other treatment processes (McDade et al., 2005). Zero-valent iron is effective but may be limited by difficulty placing the reactant to the desired depth and the cost associated with the material. Soluble substrates work effectively to enhance anaerobic bioremediation, but require frequent or continuous re-injection and require additional O&M that increases costs.

Since the inception of this project, the use of emulsified oil for groundwater bioremediation has been patented[2] and been shown to significantly reduce the cost and improve the effectiveness of aquifer remediation of many chlorinated solvents (e.g., chloroethenes, chloroethanes, pentachlorophenol), perchlorate, nitrate and chromate. Laboratory studies suggest this approach may also be effective for treatment of acid mine drainage and certain oxidized radionuclides (TcO_4^-, UO_2^{+2}). These are major environmental problems for the DoD and the public as a whole.

[2] Ibid

2.0 Technology Description

2.1 Technology Development and Application

Emulsified oil can be injected into the subsurface to enhance the anaerobic biodegradation of chlorinated solvents and other anaerobically biodegradable contaminants. As the emulsified oil slowly biodegrades over time, it provides a continuous source of dissolved organic carbon; (i.e., fermentation products) to support anaerobic biodegradation of the target contaminants. Degradation of the oil results in removal of oxygen and production of acetic acid (CH_3COOH) and molecular hydrogen (H_2). This reaction is illustrated below.

$$C_{56}H_{100}O_6 \text{ (\textbf{oil})} + 50\ H_2O \xrightarrow{\textit{Bacteria}} 28\ CH_3COOH + 44\ H_2$$

CH_3COOH can be used as an electron donor for PCE and TCE dechlorination to *cis*-DCE, and for removal of other competing electron acceptors (oxygen - O_2, nitrate - NO_3, ferric iron - Fe^{+3}, and sulfate - SO_4). However, reduction of *cis*-DCE to ethene also requires H_2 as an electron donor. As shown above, one mole of soybean oil can be fermented to produce 44 moles of hydrogen.

Implementation of the emulsified oils process involves preparation or purchase of the emulsion and injection into the treatment zone. All materials used in preparation of the EOS® emulsion are Generally Recognized As Safe (GRAS), food-grade materials (21 CFR 184.1400). Emulsified oil substrate can be injected into "hot spots", throughout the plume, or as a PRB using conventional wells or direct-push injection points (ESTCP, 2006a). The amount of emulsified oil injected into the subsurface is determined based on the concentrations of the target compounds, the concentrations of various biodegradation and geochemical parameters, and hydrogeologic conditions.

2.2 Previous Testing of the Technology

The current field demonstration project was funded by ESTCP. Concurrently, the Strategic Environmental Research and Development Program (SERDP) have supported fundamental research examining the effects of the oil distribution technique on aquifer permeability and the rate of oil biotransformation (Borden, 2007a). AFCEE and private industries have also supported pilot and full-scale field evaluations of this process for the degradation of chlorinated aliphatic hydrocarbons (AFCEE et al., 2004, AFCEE, 2007). This work has provided much valuable information on both the theoretical and practical aspects of oil and oil emulsion injection and distribution in the subsurface, as well as the effectiveness of the process for stimulating anaerobic reductive dechlorination in groundwater.

At the start of this project, use of emulsified oils was a relatively new, unproven process. However, emulsified oils have now been applied at hundreds of sites throughout the US and at selected sites in Canada, South America, Europe, Africa, Asia and Australia. **Table 2-1** provides an abbreviated list of DoD facilities where emulsified oils have been used.

Table 2-1
Summary of Department of Defense Edible Oil Process Applications

Site Name	Location	Scale	Date	Injection Summary
Air Force Facilities				
Hangar K	Cape Canaveral Air Force Station, FL	Pilot Expanded	June 1999 July 2000	Single Well Push-Pull Test Straight Injection/Water Push
SS015	Travis Air Force Base (AFB), CA	Pilot Expanded	April 2000 December 2000, April 2002	Straight Injection/Water Push Straight Oil/Water Push and Emulsions. Injection Points and Direct Injection
Site FF-87	Former Newark AFB, OH	Full Expanded	September 2001 September 2003	Injection Points with Emulsion
Site LF-08	Whiteman AFB	Pilot	July 2002	Direct Injection with Emulsion
AOC 2	NAS Fort Worth JRB, TX	Pilot	August 2003	Injection Points with Emulsion
FTA-2	Tinker AFB, OK	Pilot	October 2003	Injection Points with Emulsion
LF-05	Hickam AFB, HI	Pilot	April 2003	Injection Points with Emulsion into DNAPL Zone
DP98	Elmendorf AFB, AK	Pilot	July 2005	Injection Points with Mixed Substrate of Lactate and Emulsion
WP-21	Dover AFB, DE	Pilot	April 2000	Injection Points with Emulsion
WP-21	Dover AFB, DE	Pilot	April 2000	Soybean Oil/Water Push into Injection Points
WP-21	Dover AFB, DE	Expanded	August 2003	Injection Points with Emulsion
Site 14	Edwards AFB, CA	Pilot	September 2000	Injection Points with Emulsion
SS-17	Altus AFB, OK	Pilot	December 2001	Injection Points with Emulsion
OU-1	Altus AFB, OK	Pilot	December 2001	Injection Points with Emulsion
SWMU 10	Arnold AFB, TN	Pilot	December 2003	Straight Injection into DNAPL Zone
SWMU 10	Arnold AFB, TN	Pilot	December 2003	Injection Points with Emulsion
	Beale AFB, CA		2004	Emulsion Injection
	Ellsworth AFB, SD		2004 and 2005	Emulsion Injection
	Kelly AFB, TX		2005	Emulsion Injection
	McCoy AFB, FL		2005	Emulsion Injection
	Moody AFB, GA		2005	Emulsion Injection
	Seymour Johnson AFB, NC		2005	Emulsion Injection
Navy Facilities				
Site N-6	NSA Mid-South, TN	Pilot	August 2000	Straight Injection/Water Push
NIROP	NIROP Fridley	Pilot	November 2001	Injection Points with Emulsion
	Charleston NWS, SC	Pilot	May 2004	Recirculation of Emulsion
Site 13	NAB Little Creek, VA		2004	Injection Points with Emulsion
	White Oak NSWC, MD		2004	Emulsion Injection
OU-4 and SA-17	Orlando NTC, FL	Pilot	2005 (planned)	Emulsion Injection
Army Facilities				
Waste Accumulation Pad	Tarheel Army Missile Plant, NC	Pilot	July-Aug. 2004	Recirculation of emulsion through source cell

Site Name	Location	Scale	Date	Injection Summary
Other DoD Facilities				
	Confidential Site, MD	Pilot	Oct 2003	Injection Points with Emulsion (PRB configuration)
DDMT	DDMT, TN	Pilot		
ANGB	ANGB, VT	Pilot		
Site 2	ANGB, VT	Pilot	June 2002	Injection Wells with Emulsion
OU-2	DDHU, UT	Pilot	July 1999	Single Well Push-Pull
OU01	DDHU, UT	Pilot	April 2000	Injection Points with Emulsion
BRAC-51	DDHU, UT	Full-Scale	July 2002	Excavation Backfill with Neat Oil
IC-42	McClellan AFB, CA (AFRPA)	Pilot		Injection Wells with Emulsion
SWMU-97	Dugway Proving Grounds (USACE)	Pilot	November 2004	Injection Wells with Emulsion
OU-2	DDHU, UT	Pilot		Single Well Push-Pull
OU-4	DDHU, UT	Pilot		Injection Points with Emulsion

Two different procedures have been used to inject and distribute the oil: (1) direct injection of pure liquid (neat) oil and (2) preparation or purchase of an oil-in-water emulsion followed by injection into the aquifer. This report focuses on the use of oil-in-water emulsions to enhance anaerobic biodegradation processes.

2.3 Factors Affecting Cost and Performance

The primary costs associated with installation of emulsified oil substrate as PRBs or for source cell treatment include injection point installation, substrate purchase, and labor for injection. These costs are affected by the mass of contaminants in the aquifer, the subsurface lithology, the depth to groundwater, and the vertical extent of contamination. The performance of an emulsified oil substrate for stimulating remediation of chlorinated solvents is primarily related to the ability to distribute the emulsion throughout the treatment zone, the presence of appropriate biogeochemical conditions, the presence of microorganisms capable of contaminant biodegradation, contact time between the contaminants, bacteria and emulsion, and the rate of biodegradation of the target contaminants that can be achieved *in situ*. In 2008, Weispfenning and Borden published a simple, yet sophisticated design tool that considers the interrelationship of these factors. The effort was funded by ESTCP and takes into account the factors discussed below when planning emulsified oil injection systems.

2.3.1 Substrate Costs

The amount of emulsified oil required at a specific site depends on the amount of oil needed for biodegradation (e.g., contaminant concentrations, competing electron acceptors) and the oil retention by sediment. Material costs for anaerobic bioremediation using emulsified oils are generally higher than for soluble substrates such as molasses and lactate. However, the greater longevity of oil in the subsurface often results in lower total costs because of the much less frequent substrate injection. Costs for installation of an emulsified oil PRB or treatment cell are influenced by the number of injection points, injection point spacing, the time needed to complete the injections, and how the injections are completed (i.e., direct-push points or wells). All of these factors are related to the subsurface lithology and the depth to groundwater. Emulsified oils can be injected

through direct-push points, temporary wells, or conventional drilled wells. The subsurface lithology (i.e., heterogeneity and permeability) greatly influences the ability to distribute emulsified oil throughout the aquifer. This affects the number and spacing of the injection points.

2.3.2 Emulsified Oil Distribution

To be effective as a barrier or source cell treatment, emulsified oil should be distributed vertically and horizontally throughout the target treatment zone. If the emulsified oil is not effectively distributed, contaminated soil and groundwater will not come in contact with the substrate and could remain untreated.

2.3.3 Emulsified Oil Biodegradation

If the edible oil emulsion is biodegraded too rapidly, then more frequent emulsion injection will be required to maintain performance, increasing costs. Operating experience at other sites indicates that a single emulsion injection will be effective in stimulating biodegradation for three to five years. In an ESTCP supported pilot study, injection of 110 gallons of the EOS® concentrate was effective in enhancing chlorinated solvent degradation for over two years and perchlorate degradation for over 3.5 years in a 50 ft wide PRB (ESTCP, 2008).

2.3.4 Presence of Appropriate Microorganisms

Available information indicates that the indigenous microbial population may not be capable of complete reductive dechlorination of PCE and TCE to ethene at all sites. At sites where the required microorganisms are not present, commercially available bioaugmentation cultures may be added to the aquifer for improved treatment. Additional information on aquifer bioaugmentation can be found in ESTCP (2005).

2.3.5 Appropriate Geochemical Conditions

A variety of geochemical factors including levels of competing electron acceptors, presence/absence of inhibitory compounds, and pH can have a major impact on the efficacy of anaerobic bioremediation. In most cases, competing electron acceptors (oxygen, nitrate, ferric iron, and sulfate) can be depleted by injecting additional oil. However, high levels of competing electron acceptors may reduce substrate longevity, increasing long term operation and maintenance costs. Elevated levels of heavy metals (Cu, Hg, Zn) and some organic compounds can inhibit anaerobic biodegradation processes.

A number of studies have shown that anaerobic bioremediation processes can be inhibited by low pH. This is discussed in further detail in Section 6.2.1 of this report. The pH may decline during anaerobic bioremediation due to several different processes including release of free protons (H^+) during reductive dechlorination, and production of carbonic acid (H_2CO_3) and volatile fatty acids (VFAs) during substrate fermentation. If the aquifer buffering capacity is low, the pH may decline inhibiting contaminant biodegradation.

2.4 Advantages and Limitations of the Technology

2.4.1 Advantages and Limitations of Anaerobic Bioremediation

Many of the advantages and limitations of emulsified oils are similar to other substrates used for *in situ* anaerobic bioremediation. *In situ* anaerobic bioremediation can be effective for treatment of a variety of contaminants including chlorinated solvents, chlorobenzenes, chlorophenols, chlorinated pesticides (e.g., chlordane), perchlorate, explosive and ordnance compounds (e.g., TNT, RDX, HMX), hexavalent chromium, nitrate and sulfate. The technology is relatively simple and inexpensive to apply. However, there are some potential limitations to use of anaerobic bioremediation that need to be carefully considered.

2.4.1.1 Adverse Impacts on Groundwater Geochemistry and Biology

The successful application of anaerobic bioremediation will typically result in changes to groundwater geochemistry and biology. Essentially all liquid, solid and dissolved substrates will release fatty acids, increasing the Biochemical Oxygen Demand (BOD) of the groundwater and imparting secondary taste and odor to the groundwater. Substrate addition will also stimulate growth of denitrifiers, iron, manganese and sulfate reducers, and methanogens which may result in increased levels of dissolved manganese, iron, sulfide and/or methane downgradient from the treatment zone. Prior experience indicates these impacts dissipate within a few hundred feet of the anaerobic treatment zone. However, if a water supply well is located a short distance downgradient, then anaerobic bioremediation may not be appropriate.

Anaerobic bioremediation of chlorinated solvents results in the sequential reduction of more highly chlorinated compounds (e.g. PCE and TCE) to less chlorinated compounds, which are further degraded to non-toxic end-products such as ethene, ethane, carbon dioxide, and chloride. However, if the process does not go to completion, anaerobic bioremediation can release partially reduced contaminants (e.g., DCE and VC) to the downgradient aquifer.

Anaerobic bioremediation can also result in release of carbon dioxide and methane to the vadose zone. Past experience is that methane is oxidized to carbon dioxide relatively quickly in the vadose zone. However, if the water table is shallow or the treatment zone is in close proximity to buildings or underground utilities, then there can be an increased risk of vapor intrusion, especially if dechlorination is incomplete. Several guidance documents provide recommendations on soil gas monitoring at anaerobic bioremediation sites (AFCEE et al., 2004; ESTCP, 2006a; AFCEE, 2007).

2.4.1.2 Hydraulic and Physical Limitations

Aquifer permeability influences the application and distribution of any substrate, treatment material, or solution. In low permeability environments, it may be difficult to distribute substrate throughout the treatment zone, reducing effectiveness and increasing costs. This difficulty may be further amplified when

groundwater velocity is low. Substrate addition can also result in biomass and/or gas bubble accumulation with associated reductions in aquifer permeability.

The depth at which anaerobic bioremediation can be applied is based on available drilling technologies. Application at greater depths will increase the drilling cost resulting in greater overall project costs.

2.4.1.3 Microorganisms

For enhanced *in situ* biodegradation to successfully degrade chlorinated solvents completely to their non-toxic end products, the appropriate microorganisms must be present. Available information suggests that microbial reductive dechlorination is fairly ubiquitous in anaerobic, chloroethene-contaminated aquifers, but the extent of dechlorination is highly variable from site to site (Bradley, 2000). Certain dehalorespirers are able to grow using chloroethenes as sole terminal electron acceptors.

2.4.2 Advantages of Emulsified Oils over Other Substrates

Emulsified oils have many important advantages over other substrates for use in anaerobic bioremediation.

2.4.2.1 Long Lasting Substrate

One of the primary advantages of emulsified oils over soluble substrates is their persistence in the subsurface. Most soluble substrates require frequent or continual application to maintain activity. In contrast, a single application of emulsified oils often lasts three to five years. For a source area treatment, this single application may be sufficient to completely remediate the source area. For barriers, periodic reinjections of emulsion will be required to maintain long-term performance. However, reinjection is relatively simple and does not require any permanent on-site equipment. Capital and operation and maintenance (O&M) costs are generally lower for both source area treatments and barriers using emulsified oils than similar systems using soluble substrates.

2.4.2.2 Effective Transport in Many Aquifers

There are several solid and liquid organic substrates that are reported to be long-lasting in the subsurface including mulch, chitin, neat vegetable oil, and certain specialty chemicals (e.g., polymerized lactate). These materials can be added to the surface by trenching, hydraulic fracturing, high pressure injection, or mechanical mixing. However, distribution of these materials away from the point where they are added appears to be relatively limited.

In contrast, emulsified oils can be distributed over relatively large areas by flushing the oil droplets through the aquifer material with water. This allows treatment of larger aquifer volumes with fewer injection points, reducing costs. The maximum distance that emulsified oils can be transported in the subsurface is not known. Laboratory and mathematical modeling studies (Borden, 2007b; 2007c; Clayton and Borden, 2008, Coulibaly and Borden, 2004; Coulibaly et al.,

2006) indicate that oil droplets can be effectively distributed at least five to ten meters, assuming sufficient emulsified oil and water are injected. In practice, injection well spacings of 10 to 20 feet are common and emulsions have been observed 50 to 100 ft from the injection point in some aquifers.

The major limitation on emulsion distribution in aquifers is the amount of oil retained by the aquifer material and the rate that water can be injected. Aquifer material with a high clay content will retain more oil droplets, requiring injection of more emulsion to achieve the same radius of influence. Aquifer material with a high clay content will also have a lower permeability making it more difficult to inject large volumes of water to distribute the oil droplets. In practice, it may be difficult to effectively treat relatively homogeneous sediments with more than 10% clay due to the high oil retention and low permeability. However, if the clayey material is fractured or contains sand layers, the oil droplets can be easily transported through the higher permeability zones, effectively encasing the low permeability clays in an oil rich zone. Over time, contaminants released from the clays will diffuse out and be treated in the oil treated zones.

2.4.2.3 More Effective Contaminant Contact

Sweeping soluble substrates throughout the aquifer can initially be effective for enhancing contaminant biodegradation. Since the entire source area initially contains some dissolved contaminants, uniform distribution of soluble substrate initially results in rapid biodegradation of the more mobile, widely distributed contaminants. However over time, contaminants are depleted from most of the aquifer and biodegradation is restricted to the few remaining pockets of contamination. Injecting soluble substrate directly into isolated pockets of contamination is not practical since these pockets are extremely difficult to locate. Continuously injecting a soluble substrate upgradient of these pockets stimulates growth of methanogens near the injection point (once the contaminant is depleted). The injected substrate is then fermented to methane before reaching the contaminant, greatly reducing bioremediation efficiency. This effect has been observed in two well controlled laboratory studies.

Yang and McCarty (2002) stimulated dissolution of a PCE DNAPL by continuously injecting pentanol into the inlet of a column containing residual PCE droplets. PCE was initially reduced to *cis*-DCE, significantly increasing the DNAPL dissolution rate. However after ~150 days, a large methanogenic population developed near the column inlet resulting in rapid conversion of pentanol to methane. Since the pentanol never reached the DNAPL, biotransformation and dissolution of PCE was greatly inhibited.

Sleep et al. (2006) had similar problems when attempting to stimulate reductive dechlorination of PCE in a 2-D sandbox. Ethanol addition initially stimulated PCE degradation. However over time, biological growth near the injection point resulted in rapid depletion of the soluble substrate. Reductive dechlorination rates declined to low levels as the injected substrate was fermented to methane before it

reached the DNAPL. This occurred even though a substantial portion of the original PCE was still present in the sandbox.

The problem of substrate fermentation before it reaches the target contaminant can be overcome through an initial treatment with emulsified oils. As the oil droplets migrate through the treatment zone, hydrophobic contaminants (e.g., chlorinated solvents) will partition into the oil droplets forming a new mixed NAPL (Fisher et al., 2007). This mixed NAPL provides an ideal environment for growth of dechlorinators since it contains both electron acceptor and electron donor. Once this mixed NAPL is formed, there is no opportunity for the substrate to be fermented to methane before it reaches the contaminant. Yang and McCarty (2002) demonstrated the effectiveness of this approach in laboratory studies – a single injection of PCE and olive oil stimulated PCE dissolution-biodegradation for over 1.5 years.

2.4.3 Limitations of Emulsified Oils compared to Other Substrates

The primary limitations of emulsified oils compared to other substrates are related to the unit cost of the material and amount of material required.

Unit cost ($ per pound substrate) are generally higher for emulsified oils than for soluble substrates such as carbohydrates and lactate. However, soybean oil contains more reducing equivalents per gram than soluble substrates so the cost per reducing equivalent may be lower. More importantly, the greater longevity of oil in the subsurface requires less frequent substrate addition, greatly reducing labor costs for substrate reinjection.

The total amount of emulsified oil required to treat depends on the amount of oil required to support biodegradation and the oil retention by aquifer material. In formations with a high clay content, the amount of oil required to achieve effective distribution may be greater than the amount required to support biodegradation. In these cases, excess emulsified oil must be injected for good distribution. This can increase the initial substrate costs. However, the greater amount of oil injected may increase longevity, reducing future O&M costs.

2.4.4 Comparison of Emulsified Oil to Other Technologies

Several technologies have been used historically for remediation of chlorinated solvents in groundwater including pump-and-treat with air stripping and air sparging, both of which rely on physical dissociation of the contaminants from the aqueous phase to the gaseous phase for removal. Pump-and-treat with activated carbon adsorption also removes contaminants, but these methods simply transfer the contaminants from one medium to another without destroying them. Pump-and-treat and air sparging methods both require aboveground treatment equipment, associated O&M costs, and higher capital costs which make these options more expensive than *in situ* bioremediation.

Advantages of *in situ* treatment compared to active aboveground treatment technologies include lower capital and O&M costs, minimal impact on site infrastructure, and no secondary waste stream to treat. An example of non-biological materials used for *in situ*

treatment of chlorinated VOCs is zero valent iron (ZVI) which has been successfully installed as PRBs to promote chemical reductive dechlorination. *In situ* bioremediation can be enhanced using a variety of substrates including soluble substrates (e.g. lactate, molasses), slow-release substrates (e.g., HRC®, vegetable oil, emulsified oils), and solid substrates (e.g., mulch, compost, chitin). These substrates can be applied in various configurations to remediate source areas, contain plumes (biobarriers), and provide plume-wide treatment.

ZVI PRBs have higher life cycle costs compared to emulsified oil, primarily because of higher capital and installation costs (see Section 1.4)**.** Natural materials such as chitin, compost, and bark mulch are relatively inexpensive to acquire, but may suffer from inconsistency of composition and are limited to installation in shallower aquifers. The prominent technologies that compete with emulsified oil are materials that can be injected into the aquifer to stimulate anaerobic conditions and *in situ* anaerobic biodegradation. These include soluble substrates (lactate, molasses) and HRC® and HRC®-X (which are polymeric lactate-based materials marketed as a slow-release carbon source for stimulating reductive dechlorination of chlorinated solvents).

Approaches using soluble substrates, slow-release, and solid substrates to treat chlorinated solvents and perchlorate are all based on the same microbial processes. As a consequence, none of these approaches is inherently more or less effective in degrading chlorinated solvents. The primary difference is in the short- and long-term costs of delivering substrate to the bacteria. Emulsified oils are relatively inexpensive, innocuous, food-grade substrates. When properly prepared and injected, emulsified oils are immobile and slowly biodegraded in most aquifers. A single, low-cost injection can provide sufficient carbon to drive anaerobic biodegradation for several years. This is expected to significantly lower O&M costs compared to aqueous-phase injection of soluble carbon sources (e.g., lactate and carbohydrates) and will allow addition of slow-release substrates at locations where placement of solid-phase carbon in trenches is not feasible (e.g., large depths, fractured rock).

3.0 Performance Objectives

3.1 Performance Objectives

The overall objective of this demonstration project was to evaluate the performance of Emulsified Oil Substrate (EOS®) for remediating TCE in groundwater. The performance of the cell treatment was evaluated by monitoring changes in contaminant concentration and mass flux, the distribution of EOS® in the subsurface, and the impact of the emulsion injection on aquifer permeability and groundwater flow.

3.1.1 Phase I Performance Objectives

The Phase I performance objectives, as derived from the Technology Demonstration Plan for this project (Solutions-IES, 2004) are summarized in **Table 3-1**. The success achieved in meeting these objectives is shown on the table. The scope-of-work and results of performance monitoring during Phase I of the project are discussed in more detail in Sections 6.0, 7.0 and 8.0.

3.1.2 Phase II Performance Objectives

After reviewing the performance monitoring results for up to 24 months after implementing Phase I, it appeared that low groundwater pH was inhibiting reductive dechlorination. ESTCP funded supplemental laboratory and field studies to test this hypothesis and seek ways to overcome this apparent limitation. The objectives of Phase II were to evaluate the ability to increase the pH of the aquifer into the optimal range for dehalorespiring bacteria to thrive using an injectable, pH-buffered emulsion and determine the effectiveness of the approach for improving *in situ* reductive dechlorination of TCE. The scope and objectives of the additional work were as follows:

- Perform laboratory studies to determine the buffering needs of the site and test various buffers to find a suitable material for field use.
- Perform bench studies to evaluate the ability of the buffering agent(s) to be blended with EOS® to form a single emulsion that could be injected into the subsurface or decide to inject separately.
- Extend the monitoring program to allow at least one year of post-adjustment monitoring to evaluate the effectiveness of the buffering process for stimulating anaerobic reductive dechlorination.
- Use the laboratory and field studies to evaluate the need for bioaugmentation to reach the regulatory goals.
- Measure the distribution of the pH-buffering agent throughout the test cell.

Table 3-1
Phase I Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance (Objective Met?)	Discussed in Report
Qualitative	1. Reduce risk	Reduce mass of contaminants in treatment zone and downgradient mass flux of regulated contaminants.	Yes	Section 7.4.6
	2. Capital Costs	Capital costs are significantly lower than other zone treatment technologies.	Yes	Section 9.0
	3. Maintenance	Re-injection is not required for at least five years.	Not Determined[1]	
	4. Ease of Use	Installation of treatment zone using readily available equipment.	Yes	Sections 6.1 and 6.4
	5. Compatible with Monitored Natural Attenuation (MNA) approaches	Chemical changes in downgradient groundwater do not adversely impact any ongoing MNA processes.	Yes	Sections 7.2 and 7.3
Quantitative	1. Reduce TCE levels.	>90% reduction in average TCE concentration in monitoring wells in treatment zone.	Yes	Section 7.4.2
	2. Convert TCE to non-toxic end-products.	> 50% reduction of TCE is converted to ethene or ethane.	Yes. CVOCs reduced by >80%	Section 7.4.3
	3. Reduce contaminant mass flux	Reduce mass flux of chlorinated ethenes by over 75%.	Yes	Section 7.4.6
	4. Reduce mass of TCE in soil.	Reduce average TCE concentration in treatment zone by >80%	Yes	Section 7.5

1. Phase I operated without maintenance for 28 months. Continued monitoring would be required beyond the duration of this project to determine the eventual time when re-injection for replenishment might be recommended.

3.2 Selecting the Test Site

The following selection criteria were used to identify at the Charleston NWS as a promising demonstration test site:

- Site hydrogeology and contaminant distribution were reasonably well defined.
- Contaminants are present at moderate to high concentrations.
- The test site is not immediately upgradient of a critical receptor.
- Sufficient working area is available.
- No active remediation is currently being conducted in the vicinity.
- Routine groundwater monitoring of an existing well network is managed by the Navy.
- The proposed test cell is located in an out-of-the-way location along a powerline utility easement within an undeveloped wooded portion of the base.

4.0 Site Description and Conceptual Design

There are two basic designs options when using emulsified oil substrate for *in situ* groundwater remediation. These are: 1) Permeable Reactive Barriers (PRBs) designed to intercept and treat dissolved contamination as it migrates with groundwater; and 2) cell treatments (e.g., grids or multiple rows of injection points) designed to treat both mobile dissolved contaminants and relatively immobile sorbed/residual contaminants. The effectiveness of the PRB design was shown successfully at the demonstration site in Elkton, MD in the first part of this ESTCP project (ESTCP 2006b, 2008). Area treatment of chlorinated solvents is evaluated in this Technical Report.

4.1 Test Site Description

Based on the site-selection criteria described in the Technology Demonstration Plan (Solutions-IES, 2004), the Naval Weapons Station (NWS) in Goose Creek (near Charleston), South Carolina was selected as the test site for this demonstration. More specifically, the project was performed within a chlorinated solvent plume in an area designated as Solid Waste Management Unit (SWMU 17). **Figure 4-1** shows the location of SWMU 17 relative to the NWS. The following sub-sections briefly describe the site history and characteristics.

The following information is taken from the *RCRA Facilities Investigation Work Plan for Old Southside Landfill – SWMU 16 and Old Southside Missile and Waste Oil Disposal Area* – (Tetra Tech, 2001):

"SWMU 17 is located in the southern part of NWS… The site is rectangular in shape and reportedly 180 feet long and 90 feet wide. However, the actual size is suspected to be larger. The site was used primarily for surface disposal of solid waste between 1950 and 1978, but oils and missile components were also disposed at the site. Solid wastes observed across the site during the Initial Assessment Study (IAS) in 1984 included rubble, paint cans and buckets, and missile components. A Thorium-alloy missile nose cone exhibiting low-level radioactivity was removed from the site following the onsite survey of the IAS. An estimated 3,000 to 4,000 gallons of engine oil were disposed of at the site between 1965 and 1966…."

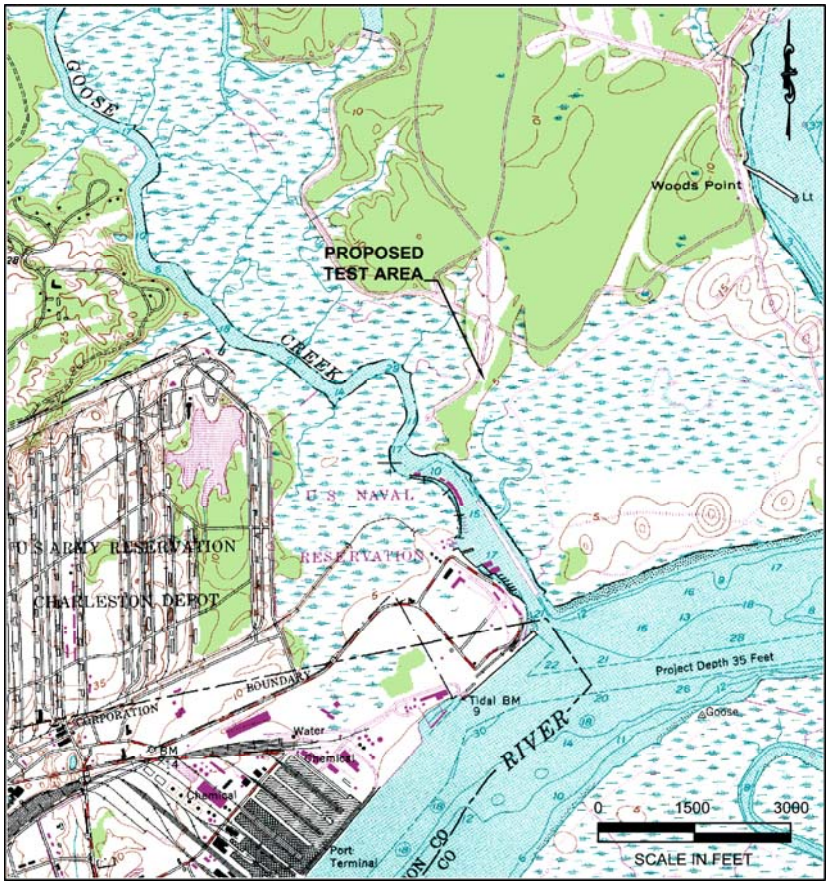


Figure 4-1. Location of Pilot Test Area at Charleston NWS, Charleston, SC

4.2 Hydrogeologic Framework of the Test Site

Portions of NWS have been extensively investigated to address environmental conditions at SWMUs 12, 16 and 17. The general hydrogeologic framework of the area consists of 20 to 25 feet of undifferentiated Quaternary age sands, silts, and clays of the Wando Formation that rest on undifferentiated Tertiary age marine sediments of the Cooper Group. The Cooper Group sediments are estimated to on the order of 200 feet thick in the Charleston, SC area (Siple, 1957). The surficial aquifer is contained within the Quaternary sediments. The top of the surficial aquifer may be partially confined in some areas by near-surface clays. The Cooper River marl (top of the Cooper Group) defines the base of the surficial aquifer; its high fines content acts as a regional aquiclude and restricts further downward movement of shallow groundwater.

Figure 4-2 shows the approximate location of the demonstration test cell compared to nearby site features. SWMU 17 is bordered on the west by Goose Creek and on the south and east by a small stream tributary to Goose Creek. The small circle shown in the figure represents the approximate location of test cell.

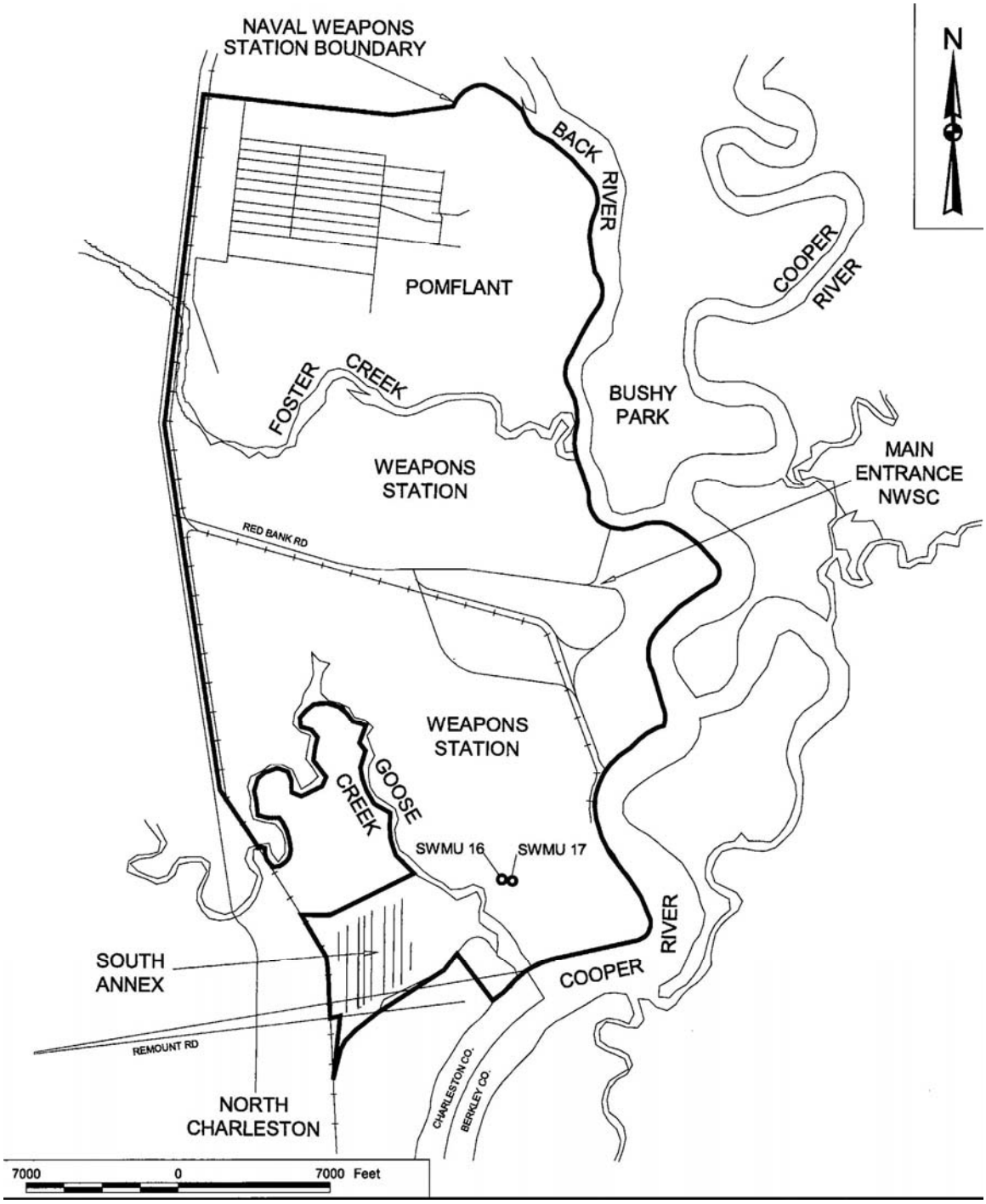


Figure 4-2. Location of SWMU 17 and Nearby Site Features

Some tidal fluctuations of groundwater levels have been reported in monitoring wells close to Goose Creek and the Cooper River (Tetra Tech, 2001). But, in general, the groundwater potentiometric surface beneath the portion of SWMU 17 identified for this pilot study is relatively flat with minimal tidal influence. The depth to the water table varies seasonally in response to precipitation and evapotranspiration and typically ranges between 0.5 foot and 6 feet below ground surface (ft bgs). Aquifer tests performed at SWMU 12, located 2 miles north, suggest the hydraulic conductivity of the surficial aquifer is low, on the order of 1 to 10 ft/d (Vroblesky, 2007). The relatively low hydraulic conductivity combined with a nearly flat gradient, suggest groundwater flow velocity is also low, in the order of 1 to 5 ft/yr.

An aerial photograph of the proposed test area is shown in **Figure 4-3**. The pilot study location is on the east side of the utility easement that bisects the wooded area in the center of the photograph. The test site vicinity is wooded, low lying, nearly flat and borders a wetland area to the east. The small stream tributary to Goose Creek is east-southeast of the proposed test area.

Figure 4-3. Aerial Photograph of Area Showing Pilot Test Location
(Source: TeleAtlas, 2008**)**

4.3 Contaminant Distribution

The Southern Division Naval Facilities Engineering Command (SOUTHDIV) has performed extensive characterization of SWMU 17. A tree-coring survey indicated that shallow groundwater in the southern portion of SWMU 17 was contaminated with TCE and a TCE plume was migrating to the east towards the Cooper River (Vroblesky, 2008). The TCE source area was then further delineated through installation of 21 temporary wells. TCE monitoring results from the area immediately adjoining the pilot test cell are shown in **Figure 4-4** and indicated up to 95,000 µg/L of TCE (Tetra Tech, 2004). Additional assessment was performed using the Membrane Interface Probe (MIP). The highest concentrations in the source area were present in a relatively small area in the southern portion of SWMU 17, south of the proposed pilot test cell. Relevant historical groundwater data from 17MIP16 and 17MIP21 are summarized in **Table 4-1**.

Table 4-1
Historical Groundwater Concentrations in the Vicinity of the Pilot Test Cell at SWMU 17, Naval Weapons Station, Charleston, SC

Volatile Organic Compounds (µg/L)	17MIP16 (4/26/03)	17MIP21 (4/26/03)
Tetrachloroethene (PCE)	0.7 J	1 J
Trichloroethene (TCE)	2,600 J	7,000 J
Cis-1,2-Dichloroethene	460 J	200
Trans-1,2-Dichloroethene	<5	8
Vinyl Chloride	7	6
1,1,2,2-Tetrachloroethane	13	140
1,1,2-Trichloroethane	40	62
1,1-Dichloroethene	5 J	4 J
Chloroform	24	12
Dichlorodifluoromethane	<5	<5
1,1,2-Trichlorotrifluoroethane	18	4 J
Benzene	16	2 J
Toluene	0.2 J	0.4 J
Total Xylenes	<5	0.5 J

Source: TetraTech, 2004
J = Estimated concentration reported by laboratory

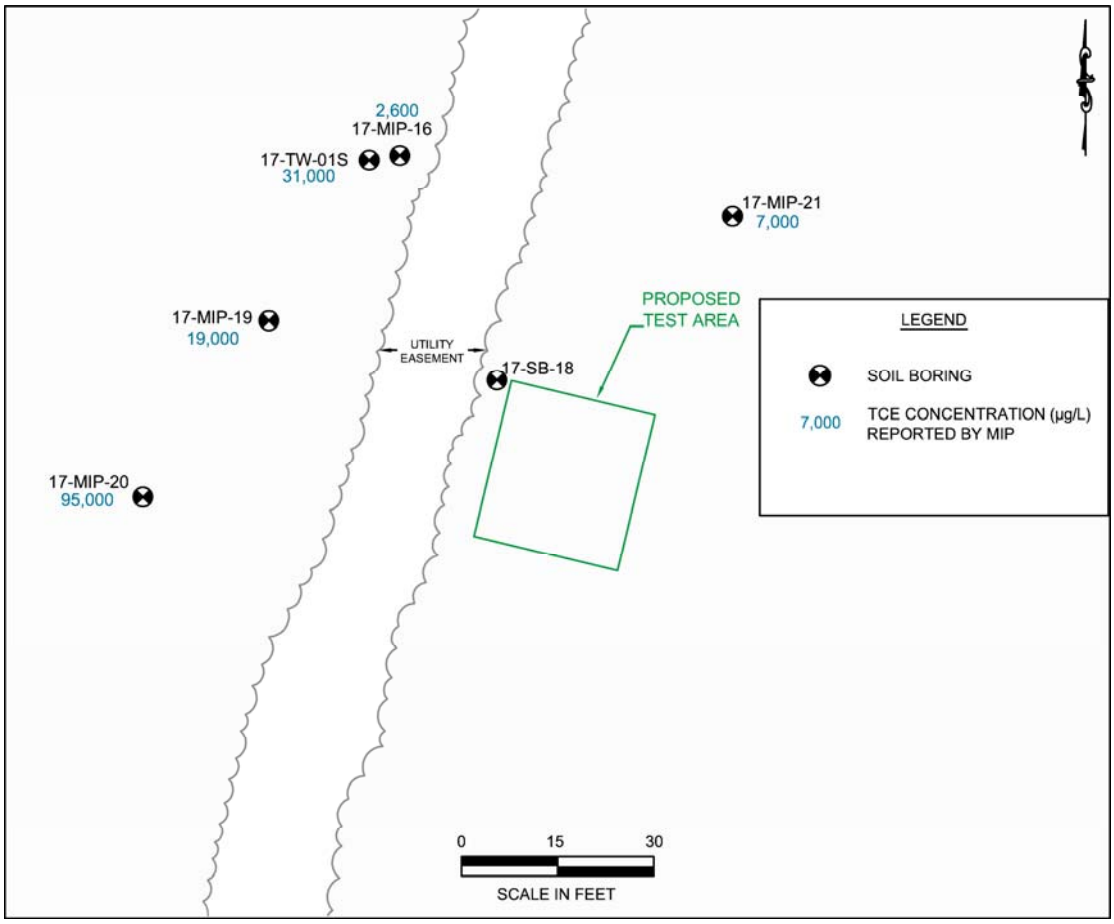


Figure 4-4. Location of Proposed Test Cell Relative to Concentrations of TCE in MIP Borings Collected in April 2003 along Utility Easement at SWMU 17

4.4 Conceptual Design and Monitoring

Although simple in concept, the implementation of a treatment grid requires a thorough understanding of the subsurface geology and hydrogeology to maximize the potential for success. Solutions-IES carefully evaluated the site conditions at SWMU 17 and evaluated several different alternatives for emulsion injection.

In most projects, the concentrated emulsion is diluted with potable (or other uncontaminated) water and injected either by high pressure injection through direct push rods as the rod is withdrawn; or low pressure injection through temporary or permanent wells. With both methods, additional chase water may be injected to push the emulsion away from the injection points or wells. However, injection of large volumes of uncontaminated potable water has the potential to dilute site contaminants, making data interpretation more difficult.

An alternative approach is to dilute the concentrated emulsion with site groundwater and to recirculate this solution through the target treatment zone using a system of injection and extraction wells. A major advantage of this approach is that very little uncontaminated water is injected, dramatically reducing the potential for dilution of the groundwater contaminants.

However, injection rates are limited by the rate that groundwater can be extracted. In some cases, this can greatly extend the time required for emulsion injection.

At SWMU 17, the groundwater velocity is low (1 to 5 ft/yr) and dilution effects could persist for an extended time period, complicating data interpretation. Consequently, a recirculation system was used to help distribute emulsion throughout the target treatment zone while minimizing injection of off-site water. The target treatment zone consisted of a 20 x 20 ft test cell as shown on **Figure 4-4**. Contaminant concentrations are highest at between 8 and 16 ft bgs in this cell, in a moderate to lower permeability silty sand layer. As described in the Technology Demonstration Plan for the site (Solutions-IES, 2004), the injection system consisted of a grid of 16 temporary 1-inch diameter injection/extraction wells installed using direct push methods, approximately 5-ft on-center (OC) across the test cell. During the injection process, groundwater was extracted from eight of the wells, amended with EOS® concentrate, and injected in the other half. Once half of the EOS® was injected, the former injection wells were converted to extraction wells and the process was reversed. Underground Injection Control Permit #741 was approved by the SCDHEC on April 26, 2004 permitting the use of 16 Class VA-I (Aquifer Remediation) injection wells at the site.

The Technology Demonstration Plan also described installing up to 12 additional monitoring wells to monitor impact of the emulsified oil treatment upgradient (3 wells), within (2 wells), and downgradient (7 wells) of the treatment cell. As described in Section 7.4.4, twelve temporary direct push wells were installed surrounding the test cell approximately six months after EOS® injection. Monitoring data showed TCE was significantly reduced within the pilot test cell. However, there was little or no evidence of downgradient impacts from the EOS® injection. This was not surprising given the low groundwater velocity at the site. Based on the low groundwater velocity and absence of measureable impact in temporary direct-push wells, the monitoring network was modified to include three background monitor wells located west of the treatment cell along the edge of the power line easement, and three monitor wells within the treatment cell. No wells were installed east (presumably downgradient) of the treatment cell.

Several steps comprised the performance monitoring activities. During the injection process, pressures and flow rates were recorded and adjusted to try to optimize the injection process. After the EOS® was distributed, soil and groundwater sampling was performed periodically to evaluate the distribution of the emulsion away from the injection points. Hydraulic conductivity and groundwater elevation measurements were collected throughout the study to observe the impact of the treatment on the groundwater flow regime. Changes to contaminant concentrations, groundwater geochemistry, and microbial communities were also determined. The results obtained from samples within the test cell were compared to baseline conditions prior to injection and background locations.

The Technology Demonstration Plan for the site called for the monitoring to last approximately 18 months. However, data collected during the first 18 months of this project suggested that changes to conditions within the treatment cell had resulted in a decrease in pH and a reduction in anaerobic reductive dechlorinating bioactivity. As a result, the project was extended to allow for new laboratory testing, and subsequently, additional field testing to evaluate methods of correcting the apparent low pH problem and monitoring the impact of the approach.

Parallel to conducting the laboratory treatability study, an additional 10 months of monitoring occurred, thus carrying the original performance monitoring program to 28 months. The solution to the pH problem that was developed in the laboratory treatability study was implemented by injecting a newly-formulated buffered emulsified oil substrate product into the treatment grid. The Underground Injection Control permit to inject the buffered oil product was approved on August 21, 2006. Twenty locations were chosen throughout the test cell for pressurized direct high pressure injection (via Geoprobe® injection tool) of a dilute suspension of the buffered emulsion.

The baseline characterization of the test site is described in Section 5.0. Because the project was extended beyond the original schedule proposed in the Technology Demonstration Plan, the performance evaluation was conducted in two phases. Details on the initial Phase I emulsion injections are provided in Section 6.1. The laboratory studies conducted to help design the injection strategy for the buffered emulsion are described in Sections 6.2 and 6.3. Section 6.4 provides information on the start of Phase II including injection of the buffered emulsion. The performance monitoring results from both Phase I (the first 28 months) and Phase II (the last 12 months) are discussed in Section 7.0 of this report.

5.0 Baseline Characterization

The tentative location for the pilot study was selected based on historical information about and site accessibility. Before selecting the final location of the test cell, several tasks were completed to confirm suitability of the location and establish site conditions. The baseline characterization activities conducted between February and April 2004 are described in the following sections.

5.1 Soil Characterization

Prior work at SWMUs 16 and 17 by Base contractors described sediments in the vicinity of as generally consisting of 5 to 8 ft of silty sandy clay to sandy silt underlain by 8 to 10 ft of silty sand. This is then underlain by 8 to 18 feet of silty clay with shell fragments throughout. The Cooper Group sediments were identified below a depth of approximately 26 ft bgs.

Several investigative steps were taken to obtain a pre-injection baseline characterization of site-specific soil conditions to optimize placement of the treatment cell. These are discussed in the following sub-sections.

5.1.1 Lithology and Contaminant Profiles

5.1.1.1 Membrane Interface Probe (MIP) Assessment

The MIP is a soil logging tool developed for commercial use by Geoprobe® Systems of Salina, KS. The tool is used to determine lithology and relative contaminant concentrations in soil (Christy, 1996). The MIP contains a soil electrical conductivity probe, thermistor, heating element, and permeable membrane that is in contact with nitrogen carrier gas. As the MIP tip is pushed into the subsurface, VOCs penetrating the membrane are carried by the gas past a series of three detectors used to estimate VOC concentrations. Electrical conductivity is used to estimate soil type; fine-grained soils usually have higher conductivity values than sandy soils.

The initial MIP investigation was performed at SWMU 17 in conjunction with tree core sampling as reported by Vroblesky (2008). The MIP investigation found evidence of elevated concentrations of VOCs (later identified as TCE) in groundwater underlying the southern portion of SWMU 17.

Solutions-IES contracted with Columbia Technologies of Baltimore, MD to conduct a limited MIP evaluation in the vicinity of the proposed treatment cell. The objective of the MIP investigation was to identify an area with relatively high VOC concentrations that would be accessible for emulsion injection and sampling. On February 27, 2004, six MIP points were installed on 20-foot centers along the east side of the utility easement bisecting SWMU 17. **Figure 5-1** shows the MIP locations (17PSMIP-01 through -06) along the easement and the eventual location of the treatment cell. The MIP data for 17PSMIP-01 through 17PSMIP-06 are provided in **Appendix I** and show a vertical series of six responses. The

top-most response curve shows soil conductivity. The response curve second from the top shows probe penetration rate into the subsurface. The small dips are where Geoprobe® rods were added to advance the boring deeper. The third response shows the photoionization detector (PID) response. The fourth curve shows flame ionization detector (FID) response. The fifth curve shows electron capture detector (ECD) response and the bottom response shows probe temperature. Temperature is maintained above 100 °C to volatize any VOCs present into the carrier gas for detection.

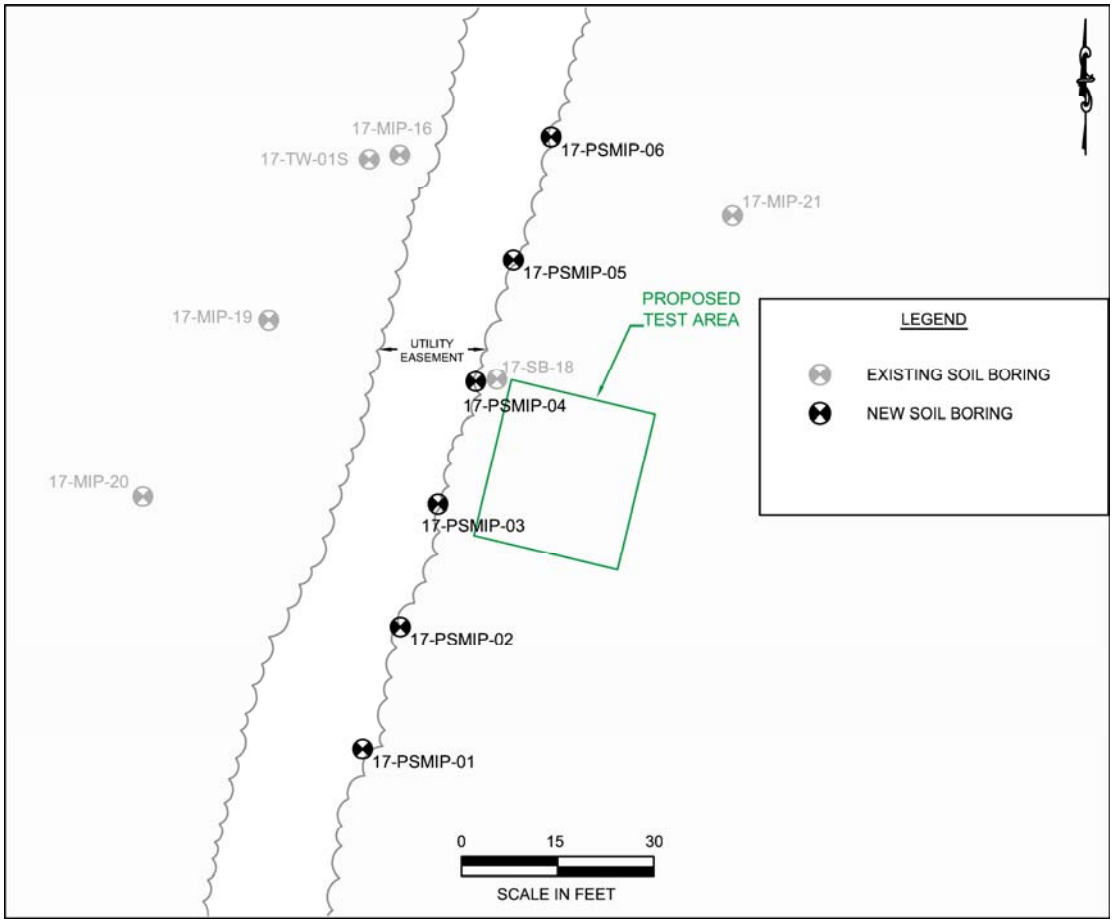


Figure 5-1. Location of New MIP Borings along Utility Easement

In general, the logs for 17PSMIP-01 through 17PSMIP-06 are similar. Soil conductivity increases to a maximum value between 9 and 10 ft bgs, then decreases to the termination depth of the borings (19 to 23 ft bgs). This is inferred to represent a more clayey horizon occurring between 8 and 12 feet with more sandy soils overlying and underlying this zone. The PID, FID and ECD responses are also similar among the six logs, showing one large or two smaller spikes occurring between 6 and 8 ft bgs. The largest response was noted for the ECD at 17MIPS-03 where the top of the response is truncated. The ECD response also shows a wide sweeping response below 8 feet extending to 16 to 19

ft bgs. The deeper response was generally not reflected in the FID or PID response curves, with the exception of 17PSMIP-04 where it is identical to the ECD response. Based on the MIP data, the highest VOC concentrations appear to occur within a depth interval of 6 to 9 ft bgs.

5.1.1.2 Soil Assessment

Using historical groundwater data along with the MIP data, and taking equipment accessibility into account because the areas beside the easement are heavily wooded, the treatment cell location was finalized. Columbia Technologies used a Geoprobe® to advance four soil borings to 20 ft bgs in the corners of the anticipated treatment cell. These borings were designated as 17PSI-1, 17PSI-4, 17PSI-13 and 17PSI-16 (**Figure 5-2**).

Soil samples were obtained from Macro-Core® sampler sleeves. Continuous soil samples from each boring were placed in re-sealable plastic bags to allow volatile vapors to equilibrate into the headspace of the bag. After approximately 20 minutes, the headspace of the bag was scanned by inserting the tip of a hand-held PID into the bag. The PID results are shown **Table II-1** in **Appendix II.**

Selected sub-samples from three depths in each boring, chosen to broadly cover intervals from 5 to 8 ft bgs, 9 to 12 ft bgs and 14 to 18 ft bgs, were collected in laboratory-supplied bottles and submitted to Prism Laboratories Inc. in Charlotte, NC (Prism Labs) to be analyzed for VOCs by EPA Method 8260, and total organic carbon (TOC) by EPA Method 415. The results confirmed the presence of TCE and virtually no *cis*-DCE or VC in the soil. Concentrations of TCE ranged from 3.1 to 14 mg/kg in depths ranging from 5 to 16 ft bgs. TOC concentrations ranged from 190 to 1880 mg/kg throughout the soil profile. The four preliminary borings were abandoned after collection of the soil samples.

After evaluating the MIP, VOC and TOC data from the initial four borings, the final test cell location was confirmed. Between March 22 and 25, 2004, installation of the test grid commenced and 18 soil borings were advanced by direct push drilling throughout the test cell. Work was performed by Gregg Drilling Co. of Columbia, SC. Four of the borings were located close to the first four borings that were installed and abandoned on March 1, 2004; these were given the same designations (i.e., 17PSI-1, 17PSI-4, 17PSI-13 and 17PSI-16). Twelve additional borings (designated 17PSI-2, 3, 5 through 12, 14 and 15) were arranged in a grid pattern approximately 5 ft OC in both a north-south and east-west direction to create the 20 ft x 20 ft test cell **(Figure 5-2**). These borings penetrated the aquifer to approximately 20 ft bgs; all were converted to 1-inch diameter injection wells for later use (See Section 5.2 below). Two other borings (17PSG-1 and 17PSG-2) were terminated above the water table for soil gas monitoring as discussed in Section 5.1.2 below.

During this mobilization, three other borings (PS-series) were emplaced centrally in the treatment cell. These were drilled using hollow stem augers; some split-

spoon samples were collected for analysis. These borings were designated as 17PS-1, 17PS-2 and 17PS-3 and were later converted to 2-inch diameter monitoring wells with the same identification as discussed in Section 5.2 below. The locations of all the borings that were emplaced in the test cell were located by survey and are shown on **Figure 5-2.**

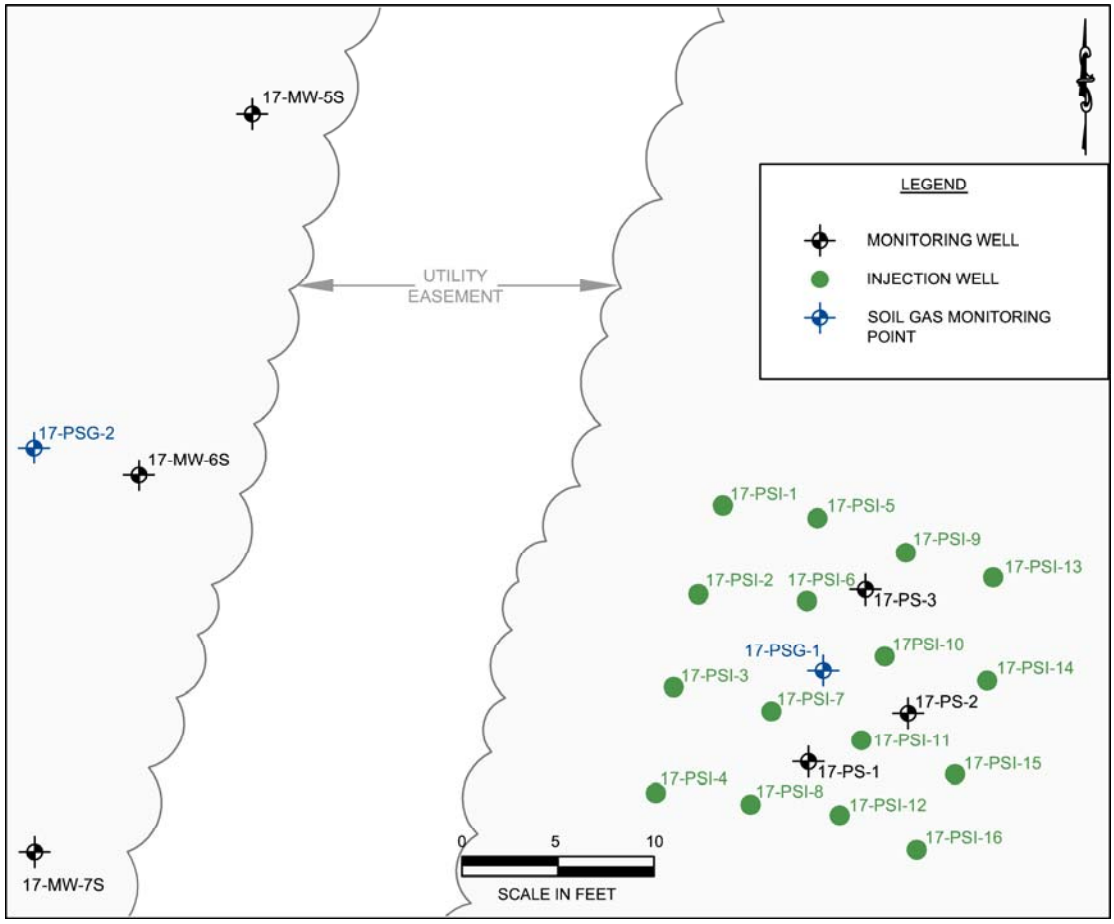


Figure 5-2. Treatment Cell Layout for Phase I.
(Soil and groundwater sampling locations use the same designations.)

Soil samples were collected for characterization from different depths in multiple borings. Samples from each depth interval were screened with the PID as described above. Results of the pre-injection PID screening are provided on the boring logs in **Table II-1** in **Appendix II**. Soil samples from one depth in seven of the 16 borings, two depths from 17PSI-16, and 10 continuous 1-foot depth intervals ranging from 8 to 18 ft bgs in boring 17PSI-06 were placed in bottles and transported to Geotechnologies Inc. of Raleigh, NC (Geotechnologies) for grain size and clay content analysis. Aliquots of these same samples were also placed in laboratory-supplied bottles and shipped on ice, under chain-of custody control, to Prism Labs for VOC (including TCE and chlorinated aliphatic

hydrocarbons [CAHs]) and TOC analyses. The results of the baseline soil sampling activities are provided on **Table 5-1.**

Table 5-1
Pre-Injection Soil Analytical Data
SWMU 17, Naval Weapons Station
Charleston, SC

Sample Location	Sample Date	Sample Depth	TCE (mg/kg)	Total CAHs (mg/kg)	Hexane Extractables (mg/gm)	Clay Content (%)	Total Organic Carbon (mg/kg)
17PSI-2	3/25/04	8-10	9.9	9.9	<0.10	19	280
17PSI-3	3/25/04	10-12	10.0	10.0	<0.10	18	82.5
17PSI-5	3/25/04	8-10	NA	0	<0.10	21	405
17PSI-6	3/25/04	8-9	9.0	9.0	<0.10	23	450
	3/25/04	9-10	9.1	9.1	<0.10	30	190
	3/25/04	10-11	5.3	5.3	<0.10	21	240
	3/25/04	11-12	9.8	9.8	0.12	17	125
	3/25/04	12-13	9.0	9.0	<0.10	21	180
	3/25/04	13-14	7.2	7.2	<0.10	16	110
	3/25/04	14-15	5.8	5.8	0.13	15	<1.0
	3/25/04	15-16	5.9	5.9	<0.10	13	130
	3/25/04	16-17	8.7	8.7	<0.10	15	785
	3/25/04	17-18	5.9	5.9	<0.10	14	2,115
17PSI-8	3/24/04	10-12	5.0	5.1	<0.10	19	430
17PSI-9	3/25/04	16-18	3.2	3.2	<0.10	10	150
17PSI-14	3/24/04	12-14	7.2	7.3	<0.10	18	190
17PSI-15	3/24/04	10-11	6.5	6.6	<0.10	9	<1.0
17PSI-16	3/24/04	6-8	11.0	11.2	<0.10	50	500
	3/24/04	8-12	13.0	13.3	<0.10	23	590

The data were examined to assess the relative change in TOC, concentration of TCE and clay content with increasing depth. **Table 5-1** indicates that clay content ranged from 9 to 30 % (with one outlier at 50%). There appears to be a slight decrease in clay content with increasing depth within the silty sand layer.

Figure 5-3 illustrates the results from boring 17PSI-01 that represent the typical lithology underlying the treatment cell and the relative location of TCE throughout the profile. The lithology was interpreted using the MIP and grain size along with the hydrogeologic descriptions from the boring logs. It shows that the test cell is underlain by 1 to 2 feet of highly organic (peat) soil typical of low lying woodlands. This is underlain by approximately 8 feet of clay or clayey sand (50 % clay). Most borings noted the upper

few feet of the clay was orange to tan in color. The color transitioned to green-tan color (typical of saturated soils) between 7 and 8 ft bgs. Below 8 feet, soils were predominately tan to light gray silty clayey sand (clay content of 10 to 30 percent) to a depth of approximately 18 ft bgs where the borings were terminated. The TCE concentrations with depth in this boring are as listed on **Table 5-1** and shown on **Figure 5-3** along with several other borings.

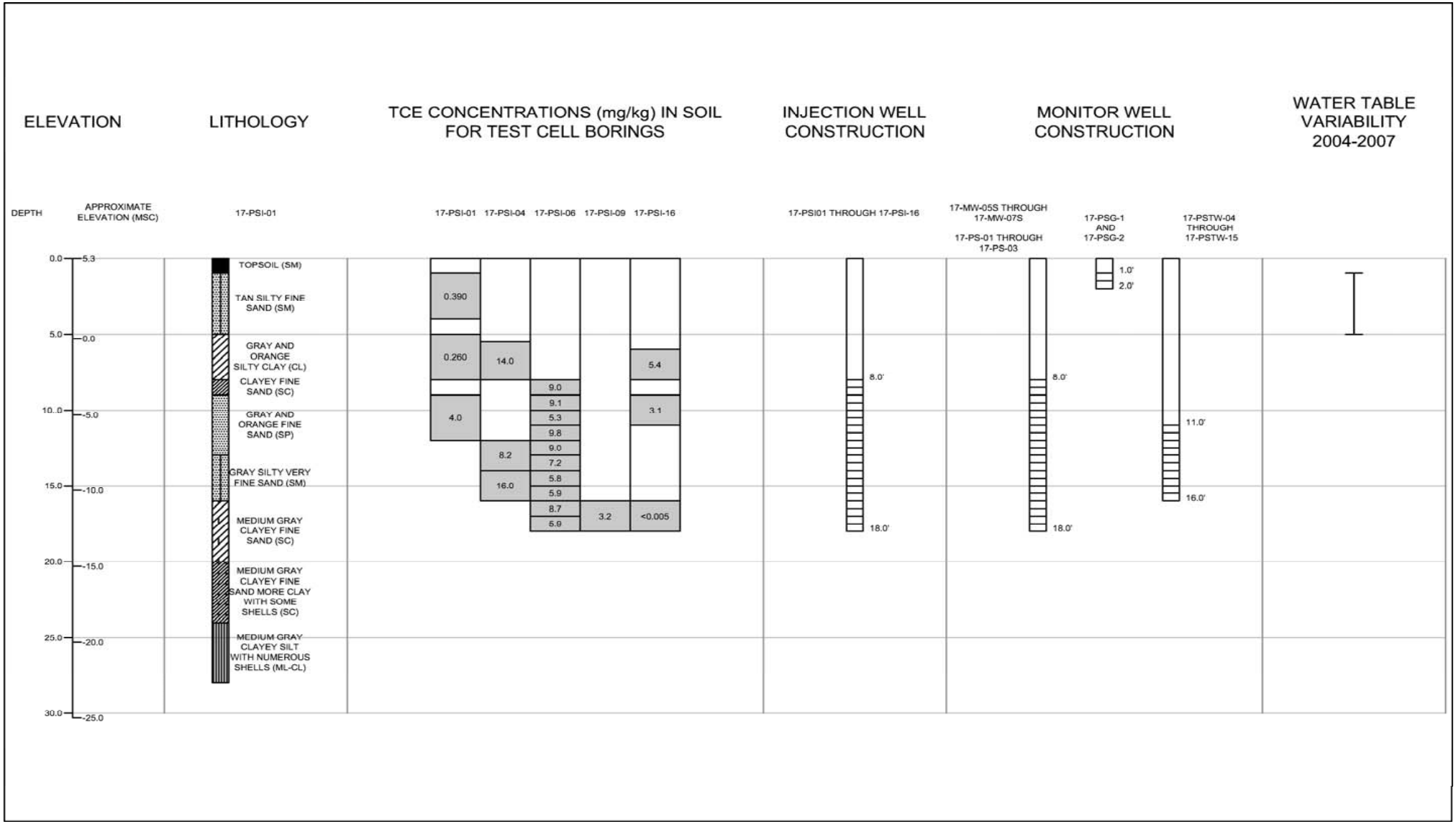


Figure 5-3. Typical Lithology and TCE Contamination Profile Underlying the Pilot Test Cell

Figure 5-4 further illustrates the range of TCE concentrations at various depths using the data obtained from soil samples prior to treatment. Overall, TCE concentrations in soil ranged from below detection to 16 mg/kg with an average of 7.5 ± 3.7 mg/kg (n = 30).

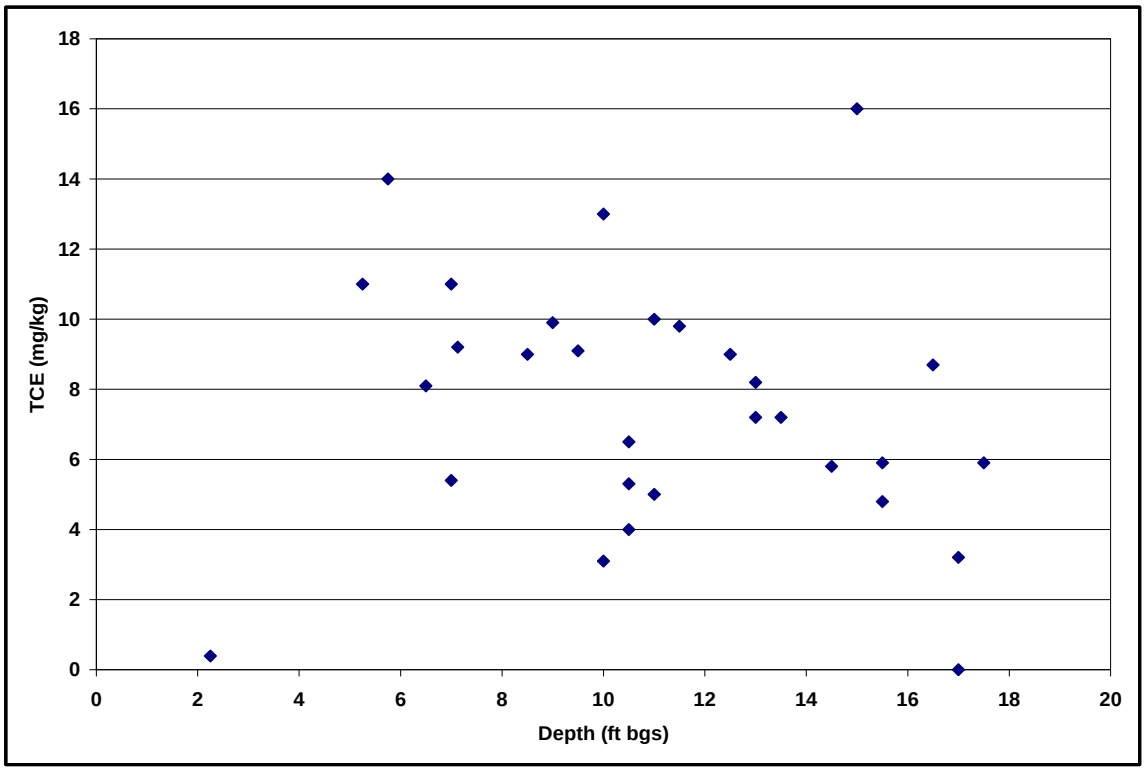


Figure 5-4. Trichloroethene Concentration in Soil vs. Depth

TCE concentrations plotted on the profiles suggest that concentrations vary with depth and do not follow any consistent pattern. This agrees with the FID, PID and ECD response curves from the MIP assessment. The relatively consistent TCE concentrations throughout the vertical profile identified in 17PSI-6 seem to support the wide response curves of the ECD for this depth interval noted on several MIP logs (**Appendix I**). The PID measurements (**Appendix II**) across the vertical profile below 6 ft bgs were fairly similar suggesting uniform smearing of TCE throughout the shallow aquifer. However, the response curve for soil conductivity doesn't correlate well with the boring logs as the logs suggest clay soils extend from 1 foot to approximately 8 feet and the conductivity log suggests soils are more clayey from 6 to 8 ft bgs.

Figure 5-5 shows that TOC throughout the soil column is generally below 500 mg/kg until 15 to 16 ft bgs. TOC increases dramatically below 16 ft where the Cooper marl is encountered.

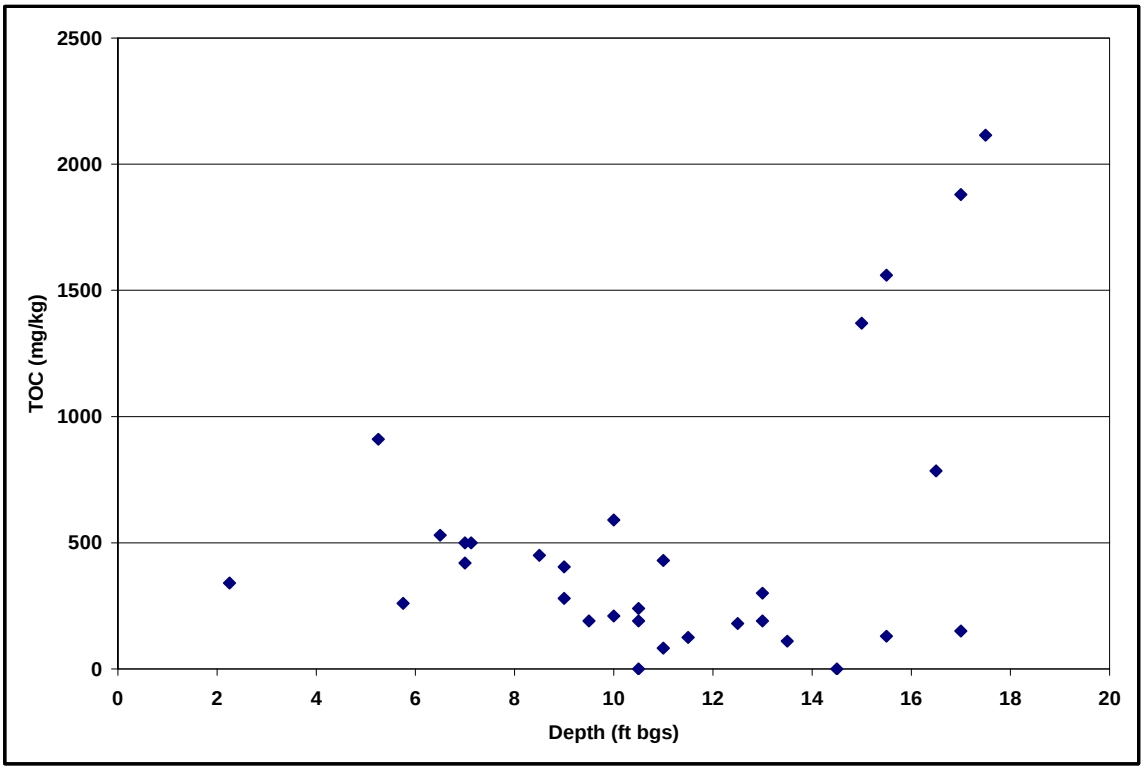


Figure 5-5. Total Organic Carbon in Soil vs. Depth

5.1.2 Soil Gas Assessment

As noted in **Section 5.1.1.2** above, the two soil-gas monitoring points were constructed by advancing borings to approximately 3 ft bgs and installing a 1-foot section of slotted screen attached to solid riser to the top. As shown in **Figure 5-2,** 17PSG-1 was located in the pilot study grid and 17PSG-2 was located across the utility easement, away from the treatment zone. The soil gas monitoring points were completed with a sand pack and bentonite seal. The monitoring point headspace was analyzed in the field for percent lower explosive limit (LEL), percent oxygen, hydrogen sulfide (H_2S), and carbon monoxide (CO) using a 4-gas meter (VRAE Model PGM-7800). Baseline soil gas samples were collected on May 11, 2004, prior to any emulsion injection. In 17PSG-1 the LEL was 4%, carbon monoxide was 1 ppm, hydrogen sulfide was 0 ppm and oxygen was 18.8 %. The headspace in each of the monitor and injection wells was also analyzed for LEL, oxygen, H_2S and CO levels during most performance monitoring events.

5.2 Groundwater Characterization

In March 2004, three new 2-inch diameter shallow monitor wells (17MW-5S, 17MW-6S and 17MW-7S) were installed by TetraTech NUS, under direct contract with the Navy. These wells were placed to serve as background control wells to compare with the treatment cell findings. The wells are positioned inside the yellow bollards visible on the left side of the photograph in **Figure 5-6**. The test site is to the right of the vehicle.

Figure 5-6. Photograph of Background Monitor Wells across the Utility Easement from the Treatment Cell. (Photograph is looking North.)

As described in Section 5.1.1.2 above, between March 22 and 25, 2004, 21 borings were installed within the treatment cell. Borings designated 17PSI-1 through 17PSI-16 were located approximately 5-ft OC to provide a grid covering the 20 ft x 20 ft test cell (**Figure 5-2).** These borings penetrated the aquifer to approximately 18 ft bgs. These 16 borings were converted to injection wells by adding 2 ft of #2 filter sand into the hole followed by 10 feet of 0.010-slotted 1-inch diameter polyvinyl chloride (PVC) well screen in order to bracket the 8 to 18 ft bgs groundwater interval. More sand was added surrounding the screen. Each well was completed with a 10-ft section of 1-inch diameter PVC riser to the surface and secured with a bentonite seal and a flush-mount finish.

Hollow-stem auger borings 17PS-1, 17PS-2 and 17PS-3 were also advanced to 18 ft bgs and converted to monitor wells by emplacing 2 ft of sand in the hole followed by 10 ft of 0.010-slotted 2-inch diameter PVC well screen from 8 to 18 ft bgs and 10 ft of PVC riser to the surface. These wells were finished with aboveground standpipes.

The final two borings were constructed to provide soil gas monitoring points as discussed in Section 5.1.2 above. A photograph of the three monitor wells, soil gas point 17PSG-1 and several injection wells is provided in **Figure 5-7.** The general information regarding the construction of the various types of wells installed for the pilot test is illustrated in **Figure 5-3**. The locations of the wells were surveyed by Palmetto Land Surveyors, a South Carolina licensed firm.

Figure 5-7. Photograph of Test Cell Showing Typical Monitor and Injection Wells (Three monitor wells and one soil gas monitoring point have above ground protective casings; injection wells are finished with flush-mount manhole covers. Two bollards are located on the left and right at the rear corners of the cell.)

5.2.1 Groundwater Flow Direction and Gradient

Well construction and survey data are presented in **Table 5-2** along with water table elevations measured in the wells in the afternoon of March 30, 2004. There are two trends in the data set shown in **Table 5-2**. One subset of wells, including injection wells 17PSI-1, 17PSI-5 and 17PSI-9, show a water table elevation of approximately 3.45 to 3.47 feet above mean sea level (ft amsl). These three wells are all located along the north edge of the treatment cell (**Figure 5-2**). The remaining 16 wells in the treatment cell and the three background monitor wells all have water table elevations ranging from 2.04 to 2.12 ft amsl.

The background monitor wells show the clearest and most consistent change in the water table surface dipping from 2.10 ft amsl in the northern-most well (17MW-5S) to 2.05 ft amsl in the southern-most well (17MW-7S). Water levels within the treatment cell are more variable. If the three wells along the north side of the treatment cell are assumed to be influenced by perched water conditions and are ignored, and the water table elevations for the remaining 16 wells in the treatment cell are averaged, the average is 2.084 ft amsl.

Table 5-2
Well Survey and Baseline Groundwater Elevation Data for March 30, 2004
SWMU 17, Naval Weapons Station
Charleston, SC

Well ID	Northing	Easting	Ground Surface Elevation (ft amsl)	Top of Casing Elevation (ft amsl)	Groundwater Elevation Pre-Injection (ft amsl)
17MW-5S	397272.7887	2321215.29	4.95	7.77	2.10
17MW-6S	397253.9852	2321209.39	5.23	7.89	2.08
17MW-7S	397234.3491	2321203.959	5.18	7.93	2.05
PSI-01	397252.4063	2321239.796	6.18	8.19	3.45*
PSI-02	397247.779	2321238.521	4.69	6.83	2.07
PSI-03	397242.9505	2321237.232	4.79	6.86	2.06
PSI-04	397237.4408	2321236.303	4.82	6.77	2.07
PSI-05	397251.7482	2321244.718	6.11	8.12	3.47*
PSI-06	397247.4348	2321244.172	4.84	7.15	2.11
PSI-07	397241.6953	2321242.324	4.98	6.74	2.05
PSI-08	397236.8438	2321241.237	4.95	6.89	2.04
PSI-09	397249.9361	2321249.322	6.04	8.07	3.45*
PSI-10	397244.5505	2321248.223	4.80	6.66	2.09
PSI-11	397240.1693	2321247.006	4.89	6.87	2.09
PSI-12	397236.2913	2321245.878	4.73	6.87	2.08
PSI-13	397248.6439	2321253.862	4.68	6.70	2.09
PSI-14	397243.2775	2321253.556	4.90	7.18	2.08
PSI-15	397238.4016	2321251.888	4.90	6.94	2.10
PSI-16	397234.4705	2321249.89	4.72	6.79	2.09
17PS-01	397239.0561	2321244.25	6.29	9.36	2.12
17PS-02	397241.5962	2321249.443	6.35	9.31	2.12
17PS-03	397248.0191	2321247.222	6.19	9.22	2.09
17PSG-1	397243.802	2321244.993	6.20	9.25	Dry (Soil gas point)
17PSG-2	397255.4217	2321203.9	5.28	7.82	Dry (Soil gas point)

Notes: Water table elevation believed to be influenced by perched water table condition
ft amsl = feet above mean sea level

Plotting the average water surface elevation at the center of the test cell and comparing the elevations for the three background wells suggests the water table has a gentle slope to the south. This hypothesis was checked by averaging groups of two to five wells arranged in a west-east orientation (normal to groundwater flow) as a check. Wells 17PSI-2, 17PSI-6, 17PS-03 and 17PSI-13 average 2.09 ft amsl. Wells along the south side of the treatment cell (17PSI-4, 17PSI-8, 17PSI-12 and 17PSI-16) average 2.07 ft amsl. The average values are consistent with a north to south slope water table (groundwater flow direction). This suggests that at the time the water levels were measured on March 30, 2004, the background wells are actually positioned nearly parallel to groundwater flow. Dividing the difference in water levels in 17MW-05S and 17MW-07S (0.05 ft) by the distance between the wells (40 ft) yields an approximate gradient of 0.0013 ft/ft. The very low gradient agrees with an estimated gradient of approximately 0.001 that was previously reported by Tetra Tech (2004) and would be expected in a coastal environment. The reader should note that the maximum difference in water table elevation is very small (0.08 ft) and is close to precision of the water table measurements. As such, there could be large relative errors in the computed water table gradient.

Previous work at SWMU 17 demonstrated groundwater levels are influenced by tidal stages. As such, groundwater flow direction should be anticipated to change progressively from east to south to west and back daily. Given the land surface topography, groundwater in the immediate vicinity of the treatment cell is expected to have a generally eastward flow direction and eventually discharge to the small stream tributary of Goose Creek that lies east of the cell.

5.2.2 Hydraulic Conductivity

Hydraulic conductivity was measured for most of the wells within the test cell. Monitoring wells 17MW-5S, 17MW-6S, 17MW-7S and 17PS-01, 17PS-02 and 17PS-03 were all constructed using 2-inch diameter PVC screens screened from approximately 8 to 18 ft bgs. The injection wells were constructed using 1-inch diameter PVC screens and risers also screened from approximately 8 to 18 ft bgs.

Aquifer testing, consisting of specific capacity and slug tests, was performed on selected wells before injection to establish baseline conditions. Data obtained from the specific capacity tests were reduced in accordance with Wilson et al. (1997). The slug tests were evaluated using the Bouwer and Rice model (Bouwer, 1989). The specific capacity test procedure and example worksheet are included in **Appendix III.**

Table 5-3 shows the results of the aquifer tests run between March 25 and May 11, 2004. Hydraulic conductivities measured in the 2-inch wells are an order of magnitude greater than those measured in the 1-inch wells. The difference is attributed to the 2-inch wells being installed with hollow stem augers and the screens having a better connection with the surrounding aquifer materials than the 1-inch wells. The 1-inch wells were installed with a Geoprobe®. Direct push boreholes often exhibit compaction and smearing of the borehole wall due to displacement of the soil during driving.

Table 5-3
Baseline (Pre-Injection) Hydraulic Conductivity Measurements
SWMU 17, Naval Weapons Station
Charleston, SC

	March 25, 2004	April 1, 2004	April 2, 2004	May 13, 2004	Baseline Average
Well ID	ft/day	ft/day	ft/day	ft/day	ft/day
Background Monitor Wells (2-inch diameter)					
17MW-5S	---	---	---	---	
17MW-6S	---	5.86	4.58	---	5.22
17-MW-7S	---	---	---	---	
Treatment Cell Injection Wells (1-inch diameter)					
17PSI-1	0.54	---	---	---	0.54
17PSI-2	0.63	---	---	0.51	0.57
17PSI-3	0.25	---	---	---	0.25
17PSI-4	0.38	---	---	0.36	0.37
17PSI-5	0.55	---	---	0.39	0.47
17PSI-6	0.39	---	---	---	0.39
17PSI-7	0.43	---	0.42	0.37	0.41
17PSI-8	0.34	---	---	---	0.34
17PSI-9	0.41	---	---	---	0.41
17PSI-10	0.37	---	---	0.32	0.35
17PSI-11	0.26	---	---	---	0.26
17PSI-12	0.39	---	---	0.31	0.35
17PSI-13	0.19	---	---	0.17	0.18
17PSI-14	0.40	---	---	---	0.40
17PSI-15	0.53	---	---	0.45	0.49
17PSI-16	0.42	---	---	---	0.42
Treatment Cell Monitor Wells (2-inch diameter)					
17PS-1	---	5.81	5.24	---	5.23
17PS-2	---	7.52	7.36	---	7.44
17PS-3	---	8.22	8.06	---	8.14

Notes: April 1, 2004 data is from slug tests. All other data are from specific conductivity tests

Comparison of specific capacity and slug tests performed on the same well shows that there is generally good reproducibility (78 to 98 percent agreement) between the two test methods with the specific capacity tests yielding values slightly lower than the slug tests for all cases.

- 2- Inch Diameter Background Monitor Well 17MW-06S:
    - Slug test value = 5.9 ft/d
  - 2-Inch Diameter Treatment Cell Monitor Wells (PS Series):
    - Slug test values = 5.8 to 8.2 ft/dy; avg. = 7.2 ft/d.

  - 1-inch Diameter Treatment Cell Injection Wells:
    - Spec. cap. test values = 0.17 to 0.63 ft/d; avg. of all values = 0.39 ft/d.

Slug tests have been shown to provide conservative hydraulic conductivity values when compared to pump tests. For this reason, the slug test data were used to calculate groundwater flow velocity. Using the specific capacity test results would be even more conservative.

Based on an assumed hydraulic gradient of approximately 0.001 ft/ft in the test cell, an average hydraulic conductivity value of 7.2 ft/d from slug tests in the 2-inch monitor wells and assuming an effective porosity of 24% for the saturated soil yields an annual groundwater flow velocity of approximately 11 ft/yr. These rates are slightly higher than those reported by Tetra Tech (2004), who calculated an average groundwater flow velocity for SWMU 17 from 1 to 5 ft/yr based on a hydraulic gradient of ~0.001 ft/ft and hydraulic conductivity of 1 to 3 ft/day. They are close to values calculated for groundwater flow at SWMU 12 where annual flow rates were estimated to be 7 to 11 ft/yr. Tritium and sulfur hexafluoride data for groundwater suggested groundwater flow rate was 5.9 ft /yr or slower (Vroblesky, 2007). The calculations for the pilot study cell may reflect more localized conditions, but nonetheless are in the same order of magnitude as those calculated by others. These results indicate that groundwater migrates very slowly in the pilot test cell and the that it could take several years before the effects of emulsified oil injection even a few feet beyond the limits of the initial injection zone are observed.

5.2.3 Contaminants and Biogeochemistry

Baseline groundwater sampling commenced on March 30, 2004. Groundwater was collected from background wells, the planned injection wells, and monitor wells in the test cell.

5.2.3.1 Groundwater Sampling and Analytical Methods

Purging and sampling protocols generally followed the procedures outlined in *Environmental Investigations Standard Operating Procedures and Quality Assurance Manual* (EISOPQAM, USEPA Region IV, 2000). Prior to the collection of groundwater samples, water levels were measured in each well using an oil/water interface probe. Wells were sampled with a peristaltic pump following low-flow sampling procedures. Sustained pumping at slow rates usually resulted in a relatively clear, low turbidity sample. Using low-flow procedures, an adequate purge was achieved when the pH, specific conductance, and temperature of the groundwater stabilized. The goals for stabilization were as follows:

- pH- Measurements remain constant within 0.1 Standard Unit (SU).
- Specific Conductance – Measurements vary by no more than 10 percent.
- Temperature – Measurements remain constant for at least three successive readings.

After an adequate purge was achieved, field measurements were recorded and groundwater samples were collected for analysis. The samples were collected in laboratory-prepared sample containers appropriate for the analytical method being used. The sample containers were immediately sealed, labeled, and placed on ice in an insulated cooler for subsequent delivery to the appropriate laboratory. Chain-of-custody forms accompanied all samples sent to the laboratory.

Groundwater samples were analyzed for chlorinated volatile organic compounds (CVOCs), electron acceptors (oxygen, nitrate, sulfate), electron donors (TOC), and indicator parameters (pH, ORP, phosphate, Fe^{+2}, ethene, ethane, methane, Cl^-, S^-). The sequence of sample collection for analysis was as follows:

1) Field parameters:
   a. Dissolved Oxygen (DO; field meter or Chemetrics Field Kit, Chemetrics, Calverton, VA)
   b. Oxidation-Reduction Potential (ORP; field meter);
   c. pH (field meter);
   d. Temperature (field meter);
   e. Specific Conductance (field meter);
   f. Ferrous iron (Fe^{+2}; Chemetrics field kit, Chemetrics, Calverton, VA);
   g. Sulfide (S^-; Chemetrics field kit, Chemetrics, Calverton, VA)

2) Laboratory parameters:
   a. Volatile Organic Compounds by Method 8260B [Prism Labs, Charlotte, NC];
   b. Ethene (C_2H_4), Ethane (C_2H_6), and Methane (CH_4) [Vapor Tech, Valencia, PA]
   c. Volatile Fatty Acids (VFAs) [Microbial Insights, Rockford, TN]
   d. TOC and Total Inorganic Carbon (TIC) by Method 415.1 [Prism Labs, Charlotte, NC];
   e. Nitrate, Nitrite, Sulfate, Phosphate, and Chloride by Ion Chromatography [Environmental Engineering Laboratory, North Carolina State University, Raleigh, NC]

5.2.3.2 Baseline Groundwater Conditions

The complete results of the analyses performed prior to beginning the remediation pilot test are provided in **Table IV-1** in **Appendix IV**. The baseline conditions

for key parameters are summarized below in **Table 5-4**. For comparison, the site conditions are presented as ranges reported for each indicated parameter in the three background wells (7MW-5S, 17MW-6S and 17MW-7S), the three permanent monitor wells directly in the test cell (17PS-01, 17PS-02 and 17PS-03), and four of the 16 temporary injection wells used to create the treatment grid (17PSI-2, 17PSI-7, 17PSI-10 and 17PSI-13). The results are consistent among the three groups of wells suggesting that these measurements are representative of site conditions. There is little evidence of ongoing natural attenuation with only minimal *cis*-DCE formation from TCE. There is no evidence of further conversion of *cis*-DCE to VC or ethene. Significant increases in the concentration of *cis*-DCE, VC or ethene would provide clear evidence for enhanced degradation of TCE resulting from emulsified oil addition.

Table 5-4
Summary of Site Conditions Prior to Addition of EOS®
(March 31 to April 1, 2004)
SWMU 17, Naval Weapons Station
Charleston, SC

Parameter	**Background Monitor Wells (n=3)***	**Test cell Monitor Wells (n=3)**	**Test cell Injection Wells (n=4)**
TCE (µg/L)	32,000 to 150,000	22,000 to 28,000	9,800 to 18,000
cis-1,2-DCE (µg/L)	230 to 610	190 to 260	170 to 410
trans-1,2-DCE (µg/L)	<50	<50	<50
Vinyl Chloride (µg/L)	<50	<50	<50
Ethene (µg/L)	0.45 to 0.80	0.40 to 0.48	0.5 to 1.36
Ethane (µg/L)	0.05 to 0.11	0.05 to 0.09	0.07 to 0.11
Methane (µg/L)	68 to 102	27.2 to 36.0	13.4 to 53.2
Volatile Fatty Acids (mg/L)$^{+}$	<4 (1 well)	<4 (1 well)	<4 (2 wells)
Dissolved Oxygen (mg/L)	2.8 to 3.0	0.4 to 1.5	1.5 to 4.7
Oxidation-Reduction Potential (mV)	+154 to +170	+158 to +178	+74 to +99
Nitrate (mg/L)	NM	NM	NM
Sulfate (mg/L)	19 to 32	58 to 78	59 to 103
Dissolved Iron (mg/L)	0.41 to 3.0	50 to 78	24 to 53
Chloride (mg/L)	NM	NM	NM
Total Organic Carbon (mg/L)	<1.0 to 1.7	<1.0 to 1.0	<1.0
pH (S.U.)	7.2 to 7.7	6.6 to 6.9	5.6 to 6.9
Alkalinity (mg/L)	NM	NM	NM
Hydraulic Conductivity (ft/d)	0.4 to 5.8	5.2 to 8.1	0.2 to 0.6

* n = number of wells included in the range;
$^{+}$VFA = Pyruvic acid, lactic acid, formic acid, acetic acid, propionic acid and butyric acid.
NM = Not measured

6.0 Substrate Injections and Treatability Study

6.1 Substrate Injection – Phase I

6.1.1 Well Development

Results from slug and specific capacity testing (Section 5.2.2) showed that the 1-inch direct push injection wells had an average hydraulic conductivity (0.39 ft/d) that was approximately an order of magnitude lower than the 2-inch monitor wells (6.5 ft/d) installed by hollow stem auger. This suggested that the formation adjoining the 1-inch direct push wells had been 'damaged' by compaction and/or smearing of the borehole wall during well installation. Solutions-IES conducted an extensive program of surging and flushing with a surfactant solution in an attempt to rehabilitate the 1-inch direct push wells prior to emulsion injection.

Solutions-IES personnel mobilized to the NWS site on May 11, 2004. In each of the injection wells, a surge block was rapidly moved up and down for approximately 5 minutes, and then the well was purged to remove fines. Polysorbate 80 (Lumisorb PSML 80, Lambent Technologies, Gurnie, IL) was added to wells 17PSI-3, -8, -9, -11 and -14 to help loosen fines that may have been entrapped in the sand pack or screen slots. Approximately 1 tablespoon of the Polysorbate 80 was introduced into well 17PSI-3. However, Polysorbate 80 mixed with the water in the well created a sticky solution that did not seem to help the development process. A mixture of the Polysorbate 80 (1 teaspoon) and water (1.5 gallons) was prepared and introduced in equal amounts into wells 17PSI-8, -9, -11 and -14. No appreciable increase in water yield from these wells was observed resulting from the addition of the Polysorbate 80 and water mixture. The process was discontinued.

6.1.2 Substrate Preparation and Injection

Groundwater was used for mixing and diluting the EOS® concentrate prior to injection. Most of the groundwater was obtained by pumping from each of the three permanent monitoring wells located in the test cell (17PS-01, 17PS-02 and 17PS-03). Additional water was obtained from groundwater stored in 55-gallon drums that were the result of the initial development of the wells installed at the site. Groundwater produced during redevelopment of the injection wells was stored in a plastic tote. The maximum sustainable pumping rate that could be achieved was approximately ¼-gallon per minute.

The 16 injection wells were divided into eight well pairs. The design prescribed a process where diluted EOS® would first be injected into eight wells while additional groundwater was being recovered from the remaining other eight wells to increase the hydraulic gradient between adjacent wells in the test cell. The EOS® was diluted by adding the concentrate to groundwater that had been removed from the injection wells and mixed in a plastic 275-gallon plastic tote. A 4:1 mixture of groundwater (208 gallons) and EOS® concentrate (52 gallons) was mixed by recirculation through a 1-inch double-diaphragm pump. Eight of the 16 injection wells were manifolded together using 1-inch polyvinyl chloride (PVC) pipe, ½-inch flexible Quest pipe, a ½-inch double

diaphragm pump and a variety of fittings and valves. Flow totalizers were initially connected to the discharge of each pump, but at flow rates of less than 0.25 gpm, they did not provide accurate readings. To determine injectate volumes, the intake hose for each of the pumps was placed into a 5-gal bucket and each time the bucket was refilled, it was recorded in the field book. Approximately 224 gallons of dilute EOS® were injected into 17PSI-2, -4, -5, -7, -10, -12, -13 and -15. The approximate number of gallons of dilute EOS® injected into each well is shown on **Table 6-1.**

TABLE 6-1			
EOS® Injection Data- Phase I			
SWMU 17, Naval Weapons Station			
Charleston, SC			
Well ID	**Gallons of Dilute EOS® (5/13/04)**	**Well ID**	**Gallons of Dilute EOS® (5/17- 5/18/04)**
17PSI-2	40	17PSI-1	75
17PSI-4	44	17PSI-3	44
17PSI-5	23	17PSI-6	51
17PSI-7	20	17PSI-8	72
17PSI-10	34	17PSI-9	61
17PSI-12	34	17PSI-11	51
17PSI-13	17	17PSI-14	55
17PSI-15	12	17PSI-16	51
Subtotal	***224***	***Subtotal***	***460***
	Total Gallons of Dilute EOS® Injected *684*		

Note: 125 mL of Vitamin B-12 solution was added to each of the 16 injection wells near the end of the water chase.

After the EOS® was injected, additional groundwater was recovered from the injection wells that EOS® had not yet been injected into and pumped into the active injection wells to help distribute the EOS® throughout the aquifer (i.e., the "recirculation/water chase"). The recovery and re-injection rate was not recorded so the volume of water that was recirculated could not be calculated. This recirculation/water chase was left on for approximately 21 hours before the pumps were all shut down and the site was secured over the weekend. The injection pairings are illustrated in **Figure 6-1.**

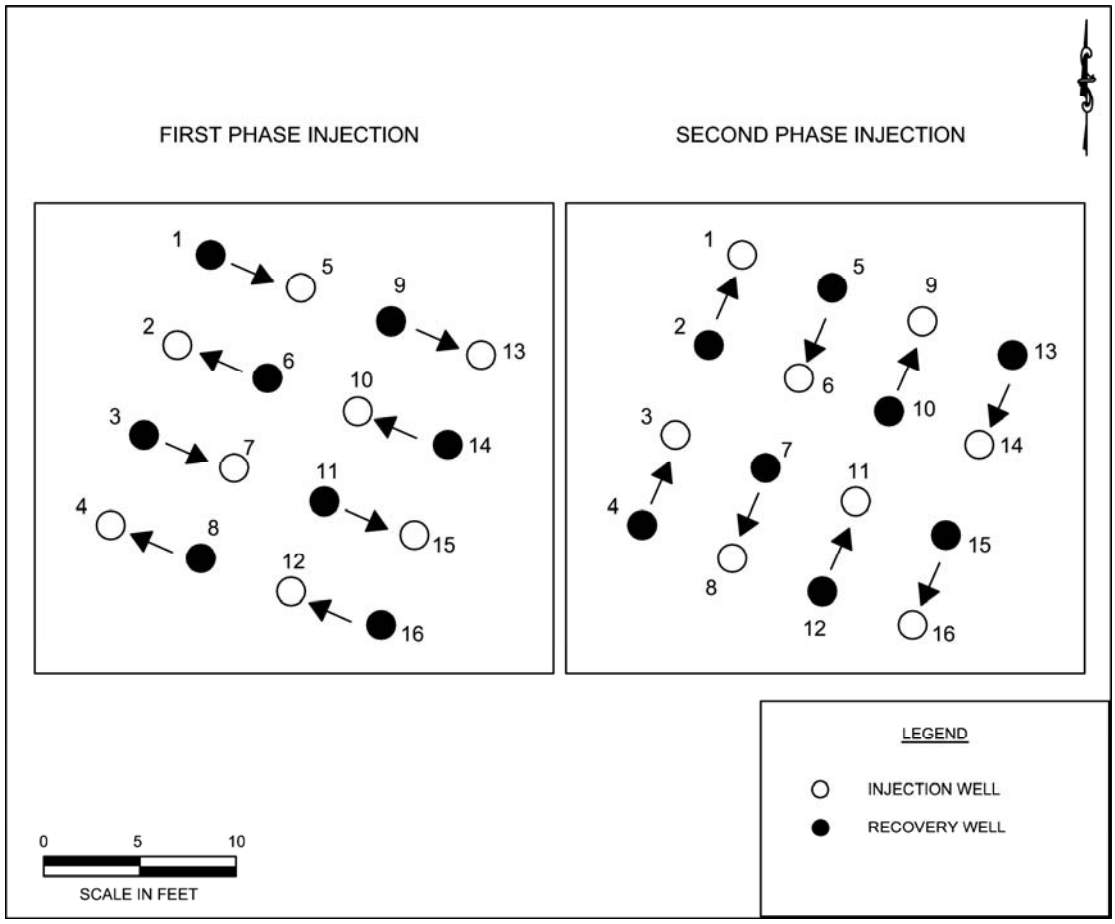


Figure 6-1. Phase I EOS® Injection Schematic (Arrows illustrate well pairs that were used during the recirculation stage of the injection process.**)**

After allowing several days for the aquifer to return to static conditions, the wells were reconfigured and a second sequence of injections was performed so that all wells received injections of dilute EOS®. On May 17, 2004, Solutions-IES personnel mixed up two additional totes of dilute EOS® (52 gallons EOS® to 208 gallons groundwater) and began injecting dilute emulsion into 17PSI-1, 3, 6, 8, 9, 11, 14 and 16. At the end of the day, 126 gallons had been injected and the water chase was set up by recovering water out of the wells that had been injected the previous week and injecting the water into the active injection wells listed above. On May 18, 2004, the recirculation/water chase was shut down after operating for approximately 12 hours. The EOS® injection was restarted and allowed to operate throughout the following day. Midway through the day, injection wells 17PSI-3, 17PSI-8 and 17PSI-9 were connected to a low pressure pumping system which significantly increased the injection rates. Approximately 460 gallons were injected into these eight wells **(Table 6-1**). When all of the EOS® had been injected, the water chase was connected and run for approximately 63.5 hours. In total, a final volume of 684 gallons of diluted EOS® mixture (i.e., 156 gallons of EOS® concentrate (1,260 lbs) diluted with 528 gal of groundwater) was injected. A layout of the test cell is provided as **Figure 6-2.**

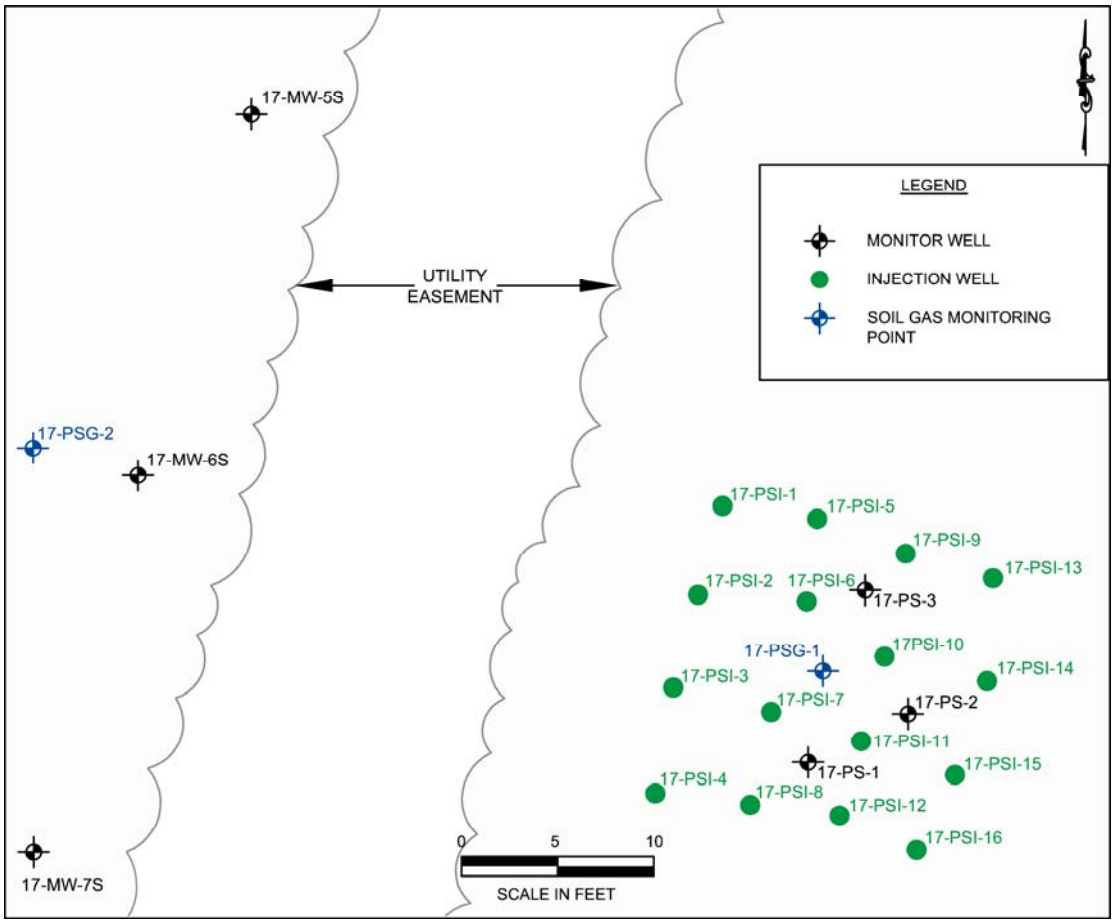


Figure 6-2. Treatment Cell Layout for Phase I Injection and Monitoring

On May 20, 2004, 125 mL of a vitamin B-12 (cobalamin) solution were added during the water chase to each of the eight active injection wells (i.e., 17PSI-1, 3, 6, 8, 9, 11, 14 and 16). Vitamin B-12 has been shown to optimize growth of *Dehalococcoides ethenogenes* and improve reductive dechlorination (He, et al., 2007).

When the recirculation/water chase was shut down on May 21, 2004, 125 mL of vitamin B-12 mixture was added to each of the other eight injection wells (i.e., 17PSI-2, 4, 5, 7, 10, 12, 13 and 15). The B-12 solution was flushed from the injection well by adding an additional 1.5 gal of groundwater to each well.

6.2 Treatability Study

The data that will be presented in Section 7.0 of this Technical Report will show that TCE degradation slowed toward the end of the first 18 months of performance monitoring. In addition, complete reductive dechlorination to VC and ethene was not readily apparent. Three hypotheses were advanced to explain these observations:

1) Low pH – the pH of the aquifer was too low, inhibiting the conversion of TCE to ethene;
2) Microbial Community - the microorganisms necessary for complete reductive dechlorination of TCE did not exist in the aquifer;

3) Low Organic Carbon - not enough dissolved organic carbon existed in the aquifer for reductive dechlorination to proceed.

6.2.1 pH Effects

Dehalogenating bacteria use hydrogen (H_2) as the electron donor in reductive dechlorination. One of the most common methods of introducing hydrogen into the subsurface is through the fermentation of organic substrates. Edible oils (injected as neat oil or oil emulsions) have been used extensively to enhance degradation of chlorinated solvents (see **Table 2-1**). Other organic substrates such as carbohydrates (e.g., sugars like molasses), alcohols, short-chain fatty acids, and lactate (Morse et al., 1998; Ellis et al., 2000; AFCEE et al., 2004) can also be used to produce hydrogen from fermentation.

Fermentation of vegetable oils leads to the formation of short-chain metabolic acids (e.g., acetic, formic, propionic, butyric acids) which can potentially lower groundwater pH. These acids have been shown to be more toxic than the corresponding salts such as acetate, propionate and butyrate found at higher pH. This is historically explained by the chemiosmotic theory that describes the passage of weak organic acids and bases across cell membranes resulting in the depression of pH below the growth range and metabolic inhibition by the undissociated acid molecules (Russell, 1992). Fang and Zhou (2006) described the inhibition of two chemolithotrophic bacteria in sewage sludge by formic, acetic, propionic and butyric acids. Mawson et al. (1991) reported that increasing concentrations of acetic acid would inhibit the degradation of propionic acid and vice-versa in an anaeorobic methane digester, attesting to the importance of controlling acid levels in these conditions.

Reductive dechlorination of TCE to ethene also releases hydrochloric acid (HCl) which can also result in an undesirable decline in pH. This effect is most pronounced when chlorinated solvent concentrations are high and alkalinity is low.

Dehalorespiring species do not appear to tolerate acidic conditions in general. Some strains, such as *Desulfitobacterium dichloroeliminans* strain DCA1, which has a pH optimum near 7.5, can maintain activity at a pH as low as 5.4 (Maes et al., 2006). However, at least some strains of *Dehalococcoides spp*. appear to be less acid-tolerant, and pH can be an important factor in determining if complete dechlorination will occur, especially because fermentation of organic electron donors can be highly acidifying (Adamson et al., 2004). The commercially available bioaugmentation culture KB-1™ is reported to have an optimal pH range of 6 to 8.3 and to be inhibited below pH 5 and above pH 10 (Rowlands, 2004). Eaddy (2008) reported optimal dechlorination by a dehalorespiring enrichment culture obtained from the Savannah River Site in South Carolina occurred at neutral pH. Overall, metabolic dechlorination slowed at pH 6.0 resulting in increased accumulation of *cis*-DCE and VC; with complete inhibition of VC dechlorination to ethene at pH 5.5 (Eaddy, 2008). Using the SDC-9 bioaugmentation culture, Vainberg et al. (2006) saw dechlorination occur in a pH range of 5.5 to 8.5, with an optimal pH for PCE degradation between 6.0 and 6.3 (**Figure 6-3).** Mixed cultures may be slightly more pH tolerant. For instance, Rosner et al. (1997) found a mixed pH

culture that dechlorinated VC in a pH range of 5.0-10.0, with an optimum pH of 8.5. However, this culture could only moderately degrade TCE or *cis*-DCE.

In general, lowering of pH to below 6 standard units may inhibit growth of dechlorinating microbes. Therefore, pH buffer amendments such as sodium bicarbonate may be required in groundwater systems with insufficient buffering capability (AFCEE et al., 2004).

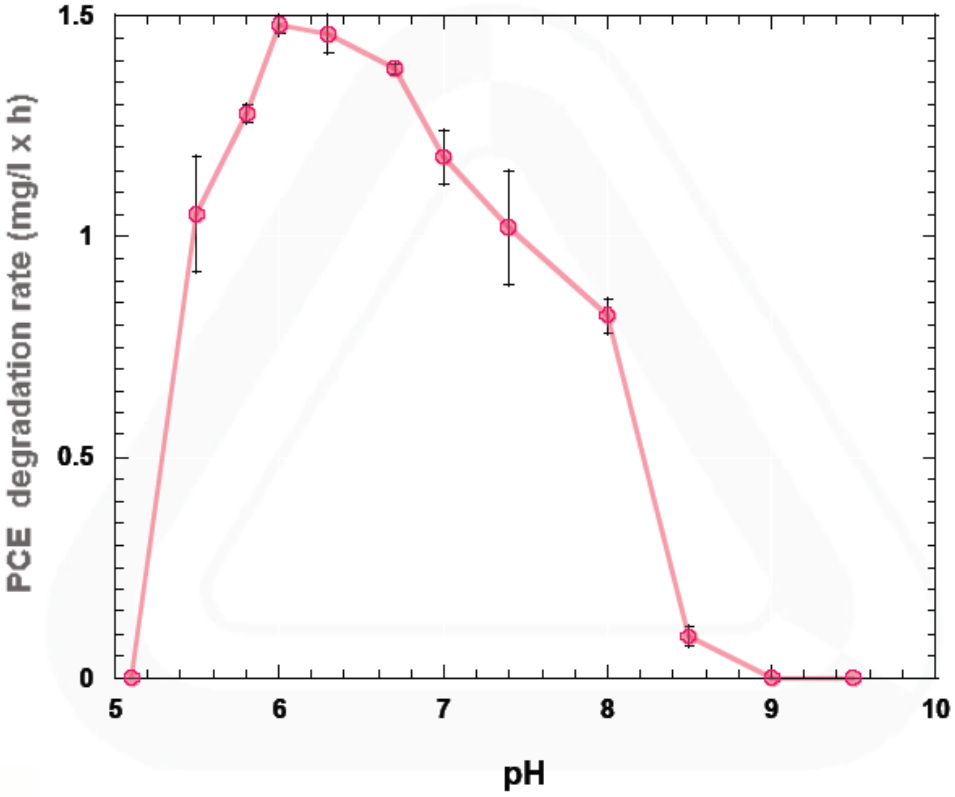


Figure 6-3. Effect of pH on PCE Dehalogenation by SDC-9
(from Vainberg et al., 2006)

6.2.2 Sample Collection

To evaluate these hypotheses, laboratory studies were initiated in August 2005, concurrent with the final performance monitoring events of Phase I, to:

> (1) Determine the chemical and biological conditions of the subsurface; and
> (2) Evaluate the effect of pH, organic substrate and bioaugmentation on the reductive dechlorination of TCE in batch microcosms.

The full details of the laboratory experiments performed are described in Tillotson (2007). The results of these studies were used to design the Phase II portion of the field demonstration. The salient laboratory methods and results are described in the following subsections.

Approximately 15 months after the initial injection of EOS® into the test cell, sediment and groundwater were collected from both background and grid locations as shown in **Figure 6-4.**

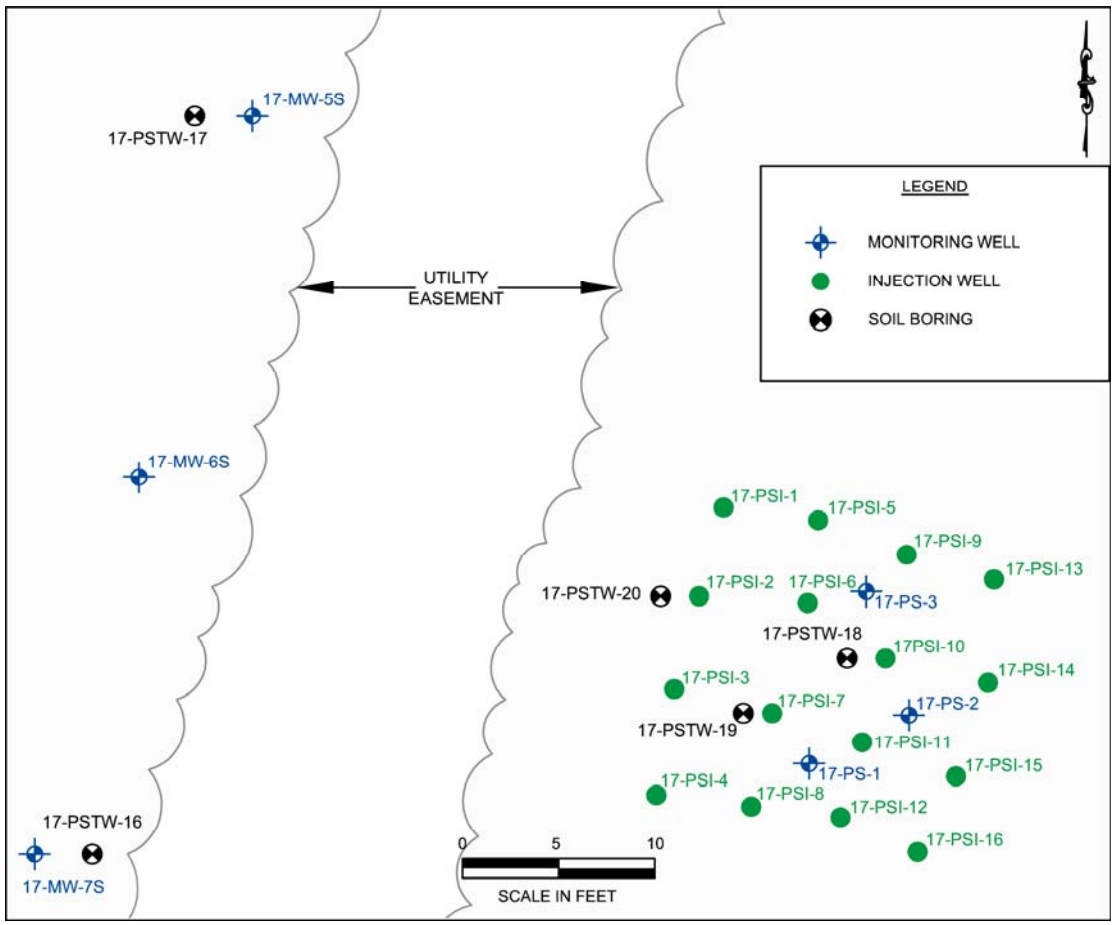


Figure 6-4. Location of Soil Borings and Wells Used to Collect Material for Laboratory Studies

Small soil samples were collected from Geoprobe® soil borings in background locations 17PSTW-16 and -17 and grid locations 17PSTW-18, -19 and -20 at intervals of 10, 12, 14 and 16 ft bgs. These samples were transferred from Geoprobe® Macro-Core® sleeves to small plastic containers, sealed and taped to exclude air. Additionally, two quarts of sediment were collected in Mason jars from borings 17PSTW-16, -17, -18 and -19. Groundwater from adjacent wells was used to cover the sediment before capping the jars to exclude air. In addition to the soil samples, groundwater samples were collected from monitor wells 17PS-03 (Test Cell) and 17MW-6S (Background). The soil and groundwater were analyzed for the following parameters: ferrous iron and total iron; pH; anions; and dechlorinating microorganisms.

6.2.3 Matrix Characterization

Table 6-2 shows the results of the iron extraction from the background and test grid sediment. The background sediments contained relatively high levels of Fe[II] indicative of moderately reducing conditions associated with the wetland environment. EOS® injection approximately 15 months earlier appears to have resulted in a small increase in the Fe[II] fraction. However the increase in the Fe[II] fraction was not significant at the 95% level. EOS® injection did result in a large increase in dissolved iron in monitor wells from a background concentration of ~1 mg/L to 200–250 mg/L within the test cell. These results are discussed in greater detail in **Section 7.0**.

As discussed above, fermentation of edible oils and other substrates releases VFAs and CO_2, which can result in a drop in pH. However, when significant amounts of ferric iron (Fe[III]) are present as hematite [Fe_2O_3] or other easily reducible iron, Fe[III] will be reduced releasing hydroxides (OH^-) according to the reaction:

$$Fe_2O_3 + H_2O + H_2 \rightarrow 2\ Fe^{+2} + 4\ OH^-$$

OH^- released in this reaction can result in a net increase in pH. However, at SWMU 17, much of the iron has already been reduced, which may limit the beneficial effects of iron reduction on pH.

Table 6-2
Laboratory Study: Average Bioavailable Fe[II] and Fe[III] Content of Background and Test Cell Sediment Samples
SWMU 17, Naval Weapons Station
Charleston, SC

Sample Depth (ft bgs)	Background			Test cell		
	Fe (II)	Fe[III]	% Fe[II]	Fe (II)	Fe[III]	% Fe[II]
	mg/g	mg/g		mg/g	mg/g	
10	0.083	0.46	18%	0.061	0.52	12%
12	0.046	0.44	10%	0.47	1.4	34%
14	0.056	0.62	9.0%	0.44	1.0	42%
16	0.62	0.75	83%	0.44	0.74	60%
Blended Microcosm Sediment	0.34	0.81	41%	0.64	1.1	57%

Notes: Background is average of two wells; test site is average of three wells; microcosm sediment is from two wells.

Table 6-3 details the pH of different soil depths from the background and test cell soil borings. The pH of the soils both from the background areas and the pilot test cell were similarly acidic ranging from pH 4.3 to pH 5.2 from 10 to 14 ft bgs. The pH of deeper soils around 16 ft bgs was closer to pH 6, presumably due to the shell fragments and other calcareous material present in the Cooper marl. The pH of the soils from 10 to 14 ft bgs is well below the range for optimal bioactivity of many dehalorespiring bacteria

including *D. ethenogenes* and is the likely cause of the limited reductive dechlorination within the test cell.

Table 6-3
Laboratory Study: Soil pH Measurements
SWMU 17, Naval Weapons Station
Charleston, SC

Sample Depth	Background Borings		Test Cell Borings		
	17PSTW-16	17PSTW-17	17PSTW-18	17PSTW-19	17PSTW-20
(ft bgs)	(pH)	(pH)	(pH)	(pH)	(pH)
10 ft	4.9	4.9	4.3	4.2	4.4
12 ft	5.1	4.9	4.8	4.8	4.2
14 ft	5.2	4.9	4.8	4.8	4.5
16 ft	5.9	6.1	6.2	5.7	4.4

Table 6-4 shows results from the microbiological characterization performed on groundwater and homogenized sediment from a background location and from the test cell. *Dehalococcoides spp*. is able to dechlorinate TCE completely to ethene, while *Desulfurmonas spp.* and *Dehalobacter spp.* are able to dechlorinate TCE to *cis*-DCE. *Dehalobacter spp.* numbers where high in both the background and test cell samples indicating there was a substantial population of bacteria that could convert TCE to *cis*-DCE. However, *Dehalococcoides spp.* numbers were very low in the background and test cell locations, indicating that further conversion of *cis*-DCE to ethene might be limited by the absence of appropriate microorganisms.

Table 6-4
Laboratory Study: Biological Assay on Groundwater and Blended Sediment
SWMU 17, Naval Weapons Station
Charleston, SC

	Background Soil (cells/g)	Background Water (cells/mL)	Test Cell Soil (cells/g)	Test Cell Water (cells/mL)
Species				
Dehalococcoides spp.	3.10E+03	5.30E+01	< 9.71E+02	2.03E+00
Desulfuromonas spp.	7.10E+00	7.74E-02	1.47E+02	1.95E-02
Dehalobacter spp.	2.28E+04	1.42E+04	1.60E+05	2.17E+03

6.2.4 Microcosm Studies

Batch microcosm experiments were initiated in August 2005 to evaluate the effect of pH adjustment, substrate addition, and bioaugmentation on reductive dechlorination. Microcosms were constructed with site matrix soil and groundwater in 245 mL serum bottles filled with 100 mL of wet aquifer (blended) sediment and 125 mL of groundwater.

Five experimental treatments were prepared from both the background matrices and from the pilot test cell materials. The experimental treatments were:

Treatment A – Abiotic Control (Inhibited)
Treatment B – Ambient (Live Control)
Treatment C – Buffered (Live with pH buffer)
Treatment D – Buffered and EOS® (Live with pH buffer and EOS®)
Treatment E – Bioaugmented (Live with pH buffer, EOS® and bioaugmentation)

All microcosms were constructed in an anaerobic chamber maintained under a N_2/H_2 (95/5 %) atmosphere. Prior to being removed from the anaerobic chamber, the microcosms were sealed with a thick butyl rubber stopper and crimped with an aluminum cap to exclude oxygen.

Treatment A microcosms were autoclaved and acidified to inhibit microbial activity. All treatments from the pilot test cell matrices were spiked with a stock solution of TCE to achieve a starting concentration of 3 mg/L. Other than the addition of TCE, Treatment B was unamended, while Treatments C, D and E all received 7.5 mL of a 0.2 N NaOH solution to raise their pH to above 6.5. Treatments D and E also received 0.23 mL of additional EOS® concentrate to provide a starting concentration of approximately 840 mg/L. All additions to the microcosms were made by piercing the rubber stopper with a needle and injecting the additives into the microcosms. All microcosms were incubated in the dark at room temperature (approximately 20^o C) in the laboratory.

The bioaugmentation culture used was the SDC-9 culture, provided by Shaw Environmental & Infrastructure, Inc. SDC-9 is a mixed culture containing two species of *Dehalococcoides* and a strain of *Desulfovibrio*. *Dehalococcoides* can completely dechlorinate PCE to ethene via halorespiration, while *Desulfovibrio* is able to dechlorinate PCE and TCE to *cis*-DCE. One-tenth mL of the bioaugmentation culture was added to the bioaugmented microcosms (Treatment E) to provide a starting concentration of ~ 4×10^4 cells/mL. The cell density of *Dehalococcoides* was ~1.08×10^2 cells/mL.

Samples from the microcosms were analyzed for VOCs, dissolved oxygen (DO), anions (chloride, nitrate, nitrite and sulfate), total organic carbon (TOC), methane, ethene, ethane, and pH. The microcosms were maintained for up to 447 days. The results of all analyses are presented in Tillotson (2007). The primary conclusions are summarized as follows:

1) Under ambient, anaerobic conditions (Treatment B) reductive dechlorination was very limited in the soils from the untreated, background locations at the site. This is not surprising, and is representative of what is happening on site.

2) In the ambient, anaerobic microcosms (Treatment B) containing material from the pilot test cell, all TCE was reduced to *cis*-DCE after just two days. The rate with which this occurred was surprising since this was far more rapid than observed in the field at the

test cell. The likely explanation is that these microcosms have a higher pH than most of the aquifer, and may not be representative of the actual field test cell. The higher pH in the microcosms is believed to be due to blending more neutral pH sediment from 16 ft bgs with more acidic sediment from the shallower zones.

3) Amending the Background microcosms with a pH buffer (Treatment C) encouraged reduction of TCE to *cis*-DCE in one microcosm, with limited transformation in the other two microcosms. However, adding a pH buffer and EOS® enhanced TCE dechlorination to *cis*-DCE after only 19 days. Further reduction of *cis*-DCE did not occur in any of the microcosms, indicating the indigenous microbial community may not be capable of complete dechlorination of TCE to ethene.

4) The test cell microcosms amended with a pH buffer (Treatment C) and a pH buffer and organic substrate (Treatment D) all reduced TCE to *cis*-DCE in two days, but with little to no subsequent transformation of *cis*-DCE to less chlorinated compounds. These results mirror those of the ambient microcosms.

5) The bioaugmentation culture (Treatment E) completely reduced TCE to non-toxic ethene in 19 days for the test cell microcosms and 75 days in the Background microcosms.

It appears that lower pH is at least partially limiting reductive dechlorination. Due to the previous injection of EOS®, organic substrate does not appear to limit reductive dechlorination in the test cell, as evidenced by the ambient microcosms. Once the pH was raised to above 6.0 in those microcosms, TCE was rapidly dechlorinated to *cis*-DCE. However, bioaugmentation was needed to further degrade *cis*-DCE. The low level of dechlorinators present in the sediment suggest that that the test cell would need to be buffered and bioaugmented in order to achieve complete reductive dechlorination.

6.3 Laboratory Buffering Studies

The microcosm studies strongly suggested that increasing the pH in the test cell would enhance reductive dechlorination of TCE to *cis*-DCE. Tillotson (2007) evaluated several different alkali materials to increase the pH of the aquifer. These included: hydrated lime ($Ca(OH)_2$), magnesium hydroxide ($Mg(OH)_2$), sodium hydroxide (NaOH), bicarbonate of soda ($NaHCO_3$) and soda ash (Na_2CO_3). **Table 6-5** shows the properties of these different bases.

Table 6-5
Properties of Different Alkalis Available for pH Adjustment

Alkali	$Ca(OH)_2$	$Mg(OH)_2$	NaOH	$NaHCO_3$	Na_2CO_3
Alkalinity (lb. $CaCO_3$ / lb. dry solids)	1.32	1.68	1.23	0.60	0.94
Max. pH of concentrate	12	10	14	8	12

The goal was to find a reagent that could be injected to provide a large amount of alkalinity per pound, but not result in an excessively high pH near the point of injection. The creation of extreme alkaline conditions is not desirable for field applications because it can lead to cation exchange in clay minerals, and disrupt soil biological, chemical and physical properties (Alshawabkeh et al., 2004). Further, as noted earlier, activity of *Dehalococcoides spp.* can also be inhibited above pH 8.5 (Eaddy, 2008).

$Ca(OH)_2$, NaOH and Na_2CO_3 have maximum pH values greater than 12, which could result in toxicity due to a very high pH near the injection point. In contrast, $NaHCO_3$ would buffer the pH near optimum (7-8), but $NaHCO_3$ provides the least alkalinity per pound. Also, addition of $NaHCO_3$ to the acidic aquifer would like result in degassing of CO_2 bubbles, which could result in partial blockage of the aquifer.

Given these different factors, $Mg(OH)_2$ was chosen for further testing. In solution, the pH of pure $Mg(OH)_2$ is ~10, so the pH within most of the aquifer can be expected to vary between background (~5) and 9. While a pH of 9 is greater than desired, it is not expected to be acutely toxic. Also, $Mg(OH)_2$ addition would require less material and would not result in CO_2 degassing.

A titration experiment was conducted using sediment from the test cell aquifer to determine how much base is required to increase the pH to neutrality. **Figure 6-5** shows the pH of the different NaOH additions to 10 g of sediment in 10 mL of deionized water.

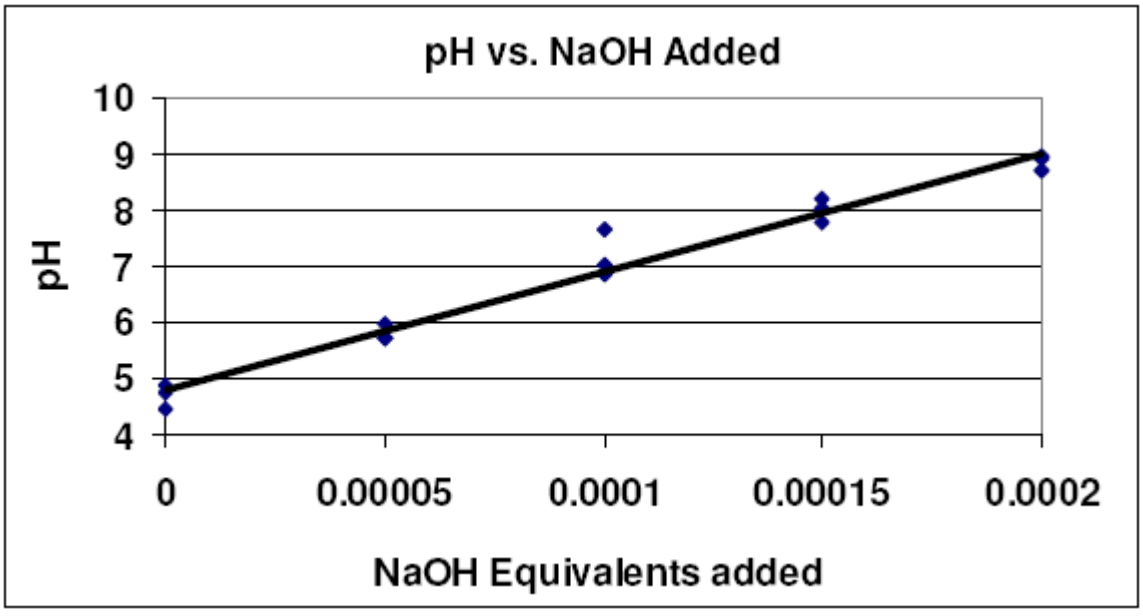


Figure 6-5. Laboratory Study: pH Versus Amount of NaOH Added

The amount of $Mg(OH)_2$ required to increase the pH of the pilot test cell is shown in **Figure 6-5.** This assumes perfectly uniform mixing of the added base with the aquifer material. $Mg(OH)_2$ addition was calculated assuming a 4,000 ft^3 (148 yd^3) treatment volume with a sediment bulk

density of 100 lb/ft^3. Using these assumptions, the results in **Figure 6-5** were converted into total amount of $Mg(OH)_2$ required to raise the pH within the pilot cell. Based on a linear regression of the data, approximately 1,200 lb of $Mg(OH)_2$ would be required to raise the pH of the pilot test cell to approximately pH 7.

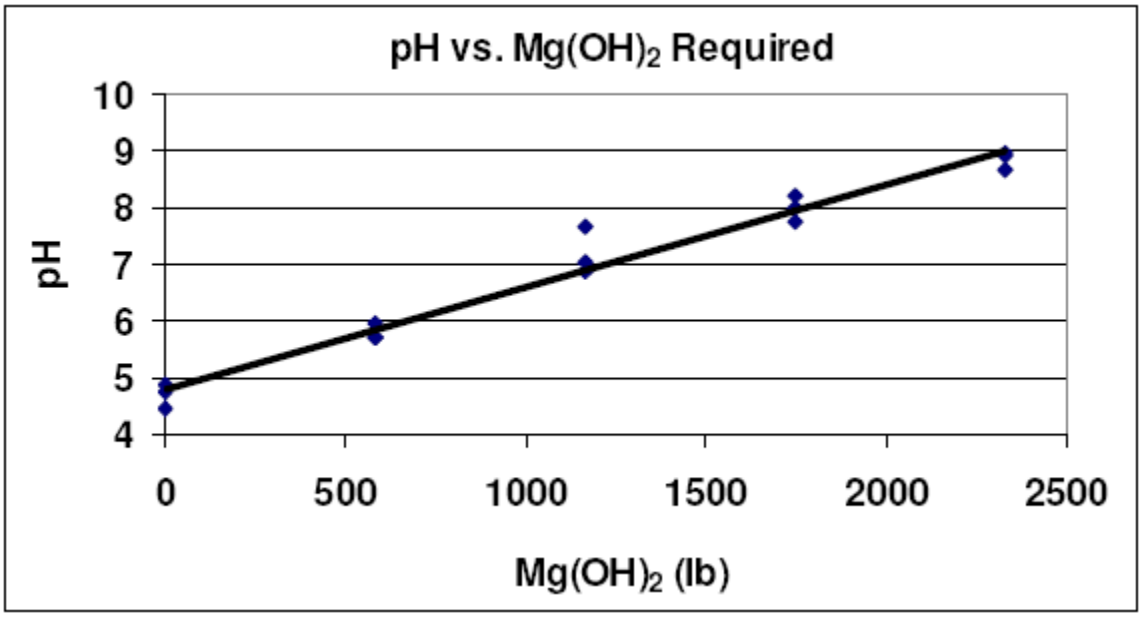


Figure 6-6. Laboratory Study: $Mg(OH)_2$ Required to Increase the pH within the Pilot Test Cell

The field data clearly showed that the pH in the pilot test plot was below optimal and the population of important dechlorinating bacteria was low for achieving high biodegradation rates. The laboratory studies showed that changing these conditions would enhance reductive dechlorination and the buffer studies indicated that $Mg(OH)_2$ was a good alternative to buffer large volumes of aquifer inexpensively. Although there was adequate TOC in the site matrices to continue supporting reductive dechlorination, it was decided to add both a pH buffer and additional EOS® to assure that substrate was not limiting.

Preliminary tests were conducted to identify a mixture of EOS® and $Mg(OH)_2$ that was stable, could be easily injected, and distributed throughout the aquifer. The final mixture contained 40% by weight $Mg(OH)_2$ and had a density of 9.29 lb/gal (specific gravity = 1.11).

6.4 Substrate Injection – Phase II

In September 2006, eight drums of pre-mixed $Mg(OH)_2$/EOS® material (buffered EOS®) were obtained from EOS Remediation, Inc. and shipped to the site. The injection of the buffered EOS® mixture into the aquifer was designed as a series of pressurized direct injections directly through standard Geoprobe® rods. **Figure 6-7** shows the locations of the injection points in relation to previously installed injection wells and existing monitor wells.

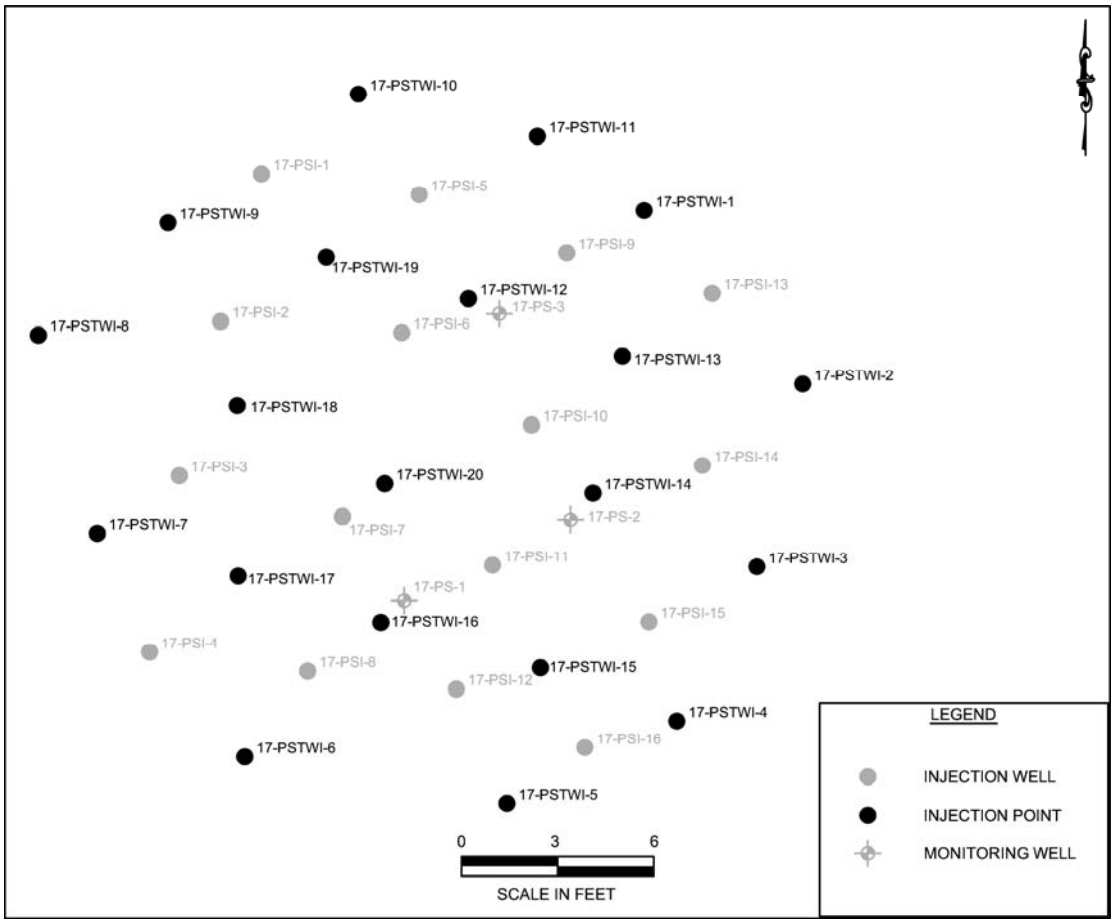


Figure 6-7. Treatment Cell Layout for Phase II Injection of Buffered EOS®
(Drawing shows injection points in relation to previously installed injection and monitor wells)

Buffered EOS® was diluted by adding 198 gallons of potable water to 55 gallons of buffered EOS® (3.6:1 ratio) in a tote. The process was repeated three times during the initial injection efforts. Injections were performed by Richard Simmons Drilling Co. of Statesville, NC. Injections began on September 26, 2006, which is 866 days (~28 months) after the first injection of EOS® into the test grid. The buffered EOS® injections were conducted by probing to 16 ft bgs and injecting the mixture while slowly withdrawing the rods. Initial plans were to inject approximately 7 gallons of the dilute mixture per foot evenly over the entire saturated zone (6 to 16 ft bgs) at all 20 injection points. However, while injecting the mixture, groundwater was observed to mound substantially across the entire pilot test plot and buffered EOS® was observed to break through the ground surface at several locations as well as "daylight" at several nearby monitor and injection wells. Reducing the injection pressure reduced this occurrence. However, injection of 666 gallons of fluid into the relatively low permeability confined aquifer resulted in excessive pressure buildup and injection was discontinued on September 28, 2006. The volume of dilute buffered EOS® that was injected into the first 10 injection points in September 2006 is summarized in **Table 6-6**.

After allowing approximately one month for the aquifer to re-establish natural water levels, Solutions-IES returned to the site to finish injecting buffered EOS® into the pilot test plot.

Between October 16-18, 2006, a second round of injections was performed. The previous process of diluting the buffered EOS® and injecting it directly through Geoprobe® rods was performed as before. However, to reduce the volume of water being added to the aquifer, the dilution ratio was reduced to 2:1. Despite this change, groundwater again mounded across the plot and buffered EOS® was observed to daylight in a few locations. **Table 6-7** summarizes the volume of buffered EOS® and dilution water injected into each point for the second set of injections.

In total, the direct injection of buffered EOS® introduced 326 gallons (3,030 lbs) of the mixture into the aquifer. The final mixture was 24 % $Mg(OH)_2$ which resulted in approximately 727 lbs of $Mg(OH)_2$ being injected. When compared with the buffering data shown in **Figure 6-6**, this was projected to meet the target amount that would be needed to raise the pH to between pH 6 and 7.

Table 6-6
Amount of Buffered EOS® Concentrate and Dilution Water Injected into Pilot Test Cell on September 26-28, 2006
SWMU 17, Naval Weapons Station
Charleston, SC

Injection Point	Buffered EOS® Concentrate Injected (gal.)	Dilution Water Injected (gal.)	Total Injected (gal.)
IP 1	15	55	70
IP 2	15	30	45
IP 3	14	52	66
IP 4	22	78	100
IP 5	22	78	100
IP 6	22	78	100
IP 7	12	23	35
IP 9	8	27	35
IP 10	22	78	100
IP 11	5	10	15
Totals	***157***	***509***	***666***

Table 6-7
Amount of Buffered EOS® Mixture and Dilution Water Injected into the Pilot Test Cell on October 16-18, 2006
SWMU 17, Naval Weapons Station
Charleston, SC

Injection Point	Buffered EOS® Concentrate Injected (gal.)	Water Injected (gal.)	Total Injected (gal.)
IP 8	5	10	15
IP 12	33	67	100
IP 13	20	39	59
IP 14	5	10	15
IP 15	Not Performed	N/A	N/A
IP 16	5	11	16
IP 17	15	30	45
IP 18	33	67	100
IP 19	20	40	60
IP 20	33	67	100
Totals	***169***	***341***	***510***

7.0 Performance Monitoring Results and Discussion

The performance monitoring period included two phases. Phase I included the initial baseline sampling discussed in **Section 5.0** and 11 performance monitor events to evaluate the effect of EOS® injection on groundwater geochemistry and contaminant concentrations. Phase II included three sampling events to evaluate the effect of buffered EOS® injection. As discussed in **Section 6.1.2** above, the initial EOS® injections were performed over a 5-day period (**Table 6-1**) between May 13 and May 18, 2004. However, for purposes of this Technical Report, May 13, 2004, was used as Day 0.

Performance monitoring events were conducted on or about the dates indicated in **Table 7-1**.

Table 7-1
Performance Monitoring Schedule for Phases I and II of EOS® Pilot Study
SWMU 17, Naval Weapons Station
Charleston, SC

Date	Approx. Days After EOS® Injection	Approx. Months After EOS® Injection	Groundwater Samples	Soil Samples
Mar. 1, 2004	-73		No	Yes (Baseline)
Mar. 25, 2004	-49		No	Yes (Baseline)
Apr. 1, 2004	-42		Yes (Baseline)	No
May 13-18, 2004	EOS® Injections Completed (Phase I)			
May 18, 2004	5	0	Yes	No
June 2, 2004	20	0.5	Yes	No
Sept. 1, 2004	111	3	Yes	No
Nov. 10, 2004	181	6	Yes (Geoprobe)	
Nov. 16, 2004	188	6	Yes	No
Feb. 8, 2005	272	9	Yes	No
Feb. 11, 2005	272	9	No	Yes
May 25, 2005	377	12	Yes	No
Aug. 24, 2005	468	15	Yes	No
Mar. 28, 2006	684	22	Yes	No
Sep. 25, 2006	865	28	Yes	Yes
Sep. 26 & Oct. 18, 2006	Buffered EOS® Injections Completed (Phase II)			
Dec. 20, 2006	951	31	Yes	No
Apr. 10, 2007	1062	35	Yes	No
Oct. 17, 2007	1252	41	Yes	Yes

Not all parameters were analyzed during all events where samples were collected. The most immediate sampling event occurred on May 18, 2004 just after the completion of the Phase I injections; this is shown and reported as 5 days after the injections were started. The first performance monitoring activity occurred on June 2, 2004, which is reported as 20 days after

initiating injection of EOS®. Day 866 marked the beginning of Phase II of the pilot study as discussed in Sections 6.4 of this report.

7.1 Post-Injection Groundwater Conditions

7.1.1 Water Table Elevation and Groundwater Gradient

During each groundwater sampling event, the depth to water was measured in each monitor well and injection well that was sampled. The results are summarized in **Table V-1** in **Appendix V**. Throughout the entire study, the depth-to-water measurements in the three background and three treatment cell monitor wells were taken from the top-of-casing within the aboveground protective standpipe.

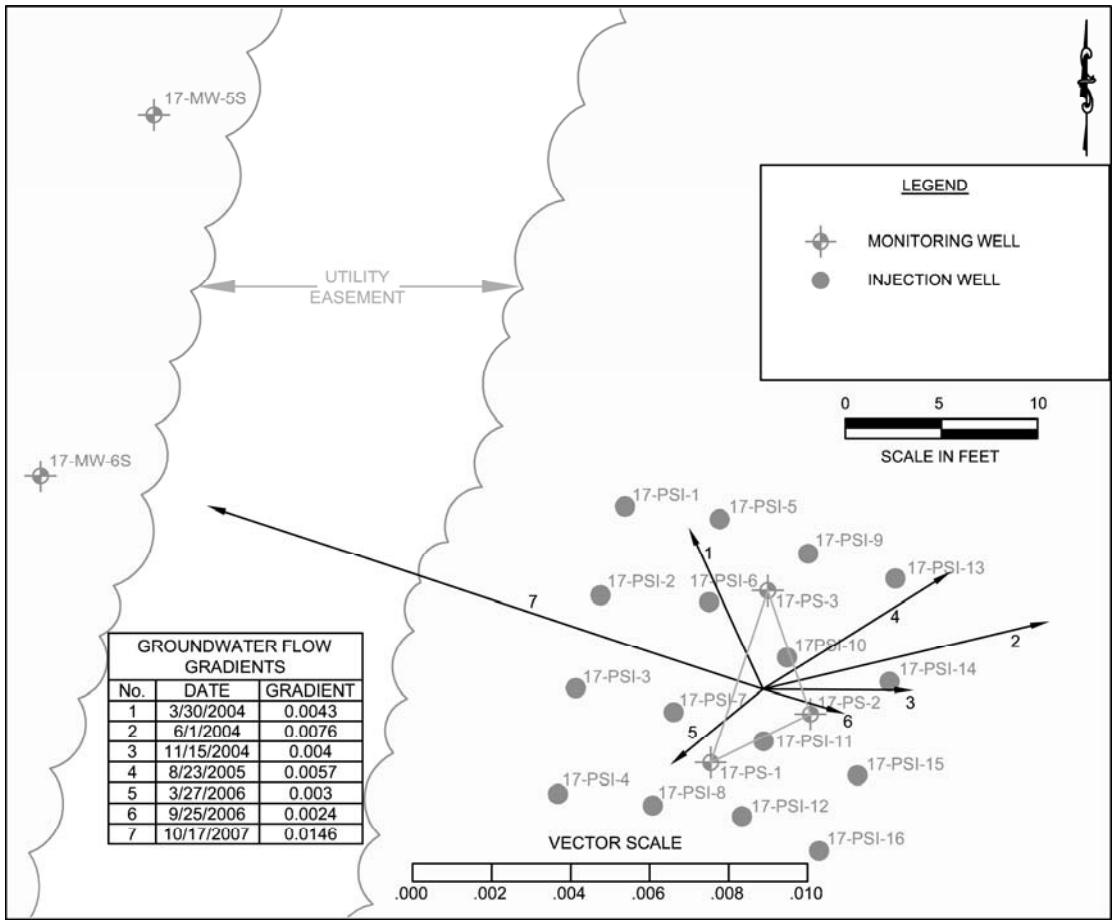
It should be noted that in June 2004, eight of the original 16 injection wells were abandoned. The casings for the remaining eight injection wells were cut off below grade and a manhole was installed around each remaining well. The wells were not re-surveyed and calculations of groundwater elevations in these wells from November 15, 2004 through to the end of the performance monitoring period were calculated by measuring the depth to water from the ground surface.

The accuracy of the ground surface elevations used and the very flat gradient present in the treatment cell did not allow accurate interpretation of water levels beneath the treatment cell. Over time, the injection wells yielded increasingly greater variation between individual injection wells and the three monitor wells in the treatment cell. The causes of these variations were likely a result of differences in well construction (2-inch vs. 1-inch diameter), uniformity and thickness of sand pack around the screen, and increase susceptibility to biofouling of the 1-inch wells resulting from use for direct injection of substrate vs. monitoring only. The appearance of residue in the wells is discussed further in Section 7.1.2 below.

Because of residue observed in the wells and the resulting data variability, only differences in water table elevations measured in the three 2-inch monitor wells located within the test cell were evaluated. Estimated groundwater flow direction in the cell encompassed by the three monitor wells in the treatment cell was solved as a three-point problem.

As expected, groundwater flow direction and gradient varied. The slope of the water table varied from northeast to southwest to northwest. **Figure 7-1** is a diagram illustrating the different groundwater flow directions calculated from the depth to water measurements in the three 2-inch monitor wells in the treatment cell. The measurements were obtained on seven different sampling events between March 30, 2004 to October 17, 2007. The calculated gradients varied between 0.0024 and 0.0146 ft/ft.

The variation of flow direction and gradient change tends to confirm that the test cell is subject to some minimal tidal fluctuations and groundwater flow reversals. For this reason, advective movement of the contaminant plume would be expected to be very slow.



GROUNDWATER FLOW GRADIENTS		
No.	DATE	GRADIENT
1	3/30/2004	0.0043
2	6/1/2004	0.0076
3	11/15/2004	0.004
4	8/23/2005	0.0057
5	3/27/2006	0.003
6	9/25/2006	0.0024
7	10/17/2007	0.0146

Figure 7-1. Groundwater Flow Diagram

7.1.2 Hydraulic Conductivity

Specific capacity tests were performed during four performance monitoring events between Day 20 and Day 271 after the injection of EOS® in Phase I. The tests were used to evaluate the impact of substrate aquifer permeability. The results are shown in **Appendix III** and averages are presented in **Table 7-2**.

Table 7-2
Specific Capacity (Hydraulic Conductivity) Results from Monitor and Injection Wells Before and After Treatment with EOS® and Buffered EOS®
SWMU 17, Naval Weapons Station
Charleston, SC

	Pre-Injection (ft/d)	Phase I – Post-EOS® Injection (ft/d)	Phase II – Post-Buffered-EOS® Injection (ft/d)
Background MWs (3)	5.22 ± 0.90 (n = 1)	6.82 ± 1.27 (n =12)	7.63 ± 2.12 (n = 6)
Injection Wells (8)	0.39 ± 0.11 (n=24)	0.32 ± 0.24 (n = 28)	0.05 ± 0.02 (n= 13)
Treatment Cell MWs (3)	7.04 ± 1.23 (n = 6)	6.27 ± 1.10 (n = 12)	0.18 ± 0.25 (n = 11)

n = number of tests included in calculating the average ± standard deviation.

The data support that there was little change in the hydraulic conductivity in the background wells away from the treatment cell throughout the entire 41-month performance monitoring period. (The difference is likely related to variability in the test process and the number of data points averaged). Similarly, there was little change in the hydraulic conductivity in the treatment cell when comparing the pre-injection and Phase I post-EOS® injection measurements.

As illustrated in **Figure 7-1**, it is difficult to assign an average hydraulic gradient for the site. If a gradient of 0.001 (estimated from previous activities at SWMU 12, 16 and 17) is used with the average hydraulic conductivity (K) measured in the treatment cell monitor wells with an estimated effective porosity of ~24 percent, the estimated residence time for groundwater passing through the 20 ft x 20 ft treatment cell is approximately 2 years. If higher "instantaneous" gradients (up to 0.0146 ft/ft) are used, then groundwater flow rates would be on the order of 0.3 ft/d (110 ft/yr). If the instantaneous gradient variations are due to tidal influences, then groundwater would tend to wash back and forth through the treatment cell with each tide change. Based on topography and apparent shape of the contaminant plume, groundwater is expected to have net eastward flow from the test cell.

Specific capacity tests were performed three times after the injection of buffered-EOS® into the aquifer. The results are provided in **Appendix III**. The changes to the average hydraulic conductivity of the injection wells and the three monitor wells in the treatment cell are shown in **Table 7-2**. The data suggest that the hydraulic conductivity decreased in the monitor wells after the addition of the buffered-EOS® material into points between the wells. Field personnel observed an accumulation of a thick residue in the upper foot of the water column in the treatment cell monitor wells. It was presumed that this

material was either buffered-EOS® that had migrated during injection or with subsequent groundwater flow from the injection points to the well bore, or a residue of biofouling from luxuriant growth of microorganisms after the pH was adjusted to neutrality, or a combination of both. The material formed oily, globular clumps, but was friable with only minimal agitation. Since the specific capacity test relies on constant drawdown at the air-groundwater interface in the well, field personnel removed the residue from each well before running the test. The presence of this material at the surface or in the well screen is likely to have adversely influenced the specific capacity measurements making an accurate calculation of the groundwater flow velocity difficult. Using the values obtained under these circumstances, it appears that the introduction of buffered-EOS® may have resulted in reduced permeability and groundwater flow velocity. However, by comparison, despite the appearance of solids in the monitor wells and apparent decrease in specific capacity, the Darcy velocity calculated during the mass flux measurements suggested no substantial impact or change to groundwater flow velocity (see Section 7.4.6).

7.2 Organic Carbon

The availability of biodegradable and fermentable organic carbon is of paramount importance for supporting and promoting anaerobic reductive dechlorination. In general, concentrations of TOC in groundwater greater than 20 mg/L are considered favorable for anaerobic reductive dechlorination to proceed (USEPA, 1998; AFCEE et al., 2004). Sources of organic carbon range from naturally occurring to intentionally added. Substrates range from readily soluble and degradable such as lactate, molasses, citrate and methanol, to more slowly degradable, slowly soluble materials such as edible oils, mulch and chitin. These substrates can generate TOC concentrations in groundwater from 100 to 1000 mg/L. The duration of their availability defines them as quick-release short-term substrates, or slow-release long-term substrates.

The production of low molecular weight VFAs such as acetic, propionic and butyric acid that can be further fermented to produce hydrogen is common to degradation processes that occur with all these substrates. Therefore, all these substrates are similar regarding how hydrogen is generated to stimulate anaerobic reductive dechlorination. The impact of the EOS® (Phase I) and the buffered EOS® (Phase II) injections into the treatment cell are discussed in the following sections.

7.2.1 Total Organic Carbon in Groundwater

On May 13, 2004, three groundwater samples were collected from injection well 17PSI-6 over a 2-hour period to assess the background concentration of TOC in groundwater that would be used as diluent for the EOS® concentrate. The samples were collected during the initial time when EOS® was being injected in nearby injection wells. The TOC concentration in groundwater was less than 1.6 mg/L and no change in TOC was observed over the 2-hour period that would indicate that the spread of EOS® was immediate. On May 17 and 18, nine groundwater samples were collected from injection well 17PSI-7 over a 23-hour period and analyzed for TOC. The samples were collected during the injection process and the water samples were reported as “milky” white from the EOS®. TOC concentrations ranged from 418 to 12,000 mg/L during the injection period. Eighteen hours after stopping the injections, samples were collected from the

three monitor wells (17PS-01, -02 and -03) in the middle of the test cell. These were situated approximately 2.5 ft from surrounding injection wells **(Figure 6-2).** They were not reported as "milky" and TOC concentrations ranged from 10.5 to 150 mg/L suggesting that some components of EOS® had spread at least the 2.5 ft from the injection point.

7.2.1.1 Background Monitor Wells

The first post-injection sampling event occurred about 20 days after beginning the injections. As shown in **Figure 7-2,** there was no appreciable change to the TOC concentration in the three background monitor wells throughout the entire 1,252 day duration of both Phase I and Phase II. The complete data set is provided in **Table IV-2** in **Appendix IV**. The average TOC in groundwater in the background wells was 3.9 ± 4.7 mg/L.

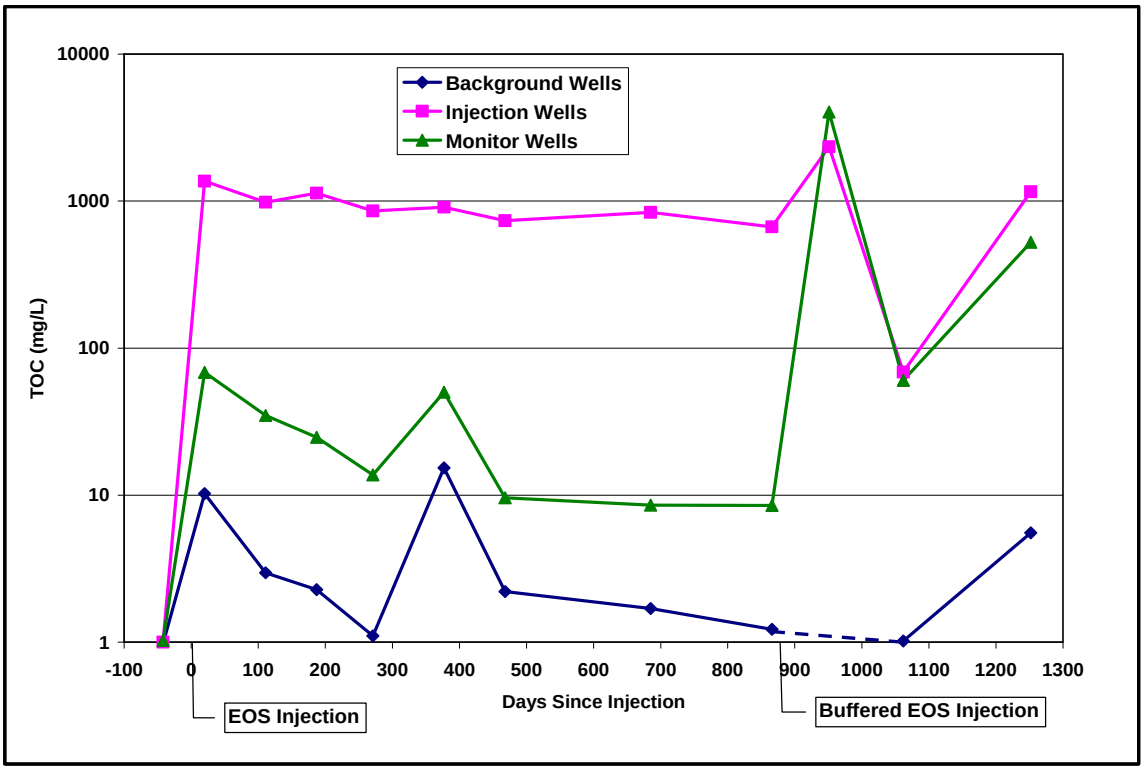


Figure 7-2. Total Organic Carbon Concentrations vs. Time since Injection

7.2.1.2 Injection Wells

As expected, the TOC in the injection wells increased immediately following EOS® injection and remained high for over 800 days. The injection of EOS® resulted in an increase in TOC from below detection to an average of 1,364 mg/L by 20 days post-injection. Over the duration of Phase I, there was a slow decrease in concentration as a result of depletion due to fermentation and metabolism. After 28 months, however, about 50% of the initial TOC concentration was still measureable attesting to the longevity of the substrate in this environment.

The addition of buffered EOS® beginning on Day 866 resulted in a 3.5-fold increase in the TOC in the injection wells indicating that direct injection through the Geoprobe® rods resulted in migration of oil droplets at least 2.5 ft away from the injection points. By 3.5 months later, the TOC concentration in groundwater had decreased substantially, presumably as a result of adsorption to soil grains. This process leaves a long-term continuing source of electron donor in the aquifer to support extended bioremediation.

7.2.1.3 Treatment Cell Monitor Wells

TOC concentrations in the treatment cell monitor wells followed the same general pattern as the injection wells, although the concentrations were not as high. The injection of EOS® immediately resulted in an increase in TOC to 70 mg/L by 20 days post-injection, followed by a slow decline over time. After 377 days (~12 months) the average TOC concentration was still 57.4 mg/L, but by 468 days (~15 months), the concentration had dropped to 9.6 mg/L. This is below 20 mg/L, a threshold commonly assumed to be favorable for reductive dechlorination (AFCEE et al., 2004).

The injection of buffered EOS® into the test cell caused a large immediate increase in TOC. Although the TOC concentration decreased thereafter, the TOC remained elevated for the remaining 301 days that comprised the Phase II performance monitoring period.

7.2.2 Volatile Fatty Acids (VFAs) in Groundwater

In the presence of oxygen, the biodegradation of the soybean oil component of EOS® proceeds by the process of β-oxidation where the long-chain fatty acids are broken into shorter fragments. Whereas the soybean oil is not soluble, these shorter fatty acids are soluble and can be transported in groundwater. The presence of VFAs (i.e., short-chain keto acids) is an indicator that the initial fermentation step required for production of H_2 is occurring.

Six VFAs were measured in groundwater in one background monitor well (17MW-6S), two injection wells (17PSI- 07 and 17-PSI-10) and one test cell monitoring well (17PS-02). These were formic acid (1-carbon), acetic acid (2-carbon), pyruvic acid (3-carbon), lactic acid (3-carbon), propionic acid (3-carbon) and butyric acid (4-carbon). The results are provided in **Table 7-3**.

Table 7-3
Summary of Volatile Fatty Acids and Total Organic Carbon in Selected Wells
SWMU 17, Naval Weapons Station
Charleston, SC

Days Since Injection	Sample Date	Pyruvic Acid (mg/L)	Formic Acid (mg/L)	Lactic Acid (mg/L)	Acetic Acid (mg/L)	Prop-ionic Acid (mg/L)	Butyric Acid (mg/L)	Total VFA Carbon (mg/L)	Total Organic Carbon (mg/L)
17MW-6S (Background Well)									
-42	4/1/04	<4	<1	<1	<1	<1	<1	<1	<1.0
20	6/2/04	<4	<1	<1	6	<1	<1	2.4	15.1
111	9/1/04	<40	<1	<10	<1	<1	<1	<1	3.8
187	11/16/04	<4	<1	<1	<1	<1	<1	<1	3.6
271	2/9/05	<4	<1	<1	<1	<1	<1	<1	1.9
377	5/25/05	<4	<1	<1	<1	<1	<1	<1	18.0
468	8/24/05	<4	<1	<1	<1	<1	<1	<1	2.4
866	9/26/06	<4	<1	<1	<1	<1	<1	<1	1.4
951	12/20/06	NA	NA	NA	NA	NA	NA	NA	NA
1062	4/10/07	<4	<1	<1	<1	<1	<1	<1	1.2
1252	10/17/07	<4	<1	<1	<1	<1	<1	<1	5.4
17PSI-7 (Injection Well)									
-43	3/31/04	<4	<1	<1	<1	<1	<1	<1	<1
20	6/2/04	<4	<1	<1	224	175	119	240	4560
111	9/1/04	<40	17.1	<10	282	44.5	250	273	1240
188	11/17/04	<80	<20	<20	664	31.7	520	569	1610
271	2/8/05	<40	<1	<1	496	34.6	396	435	1190
377	5/25/05	<4	<10	<10	473	30.3	289	364	1310
468	8/24/05	<4	<1	<1	564	26.5	308	409	892
865	9/25/06	<4	<1	<1	612	17.1	441	498	936
951	12/20/06	<4	<1	<1	834	56.1	691	743	1250
1062	4/10/07	<4	<1	<1	708	47.5	583	629	104
1252	10/17/07	<4	<1	<1	535	52.2	310	411	1010
17PSI-10 (Injection Well)									
-43	3/31/04	<4	<1	<1	<1	<1	<1	<1	<1
20	6/2/04	<4	<	<1	183	244	64.7	228	482
111	9/1/04	<40	2.4	<10	482	123	247	390	1110
188	11/17/04	<80	<20	<20	677	90.9	271	465	864
271	2/8/05	<4	<1	<1	618	50.6	258	415	784
377	5/25/05	<4	<1	<1	396	31.5	158	261	685
468	8/24/05	<4	<1	<1	491	37.6	209	330	631
866	9/26/06	<4	<1	<1	404	9.60	200	277	519
951	12/20/06	<4	<1	<1	564	78.6	285	422	642
1062	4/10/07	<4	<1	<1	423	71.3	221	326	54
1252	10/17/07	<4	<1	<1	433	70.6	193	315	646

17PS-02 (Test Cell Monitor Well)									
-42	4/1/04	<4	<1	<1	<1	<1	<1	<1	1.03
20	6/2/04	<4	<1	<1	108	5.50	1.40	47	57.6
111	9/1/04	<40	<1	<10	<1	<1	<1	<1	13.3
187	11/16/04	<4	<1	<1	24.5	2.1	<1	11	18.2
271	2/8/05	<4	<1	<1	5.40	<1	<1	2	5.1
377	5/25/05	<4	<1	<1	<1	<1	<1	<1	5.6
468	8/24/05	<4	<1	<1	<1	<1	<1	<1	3.9
866	9/26/06	<4	<1	<1	<1	<1	<1	<1	2.9
951	12/20/06	<4	<1	5.0	2219	1422	240	1712	2510
1062	4/10/07	<4	<1	<1	2933	1128	420	1954	45.6
1252	10/17/07	<4	<1	<1	717	82.2	43.9	351	525

1) Total VFA carbon calculated as the sum of carbon content of acetic acid (40%), propionic acid (48.6%) and butyric acid (55.4%).
2) The TOC data on Day 1062 are suspect and appear to be anomalous. In general, TOC should exceed VFA concentrations.
3) NA = Not Analyzed

There was virtually no evidence for VFAs in background monitor well 17MW-6S indicating that the natural degradation of background TOC in the aquifer does not result in the formation of these compounds. The response in the injection wells was immediate as concentrations of acetic, propionic, and butyric acid were detected within 20 days of initiating the injection of EOS®. Although there is a small percentage of lactic acid in the EOS® formulation, no lactic acid was detected. This suggests that it is readily biodegraded by indigenous microbes and not an end-product of breakdown of the soybean oil in EOS®.

The concentrations of acetic, propionic and butyric acids remained elevated in the injection wells for the duration of the 28-month Phase I performance monitoring period with little evidence of decrease. The addition of buffered EOS® resulted in a slight increase in VFAs over the amount that was remaining in the aquifer after 28 months.

The concentrations of acetic, propionic and butyric acids in monitor well 17PS-2 in the middle of the test cell were different than in the injection wells. After the initial detection of low concentrations of all three VFAs on Day 20, the only VFAs to be detected thereafter during the first 28 months of performance monitoring were acetic acid twice and propionic acid once. This suggests that the VFAs formed in the injection wells did not migrate from near the injection wells to the monitor wells.

The addition of buffered EOS® in Phase II resulted in a large increase in acetic, propionic and butyric acids in 17PS-02. The likely explanation is the proximity of the injections to the monitor wells meant that the VFAs could be observed in the monitor well before they had the opportunity to be degraded in the aquifer.

The concentration of organic carbon attributable to the VFAs is compared to the corresponding TOC concentration in these wells in the last two columns of **Table 7-3**. Fermentation of the long-chain (C16 and C18) fatty acids that comprise soybean oil in the

EOS® quickly begin to ferment to shorter compounds (C3 to C4) that are more useful to the bacteria. The percentage of VFAs compared to TOC in the injection wells reached a maximum of 65.7 % on Day 564 in well 17PSI-10. The maximum percent VFAs in monitor well 17PS-02 was 81%, achieved on Day 20 after EOS® injection. The TOC data gathered on Day 1,062 appear anomalous as the concentrations of VFAs greatly exceed the concentration of TOC. Overall, it appeared that the majority of the TOC in the groundwater within the treatment cell was converted to short-chain VFAs, but a significant percentage of the TOC was associated with other types of organic carbon. Nonetheless, the VFA results support the TOC results and attest to the longevity of the emulsified oil substrate in the aquifer.

7.2.3 Total Organic Carbon in Soil

Using the Geoprobe®, soil samples were collected from Macro-Core® sleeves to determine baseline TOC conditions throughout the soil profile in the treatment cell. Baseline results were shown in **Table 5-1**. The locations of the soil borings are shown in **Figure 7-3**. The results for all samples collected in March 2004 before EOS® injection are shown on **Table 7-4**. The 23 values from samples between 0 and 14 ft bgs and eight values from samples collected from 14 to 18 ft bgs were averaged separately. The baseline TOC throughout the soil profile averaged 323 ± 203 mg/kg in the upper portion of the aquifer and 999 ± 844 mg/kg in the deeper portion of the aquifer.

Figure 7-3. Locations of Soil Borings used to Collect Baseline and 9-Month Post-Injection TOC Samples

Soil samples were not collected immediately after EOS® injection but were collected on February 10 and 11, 2005, approximately 275 days (~9 months) post-injection. As shown on **Table 7-4**, six soil borings were advanced to 18 ft bgs. Samples were collected from 10 to 12 ft bgs in four samples and 16 to 18 ft bgs in all six samples. The TOC concentrations in three of the four shallower soils were below the method detection limit of 1,000 mg/kg and one was 2,140 mg/kg, whereas the mean of the deeper samples was 1,953 ± 304 mg/kg. These results provide some evidence that the addition of EOS® elevated the TOC concentrations in the soil and that the change lasted at least 9 months.

Table 7-4
Phase I: Pre- and Post-Injection Total Organic Carbon in Soil
SWMU 17, Naval Weapons Station
Charleston, SC

	Pre-Injection Samples Collected March 1, 24 and 25, 2004												9 Months Post-Injection Samples Collected February 10 and 11, 2005					
ft bgs	**17PSI-1**	**17PSI-2**	**17PSI-4**	**17PSI-5**	**17PSI-6**	**17PSI-8**	**17PSI-9**	**17PSI-13**	**17PSI-14**	**17PSI-15**	**17PSI-16a**	**17PSI-16**	**17PSSB-1**	**17PSSB-2**	**17PSSB-3**	**17PSSB-4**	**17PSSB-5**	**17PSSB-6**
0-2	340*																	
1-2																		
2-3																		
3-4																		
4-5											910							
5-6	530		260															
6-7								420			500	500						
7-8																		
8-9		280		405	450							590						
9-10	190				190			210										
10-11		82.5			240	430				<1.0			2140			<1000	<1000	<1000
11-12					125													
12-13			300		180				190									
13-14					110													
14-15			1370		<1.0													
15-16					130						1560							
16-17					785		150	1880					1770	2000	1760	2470	2090	1630
17-18					2115													

*All concentrations expressed as mg/kg.

Buffered EOS® was injected into the test cell between September and October 2006. Soil samples were collected from locations within the treatment cell three times after the injection. The soils sample locations were designated as follows:

- September 26, 2006: 17PSSB-7 through 17PSSB-9
- December 20, 2006: 17PSSB-10 through 17PSSB-16
- October 18, 2007: 17PSSB-17 through 17PSSB-21

The locations are shown on **Figure 7-4**. Soil samples were collected from Geoprobe® Macro-Core® sleeves advanced into five borings on October 18, 2007 during the last performance monitoring event of Phase II. This was approximately 386 days (~12.5 months) after the buffered EOS® was injected. Sixteen samples, all from depths greater than 8 ft bgs, were submitted to the laboratory for TOC analysis.

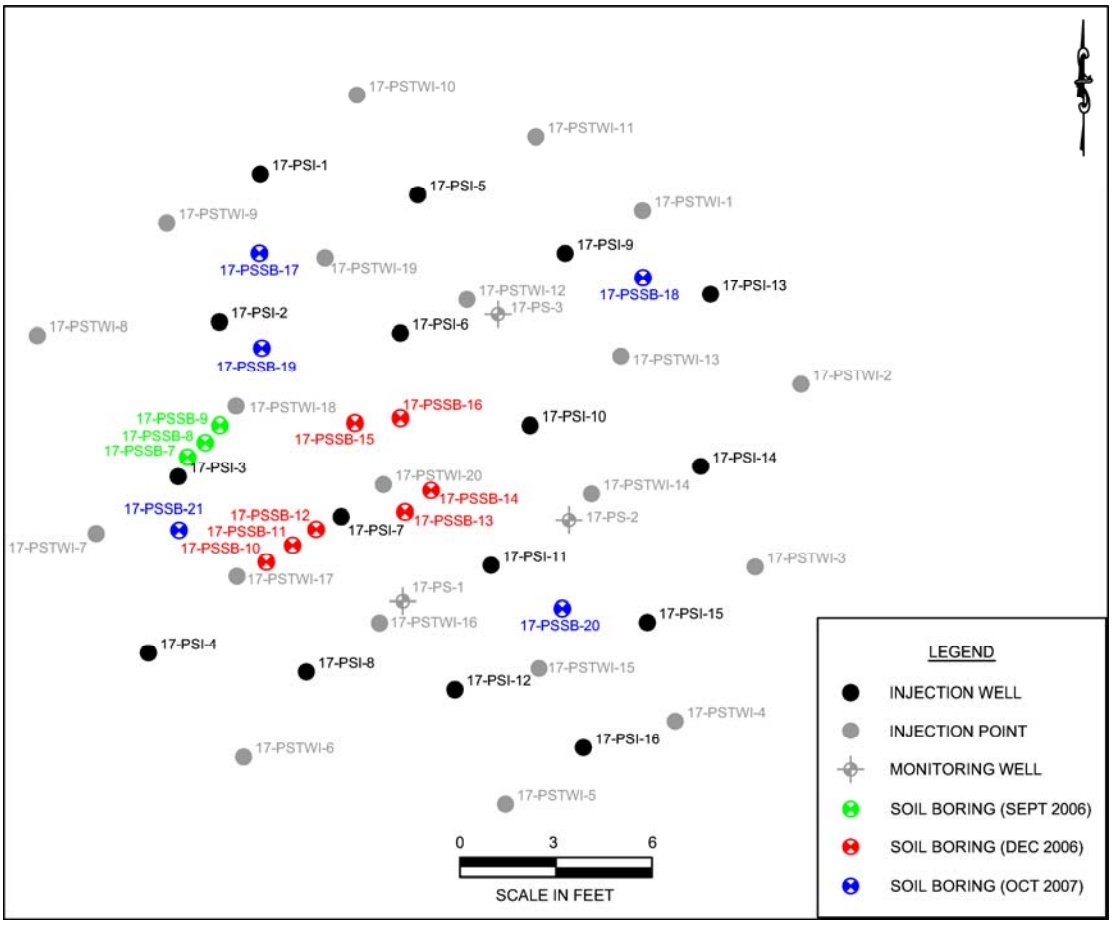


Figure 7-4. Locations of Soil Borings Advanced after Injection of Buffered EOS®.

The TOC concentrations in 15 of the 16 samples collected in October 2007 from all the depths were below the method detection limit of 146 mg/kg, except the sample from 14 to 16 ft bgs in soil boring 17PSSB-20 (8,280 mg/kg). The apparent absence of TOC from

the soil profile is likely a laboratory analysis anomaly since: a) most of the TOC measurements were below the initial background TOC of the aquifer; and b) approximately 1,800 lbs of buffered EOS® had been added one year earlier and it was expected that evidence for substantial amount of residual TOC would be measureable. It may be that high levels of $Mg(OH)_2$ in the samples interfered with volatilization of CO_2 during the TOC analysis.

7.3 Geochemical Indicator Parameters

Various electron acceptors can potentially compete with reductive dechlorination for electron donors, including dissolved oxygen (DO), nitrate, sulfate, iron (III), manganese (IV), and carbon dioxide (methanogenesis). These parameters or their byproducts (e.g., Fe[II], Mn[II], methane) were measured to assess conditions across the pilot test cell. A discussion of each parameter is provided below. In addition, to further characterize the changes to the aquifer, the oxidation-reduction potential (redox), pH and chloride concentrations were measured during the performance monitoring activities.

7.3.1 Dissolved Oxygen

Dissolved oxygen is used by aerobic and facultative microorganisms as an electron acceptor for the biodegradation of organic carbon. Reductive dechlorination is an anaerobic process and absence of DO (<0.5 mg/L) is required for optimal anaerobic biodegradation.

The average DO concentrations are shown on **Table 7-5.** The full data set is provided in **Table IV-2** of **Appendix IV**. The average DO in the injection wells and the treatment cell monitoring wells are shown in **Figure 7-5**. In general, after the injection of EOS®, DO levels decreased across the entire pilot test cell. The DO concentrations in the injection wells quickly dropped to below 0.5 mg/L and stayed less than 1.0 mg/L through the first 28 months of monitoring. It took more than 3 months for the average DO in the test cell monitor wells to drop below 0.5 mg/L, but these concentrations then remained below 1 mg/L for the duration of the Phase I monitoring period. The addition of buffered EOS® in Phase II did not change the DO within the test cell.

Table 7-5
Average Concentrations of Dissolved Oxygen, Sulfate and Dissolved Iron
SWMU 17, Naval Weapons Station
Charleston, SC

Well ID (Distance from barrier)	Sample Date	Days (Months) After Injection		DO (mg/L)	SO_4 (mg/L)	Dissolved Fe (mg/L)
Average of 3 Background Monitor Wells 30 - 40 ft from Treatment Cell	3/31/04	-43		2.89	25.2	2.0
	6/2/04	20	(~0.5)	0.52	2.0	7.7
	9/1/04	111	(~3)	0.16	14.2	6.4
	11/17/04	188	(~6)	0.56	27.2	8.4
	2/9/05	272	(~9)	0.35	23.1	2.8
	5/25/05	377	(~12)	0.33	34.7	5.4
	8/24/05	468	(~15)	0.45	26.8	8.2
	3/28/06	684	(~22)	0.55	31.1	2.2
	9/25/06	865	(~28)	1.23	NA	9.0
	12/20/2006	951	~(31)	NA	NA	NA
	4/10/2007	1062	(~35)	0.57	29.2	7.2
	10/17/2007	1252	(~41)	0.60	54.1	16.7
Average of 4 Injection Wells in Treatment Cell	3/31/04	-43		3.53	88.8	35
	6/2/04	20	(~0.5)	0.55	38.9	150
	9/1/04	111	(~3)	0.25	<0.43	198
	11/17/04	188	(~6)	0.12	<0.25	213
	2/9/05	272	(~9)	0.43	<0.43	235
	5/25/05	377	(~12)	0.27	<0.25	225
	8/24/05	468	(~15)	0.39	<0.25	198
	3/28/06	684	(~22)	0.62	<0.25	283
	9/25/06	865	(~28)	0.64	<0.25	193
	12/20/2006	951	~(31)	0.72	NA	164
	4/10/2007	1062	(~35)	0.58	8.76	183
	10/17/2007	1252	(~41)	0.80	<0.25	63
Average of 3 Monitor Wells Within the Treatment Cell	3/31/04	-43		0.86	67.0	66
	6/2/04	20	(~0.5)	1.90	19.5	104
	9/1/04	111	(~3)	0.14	10.2	137
	11/17/04	188	(~6)	0.17	13.4	160
	2/9/05	272	(~9)	0.23	19.0	150
	5/25/05	377	(~12)	0.37	9.08	134
	8/24/05	468	(~15)	0.34	14.8	177
	3/28/06	684	(~22)	0.48	15.6	237
	9/25/06	865[d]	(~28)	0.62	1.65	125
	12/20/2006	951	~(31)	NM	6.85	3.1
	4/10/2007	1062	(~35)	0.72	1.89	4.5
	10/17/2007	1252	(~41)	0.33	0.33	1.0

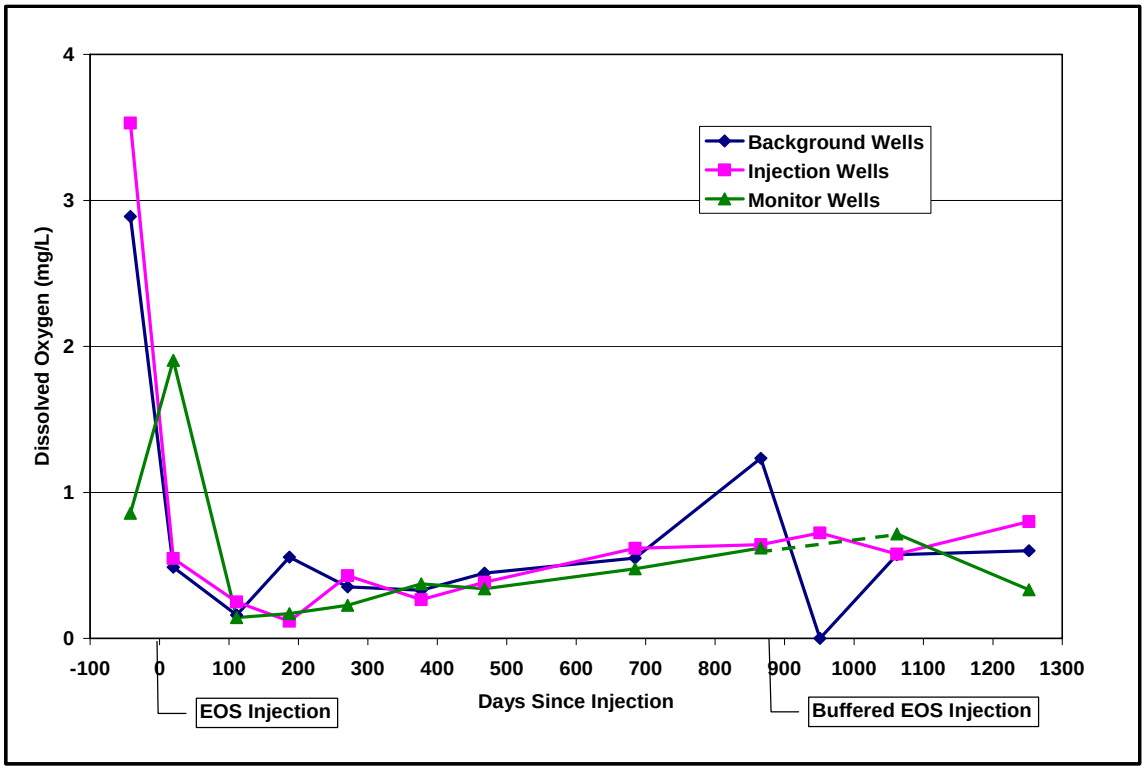


Figure 7-5. Average Dissolved Oxygen Concentrations vs. Time since Injections

7.3.2 Nitrate

Nitrate reduction is another indicator of anaerobic conditions favorable for biodegradation. Following depletion of oxygen, denitrification can occur resulting in decreased nitrate concentrations in the aquifer. The results of all nitrate analyses are presented on **Table IV-2** in **Appendix IV.** No nitrate was detected in groundwater before, during or after the pilot test. Therefore, nitrate was not a competing electron acceptor at this site.

7.3.3 Sulfate

Sulfate reduction is another indicator of favorable anaerobic conditions. The baseline sulfate concentration for all wells across the entire site prior to the addition of any substrate ranged from 19 to 103 mg/L (see Day -43 results; **Table IV-2** in **Appendix IV**) with a site wide average of 63 ± 31 mg/L. The changes in sulfate concentrations throughout the treatment cell are shown in **Figure 7-6**. During Phase I, the average sulfate concentrations in the three background wells ranged from 3 to 31 mg/L with little fluctuation. There was a sharp drop 20 days after EOS® injection which cannot be explained since these wells are a sufficient distance from the treatment cells to have remained unaffected by the injection of substrate. However, by three months post-injection, the sulfate levels had returned to background conditions greater than 20 mg/L. At the end of 42 months, the average sulfate concentration in the background wells was 54 mg/L.

By contrast, sulfate concentrations in the injection and monitor wells in the treatment cell were quickly reduced to below 20 mg/L soon after the injections occurred. For the last two years of Phase I of the pilot test (i.e., between 3 and 28 months post-injection), the average sulfate levels in the injection wells remained below detection (<0.5 mg/L). The average sulfate concentrations in three monitor wells within the treatment cell remained <20 mg/L during the same period. In Phase II, except for one detection on Day 1062, sulfate remained below detection in the injection and monitor wells in the treatment cell.

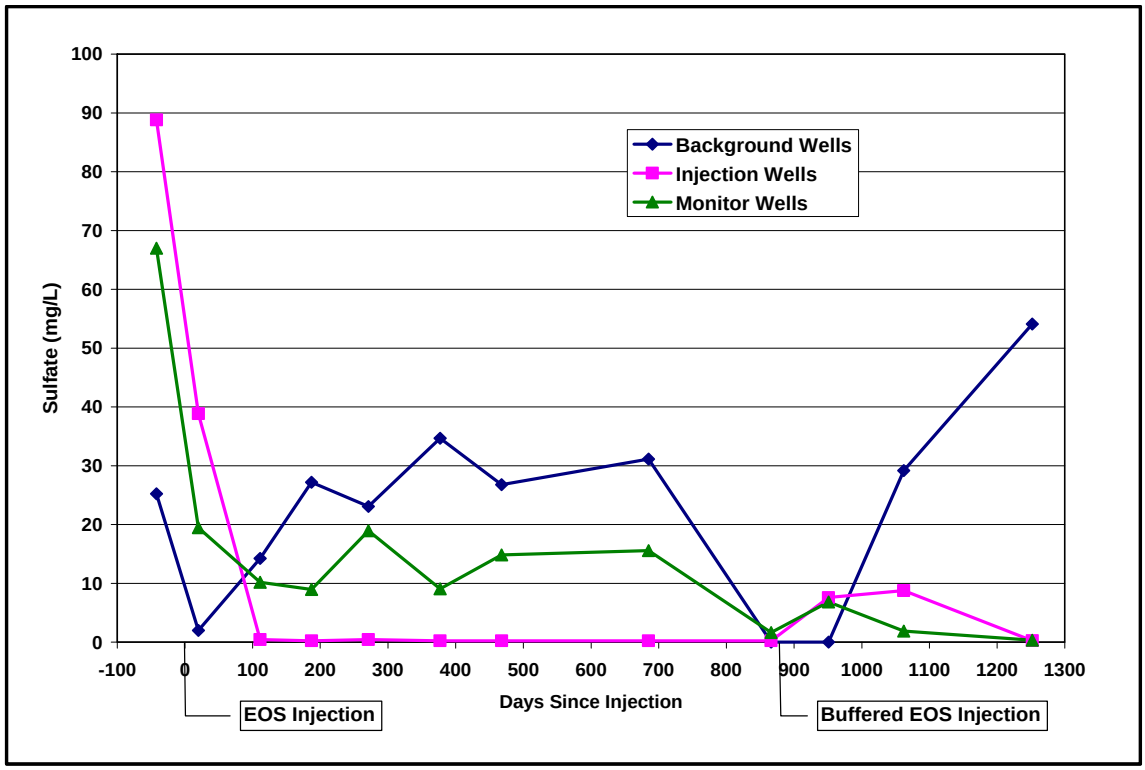


Figure 7-6. Average Sulfate Concentrations vs. Time Since Injections

7.3.4 Iron and Manganese

Iron and manganese reduction are anaerobic processes in which Fe[III] is reduced to Fe[II] and Mn(IV) is reduced to Mn(II). The reduced forms of iron and manganese are soluble in water. Thus, increases in dissolved iron and dissolved manganese can be indicators of anaerobic biodegradation.

Prior to injection, dissolved iron concentrations varied between 2.0 and 66 mg/L indicating anaerobic, iron reducing conditions. There was very little change in the concentration of dissolved iron in the three upgradient wells during the 28 months of the Phase I performance monitoring period; the average dissolved iron concentration was 7 ± 3 mg/L in the background wells (**Table 7-4**).

EOS® injection created iron-reducing conditions in the treatment cell resulting in large increases in dissolved iron (**Figure 7-7**). During Phase I, the average dissolved iron

concentration in the treatment cell injection and monitor wells reached 237 and 283 mg/L, respectively. These dissolved iron concentrations are much higher than commonly observed during anaerobic bioremediation processes and are thought to be associated with the low pH of the test cell. Under anaerobic conditions, Fe[III] minerals are reduced to soluble Fe[II]. However, Fe[II] concentrations are typically limited to 10 to 20 mg/L by co-precipitation with CO_3^{-2} as siderite ($FeCO_3$). However, we hypothesize that the decline in pH from 6 to 4 may have reduced the CO_2^{-2} activity 100-fold, preventing siderite formation.

Dissolved iron concentrations in the monitor wells dropped immediately after buffered EOS® injection, and remained below 5 mg/L for the remainder of the monitoring period. Dissolved iron concentrations in the injection wells declined more slowly, but dropped to an average of 63 mg/L by the end of the pilot test. The very rapid drop in dissolved Fe in the monitor wells is presumably due to the high pH achieved in these wells, which resulted in a conversion of H_2CO_3 to CO_3^{-2} and precipitation of Fe(III) as $FeCO_3$. The pH increase in the injection wells was less dramatic, which presumably resulted in the more gradual decline in Fe in these wells.

Manganese reduction was also observed in the pilot test cell, but the starting concentrations were not high and the changes were not as substantial. The manganese concentration across the site remained less than 1 mg/L throughout the duration of the pilot test. The manganese data are shown in **Table IV-2** of **Appendix IV**. The average background manganese concentration remained 0.15 ± 0.10 mg/L for the entire test. After EOS® was added to the treatment cell, the manganese concentrations increased to 0.75 ± 0.16 mg/L and 0.61 ± 0.11 mg/L in the four injection wells and three monitor wells, respectively. After the addition of buffered EOS®, the concentration of dissolved manganese remained elevated in the four injection wells, but declined in the three monitor wells, presumably due to the higher pH in the monitor wells. This is similar to the effect seen on dissolved iron.

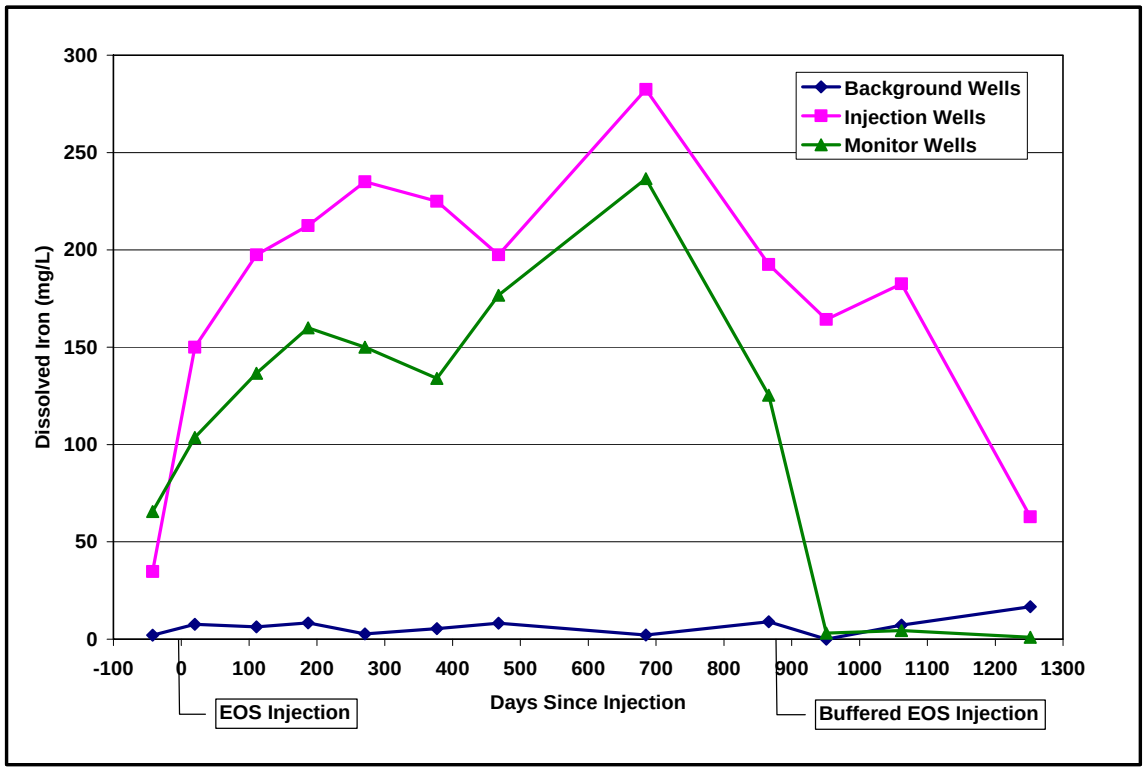


Figure 7-7. Average Dissolved Iron Concentrations vs. Time since Injections

7.3.5 Oxidation-Reduction Potential

ORP is a measure of the electron activity of the groundwater. At ORP levels less than +50 mV, reductive dechlorination pathways are possible; below –100 mV conditions are most conducive for supporting reductive dechlorination pathways. ORP measurements collected at the site are summarized in **Figure 7-8 and Table 7-6**.

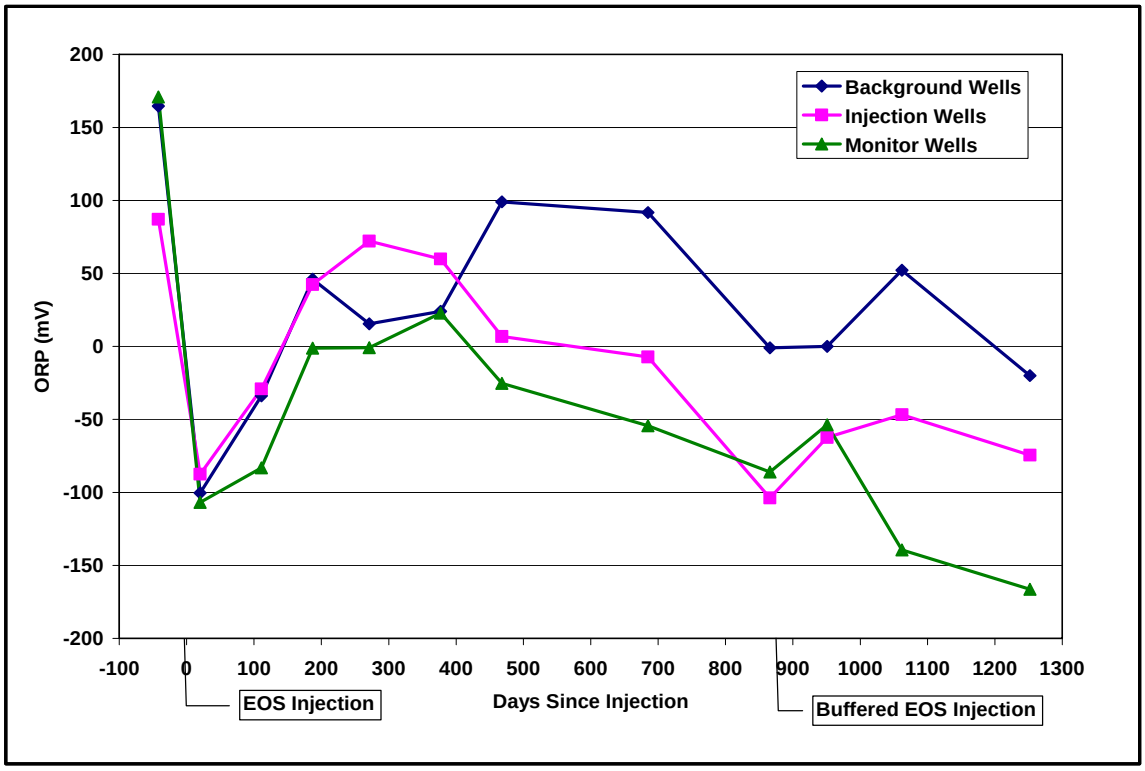


Figure 7-8. Average Oxidation-Reduction Potential vs. Time since Injections

The average ORP in the background and treatment cell monitor/injection wells was similar through the first 377 days of post-injection monitoring ranging from approximately -100 to +60 mV. Measurements of shallow groundwater ORP in this range are consistent with the location of the pilot test cell in a wooded wetland area, which might be expected to contribute to baseline conditions characterized by generally low DO concentrations, an absence of nitrate, and low levels of dissolved organic carbon, iron and methane in the groundwater. After this initial period of acclimation to the presence of substrate, the ORP in the injection wells and treatment cell monitor wells decreased compared to the untreated background wells. In the treatment cell, the average ORP stayed consistently below 0 mV throughout the balance of Phase I and II monitoring. Lowest ORP values were achieved in the three monitor wells in the treatment cell after buffered EOS® was injected reaching a low of -166 mV on the last day of sampling (Day 1252).

Table 7-6
Changes in Oxidation-Reduction Potential, Methane and pH over Time
SWMU 17, Naval Weapons Station
Charleston, SC

Well ID (Distance from barrier)	Sample Date	Days (Months) After Injection		ORP (mV)	Methane (µg/L)	pH (S.U.)
Average of 3 Background Monitor Wells 30 – 40 ft away from the Treatment Cell	3/31/04	-43		165	90.5	7.40
	6/2/04	20	(~0.5)	-100	124	6.31
	9/1/04	111	(~3)	-34	56.5	5.42
	11/17/04	188	(~6)	46	63.6	6.49
	2/9/05	272	(~9)	15	99.8	5.43
	5/25/05	377	(~12)	24	121	6.59
	8/24/05	468	(~15)	99	130	5.41
	3/28/06	684	(~22)	92	62.7	6.01
	9/25/06	865	(~28)	-1	139	4.18
	12/20/2006	951	~(31)	NA	NA	NA
	4/10/2007	1062	(~35)	52	132	5.63
	10/17/2007	1252	(~41)	-20	112	5.97
Average of 4 Injection Wells in Treatment Cell	3/31/04	-43		87.1	36	6.28
	6/2/04	20	(~0.5)	-87.5	39	5.53
	9/1/04	111	(~3)	-29.1	26	5.18
	11/17/04	188	(~6)	42.4	130	5.02
	2/9/05	272	(~9)	72.1	492	4.61
	5/25/05	377	(~12)	59.9	2,168	4.99
	8/24/05	468	(~15)	6.8	1,766	4.78
	3/28/06	684	(~22)	-7.3	1,828	5.11
	9/25/06	865	(~28)	-103.8	3,317	3.69
	12/20/2006	951	~(31)	-62.3	4,790	6.15
	4/10/2007	1062	(~35)	-46.8	7,847	6.25
	10/17/2007	1252	(~41)	-74.5	6,599	5.90
Average of 3 Monitor Wells Within the Treatment Cell	3/31/04	-43		170.9	31	6.73
	6/2/04	20	(~0.5)	-106.7	37	5.95
	9/1/04	111	(~3)	-83.1	83	5.74
	11/17/04	188	(~6)	-1.2	1,048	6.27
	2/9/05	272	(~9)	-0.9	3,009	5.66
	5/25/05	377	(~12)	22.8	1,945	6.29
	8/24/05	468	(~15)	-25.2	1,637	5.45
	3/28/06	684	(~22)	-54.3	2,474	5.90
	9/25/06	865[d]	(~28)	-86.0	2,739	5.11
	12/20/2006	951	~(31)	-53.7	9,045	8.50
	4/10/2007	1062	(~35)	-139.4	8,162	7.63
	10/17/2007	1252	(~41)	-166.3	9,012	7.50

Immediately after the Phase I EOS® addition, the ORP declined in both the background and in the test cell wells. This was followed by a gradual increase in ORP to measurements ranging between 0 and +72 mV across the site. This ORP is not considered to be strongly supportive of reductive dechlorination. After one year, the impact of the injection of substrate became more evident as the ORP of the injection wells and the monitor wells in the test cell began to decrease steadily into the more reducing range, while the background monitor wells stayed generally more oxidative.

ORP values below -100 mV are generally considered desirable for complete reductive dechlorination (AFCEE et al., 2004). The lowest average ORP measured during Phase I was -107 mV in the test cell monitor wells soon after injection. The lowest ORP in the injection wells was measured 28 months into Phase I at -104 mV. After buffered EOS® was added to the treatment cell, the ORP in the monitor wells dipped to -166 mV, closer to the desired range.

7.3.6 Methane

A low level of methanogenesis was measureable across the site before the treatment began. The presence of methane above baseline conditions indicates anaerobic microbial degradation of organic substrate is occurring and strongly reducing conditions have been established. As shown in **Table 7-6 and Figure 7-9,** before EOS® injection, baseline average methane concentrations ranged from 30 to 90 µg/L in the 10 pilot test wells. Throughout the performance monitoring period of both Phase I and II, the average methane concentration in the three background wells was 100 ± 50 µg/L (maximum = 230 µg/L). As shown in **Figure 7-9**, the concentrations of methane began to increase after approximately six months post-injection and then plateaued at 1,000 to 3,500 µg/L until buffered EOS® was injected at 866 days. Once buffered EOS® was injected, methane concentrations within the treatment cell increased to a maximum of 9,000 µg/L during the 1-year Phase II performance monitoring period.

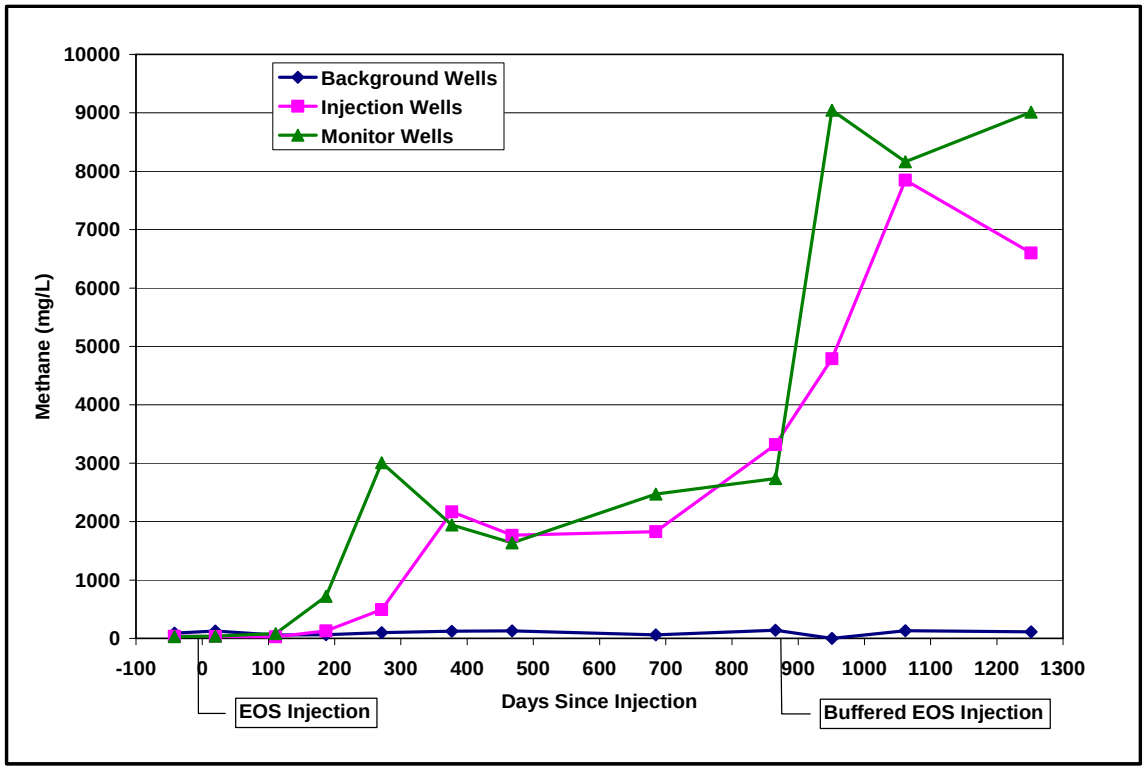


Figure 7-9. Average Methane Concentrations vs. Time since Injections

7.3.7 pH

As described in Section 6.2.1, pH values ranging from 6 to 8 standard units are generally preferable for *in situ* biodegradation, especially reductive dechlorination. Changes in pH are a concern when conducting enhanced anaerobic bioremediation projects because of the sensitivity of the microbial populations. The EOS® substrate used in the initial injections in Phase I contained lactic acid and has a low starting pH (~3.5 to 4.0). The buffered EOS® used in Phase II contained all the ingredients of the original EOS®, but also contained $Mg(OH)_2$ buffer, resulting in a starting pH of the concentrate near pH 9.

7.3.7.1 Groundwater

The average pH changes in groundwater over time are shown in **Table 7-6** and **Figure 7-10.** Over the course of the 28-month Phase I performance monitoring period, the pH levels in all wells across the site, including the background monitoring wells, generally declined. The average pH in the three treatment cell monitor wells slowly declined over time from the pH 6.7 baseline to between pH 5.9 and pH 5.1 over the last 13 months of Phase I. In the injection wells, the pH dropped from a pre-injection value of pH 6.3 to closer to pH 5.2 within three months of treatment. The pH in the injection wells continued to slowly decrease thereafter reaching a low value of pH 3.7 at the end of the 28-month performance monitoring period.

The lowering of the pH in the treatment cell monitor and injection wells was presumed to be the result of several contributing factors: low alkalinity in site

matrices; initial pH of the substrate; breakdown of the substrate into short-chain carboxylic acids (VFAs); release of HCl during reductive dechlorination; and low groundwater velocity. These possible causes for the formation of these potentially sub-optimal conditions are discussed below.

Alkalinity. Alkalinity is important in the maintenance of groundwater pH because it buffers the groundwater system against acids generated during both aerobic and anaerobic biodegradation. Natural biodegradation rarely generates enough acid to be of consequence (USEPA, 1998), but in the presence of added substrate this can become problematic. Alkalinity measures the interaction of CO_2 from biological metabolism on natural minerals. The alkalinity measured in the treatment cell and background wells was low prior to EOS® injection (**Table IV-2** in **Appendix IV**). The alkalinity was apparently insufficient to buffer acid by-products formed by the degradation of the EOS® substrate and VFAs that are formed by fermentation.

Initial pH of the EOS® substrate. The EOS® concentrate is manufactured with lactic acid to help extend its shelf life. When sufficient alkalinity is present, the lactic acid is neutralized to lactate and rapidly biodegraded. However, in the absence of natural alkalinity, lactic acid addition may result in a pH decline. Some immediate drop in pH was observed in the treatment cell injection and monitor wells within one month after injection.

Volatile Fatty Acids. Formation of VFAs during fermentation of soybean oil in the EOS® substrate would also contribute to the observed drop in pH in the treatment zone. VFAs are short-chain carboxylic acids, which at lower pH exist in an un-ionized form as acetic, propionic and butyric acid. There is a cascading effect where an initial accumulation of VFAs results in a decline in pH, inhibiting VFA conversion to methane, which results in a further buildup in VFAs and a further decline in pH. The formation of VFAs in groundwater beneath the treatment cell was discussed in Section 7.1.2. As shown in **Table 7-2**, VFAs appeared in the treatment cell monitor wells within one month of treatment and remained elevated throughout the course of Phases I and II.

Low Groundwater Flow Velocity. High groundwater flow velocities can transport VFAs away from injection zones. However, when groundwater velocities are low, VFAs can accumulate close to the injection point, resulting in fatty-acid toxicity and further declines in pH. As discussed in Section 5.2, at the pilot test site the hydraulic gradient was flat, hydraulic conductivity was generally low, and groundwater velocity was slow. The low velocity may have contributed towards buildup in VFAs and associated decline in pH.

The impact of these factors on microbial activity was discussed in Section 6.1.2 and can be applied to the data observed during the study as follows: For the period from 111 to 865 days post-injection, the average pH in the treatment cell ranged between pH 5.1 and pH 6.3 in the three monitor wells and pH 5.2 and pH 3.7 in the four injection wells (**Table 7-6**). The impact of these pH ranges and

changes over time are discussed in detail in Section 7.3. It is noted here that during this same period, there was little conversion of TCE to *cis*-DCE and very little, if any, conversion of *cis*-DCE to VC or ethene.

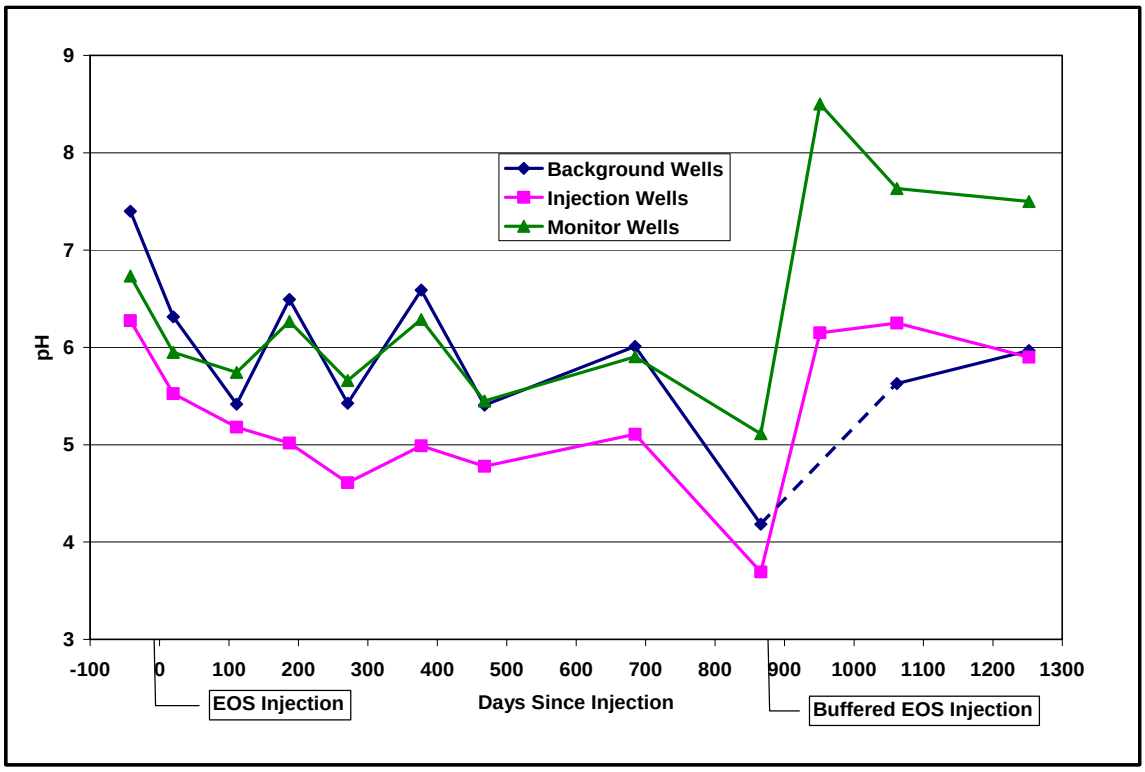


Figure 7-10. Changes in Average pH vs. Time Since Injections

Independent of the pilot test study, NWS site managers made several attempts to modify the pH in the monitor wells in the test cell. Under the direction of Mr. Cliff Casey of SOUTHDIV and Mr. Don Vroblesky of USGS, bags containing granular calcite, magnesium oxide (MgO), or sodium bicarbonate ($NaHCO_3$), were suspended across the length of the screen interval in 17PS-02 during the period between September 2005 and February 2006. Changes in pH were monitored (data not available), but performance monitoring pH results in 17PS-02 in August 2005 (Day 468) were compared to March 2006 (Day 684) and showed an increase in groundwater pH going from pH 5.29 to pH 5.98, presumably as a result of the downhole adjustment (**Table 7-7**). All materials were removed from 17PS-02 in February 2006 and the wells were allowed to re-establish aquifer conditions within the test cell. In June 2006, downhole socks containing MgO were again placed in 17PS-02, and also in 17PS-03, and left in place for about 1 month. Any long-lasting impact on pH from this brief treatment was not readily apparent, as the pH measured in 17PS-02 in September 2006 (Day 866) was still pH 4.70 and the pH in 17PS-03 was pH 5.52.

Table 7-7
Impact of pH Adjustment Approaches on Test Cell Monitor Wells
SWMU 17, Naval Weapons Station
Charleston, SC

Dates	Days Since Initial Injection of EOS	pH in Monitor Wells		
		17PS-01	17PS-02	17PS-03
August 24, 2005	468	5.48	5.29	5.58
September 2005 through February 2006			Calcite, MgO, $NaHCO_3$ adjustments	
March 28, 2006	684	5.73	5.98	6.00
June 2006			MgO adjustment	MgO adjustment
September, 26, 2006	866	5.12	4.70	5.52
September to October 2006		Buffered EOS adjustment	Buffered EOS adjustment	Buffered EOS adjustment
December 20, 2006	951	8.40	8.10	9.00

To counteract the drop in pH, Phase II was initiated to inject buffered EOS® into the treatment cell. The response was immediately apparent as within three months the pH of the injection wells (**Table 7-6)** and the treatment cell monitor wells (**Table 7-7**) increased to pH 6.2 and 8.5, respectively. One year after introduction of buffered EOS® into the test cell, the average pH in the injection wells remained close to pH 6.0, while the pH in the monitor wells was 7.5 (**Table 7-6**). Concurrent with the rise in pH, there was a large decrease in TCE, with concomitant increases in *cis*-DCE, VC and ethene. These results are discussed in more detail in Section 7.4. This demonstrated that the buffered EOS® approach can be used successfully to maintain the pH of the groundwater for an extended period of time and sustain anaerobic reductive dechlorination of TCE.

7.3.7.2 Soil

The pH and alkalinity of the soils throughout the treatment cell were measured several times during the performance monitoring periods. The initial soil pH measurements were taken while collecting soils for the laboratory testing described above in Section 6.2. These first soils collected post-injection were obtained from Geoprobe® MacroCore sleeves collected during the installation of temporary wells 17PSTW-16, 17, 18, 19 and 20 in August 2005. Temporary wells 17PSTW-16 and -17 were located adjacent to the background monitor wells 17MW-5S and 17MW-6S approximately 30 ft away from the treatment cell. The soil sampling locations were shown on **Figure 6-4**. Because this area of the site was untreated, for purposes of comparison, the pH of these soils are considered representative of the natural pH of the soils. As shown in **Table 7-8a,** the results indicate that the pH is generally acidic ranging between pH 4.9 and 5.2 from 10 to 14 ft bgs; soils at 15 to 17 ft bgs range between pH 5.9 and 6.1. This may be the

result of presence of shell debris observed and noted in boring logs and slightly higher alkalinity.

Tables 7-8a and 7-**8b** summarize the pH and alkalinity measurements, respectively, in soil samples collected from various borings from 6 to 18 ft bgs during the course of the project. EOS® was first injected in May 2004 at the start of Phase I. After 14 months in the presence of EOS®, the soils collected from 17PSTW-18, -19 and -20 (from within the treatment cell) appeared to be slightly more acidic (i.e., pH 4.2 to pH 4.8) than the background soils (i.e., pH 4.9 to pH 5.2) at similar depths. Background soils collected from 16 ft bgs in 17PSTW-18 and -19 remained closer to pH 6.0, similar to the conditions observed in the untreated background soils collected from 17PSTW-16 and -17. The soil in 17PSTW-20 averaged pH 4.4 throughout the entire vertical profile.

In September 2006, after 28 months of exposure to substrate and reductive dechlorination, three soil borings designated 17PSSB-7,-8 and -9, were advanced immediately between two original injection points **(Figure 7-4).** The pH of the soils from 6 to 14 ft bgs still ranged from pH 4.7 to 5.5 whereas soils below 14 ft bgs ranged from pH 5.5 to 6.2. Alkalinity (**Table 7-8b**), which is a measure of the natural buffering capacity of the soil, also was slightly higher below 14 ft bgs, which may help explain the consistently higher pH in the deeper portion of the aquifer.

Buffered EOS® was injected into the pilot treatment cell beginning on September 26, 2006. This marked the beginning of Phase II performance monitoring. On December 20, 2006, approximately 2 months after treatment with buffered EOS®, seven soil borings (17PSSB-10, -11, -12, -13, -14, -15 and -16) were advanced throughout the test cell **(Figure 7-4).**

Table 7-8a
Soil pH Pre- and Post-Injection of Substrates
SWMU 17, Naval Weapons Station
Charleston, SC

Phase I Post-Injection Samples						Pre - Buffered EOS® Injection			Two Months After Buffered EOS® Injection							12 Months after Buffered EOS® Injection				
August 25, 2005						September 26, 2006			December 20, 2006							October 18, 2007				
ft bgs*	17PSTW-16 (Back-ground)	17PSTW-17 (Back-ground)	17PSTW-18	17PSTW-19	17PSTW-20	17PSSB-7	17PSSB-8	17PSSB-9	17PSSB-10	17PSSB-11	17PSSB-12	17PSSB-13	17PSSB-14	17PSSB-15	17PSSB-16	17PSSB-17	17PSSB-18	17PSSB-19	17PSSB-20	17PSSB-21
6-7						4.9	4.9	5.0	5.1	5.9	6.1	5.2	4.8	5.9	6.0					
7-8																				
8-9						5.1	5.2	4.7	8.0	7.4	7.6	5.5	5.0	6.7	5.9			8.4		5.0
9-10	4.9**	4.9	4.3	4.2	4.4												5.0			
10-11						5.3	5.1	4.8	7.1	7.7				7.1	6.3	6.0		7.9	6.2	
11-12	5.1	4.9	4.8	4.8	4.2															
12-13						5.5	5.3	4.7	8.1	7.7	7.1	6.4	8.5	7.0	NA	5.8		6.1	6	5.0
13-14	5.2	4.9	4.8	4.8	4.5															
14-15						6.0	6.2	5.5	NA	NA			8.7		7.0	5.6	6.6	6.3		6.4
15-16	5.9	6.1	6.2	5.7	4.4															
16-17																		7		

*pH measurements not collected from soils shallower than 6 ft bgs.
**All pH values are rounded to two significant figures and shown as Standard Units.

NA = Not Analyzed

Table 7-8b
Soil Alkalinity Pre- and Post-Injection of Substrates
SWMU 17, Naval Weapons Station
Charleston, SC

Phase I Post-Injection Samples						Pre - Buffered EOS® Injection			Two Months After Buffered EOS® Injection							12 Months after Buffered EOS® Injection				
August 25, 2005						September 26, 2006			December 20, 2006							October 18, 2007				
ft bgs*	17PSTW-16 (Back-ground)	17PSTW-17 (Back-ground0	17PSTW-18	17PSTW-19	17PSTW-20	17PSSB-7	17PSSB-8	17PSSB-9	17PSSB-10	17PSSB-11	17PSSB-12	17PSSB-13	17PSSB-14	17PSSB-15	17PSSB-16	17PSSB-17	17PSSB-18	17PSSB-19	17PSSB-20	17PSSB-21
6-7	No alkalinity measurements taken.					61	38	50	307	198	104	173	345	299	988					
7-8																				
8-9						151	70	19	33,620	1,439	4,891	384	376	749	201			1,800		<31
9-10																	<33			
10-11						127	76	41	863	2,509				930	347	200		690	150	
11-12																				
12-13						128	161	54	6,139	1,279	787	465	4,621	425	NA	250		280	270	19
13-14																				
14-15						291	341	300	NA	NA			10,202		610	170	430	55	2,500	230
15-16																				
16-18																		1,100		

*Alkalinity measurements not collected from soils shallower than 6 ft bgs.
**All alkalinity measurements are reported as parts per million (mg/kg) $CaCO_3$.
NA = Not Analyzed

Macro-Core® sleeves were collected from each boring and the pH and alkalinity of soils at the indicated depth intervals were measured. Soils shallower than 6 to 8 ft bgs, were slightly less acidic than before the addition of buffered EOS® with pH ranging between pH 4.8 and 6.1, but the soils deeper than 8 ft bgs were consistently between pH 6.7 and 8.7. The alkalinity also increased dramatically after injection of buffered EOS®.

One year after the injection of buffered EOS®, five new soil borings (17PSSB-17,-18,-19,-20 and -21) were advanced into the test cell and soil samples were collected throughout the vertical interval and analyzed for pH and alkalinity (**Figure 7-4**). Except for a few soil samples that still measured in the pH 5.0 to pH 6.0 range, the soil profile appeared to be mostly between pH 6.0 and pH 8.8 **(Table 7-8a**). The alkalinity also remained elevated compared to the pre-injection concentrations (**Table 7-8b**).

The data show that the pH of natural soils in SWMU 17 were slightly acidic and not in the optimal range to support the microbes needed for anaerobic bioremediation to proceed most effectively. This could partially explain why the elevated concentrations of TCE were persistent in SWMU 17 with little evidence of natural biodegradation. The data also show that use of emulsified oil substrate in soils with low alkalinity and buffering capacity may exacerbate decreases in pH. The use of the buffered EOS® blend successfully increased the pH of the soil and provided pH conditions more conducive for reductive dechlorination to occur; this positive effect was monitored for over one year from injection, at which time the monitoring program was ended.

7.4 Biodegradation of Trichloroethene in Groundwater

Table 7-9 summarizes the average concentrations of TCE and its biodegradation daughter products in monitor wells across the pilot test cell before and after injection of EOS® in Phase I and buffered EOS® in Phase II. The raw data for each well are provided in **Table IV-1** of **Appendix IV**.

7.4.1 Background Monitor Wells

There was little to no change in concentrations of TCE, *cis*-DCE, VC and ethene in the three background monitor wells over the course of the 28 months of monitoring in Phase I. The addition of buffered EOS® to the test cell on Day 866 did not impact the background wells. The presence of some *cis*-DCE in the aquifer suggests that the microbial population is present that can metabolize TCE, but it is limited and not very active.

Table 7-9
Effect of EOS® on Biodegradation of Chloroethenes and Chloride in Test Cell
SWMU 17, Naval Weapons Station
Charleston, SC

Well ID (Distance from barrier)	Sample Date	Days (Months) After Injection		TCE (µg/L)	cis-1,2-DCE (µg/L)	Vinyl Chloride (µg/L)	Ethene (µg/L)	Cl #	Chloride (mg/L)
Average of 3 background monitor wells 30 – 40 ft from the test cell	3/31/04	-43		76,000	390	25	0.66	3.0	226
	6/2/04	20	(~0.5)	23,333	3,400	25	1.72	2.8	148
	9/1/04	111	(~3)	50,100	2,087	25	1.02	2.9	144
	11/17/04	188	(~6)	NM	NM	NM	NM	NM	195
	2/9/05	272	(~9)	NM	NM	NM	NM	NM	208
	5/25/05	377	(~12)	NM	NM	NM	NM	NM	206
	8/24/05	468	(~15)	NM	NM	NM	NM	NM	232
	3/28/06	684	(~22)	44,000	447	20	0.46	3.0	169
	9/25/06	865	(~28)	48,667	910	20	1.47	3.0	NA
	12/20/2006	951	(~31)	NA	NA	NA	NA	NA	NA
	4/10/2007	1062	(~35)	547,667	473	22	3.49	3.0	284
	10/17/2007	1252	(~41)	32,333	850	17.5	1.55	3.0	675
Average of 4 injection wells in test cell	3/31/04	-43		13,700	305	25	1.04	3.0	639
	6/2/04	20	(~0.5)	2,900	135	4	2.17	2.9	982
	9/1/04	111	(~3)	3,018	1,150	5	4.94	2.6	889
	11/17/04	188	(~6)	2,348	855	25	2.12	2.6	580
	2/9/05	272	(~9)	2,828	890	4	3.99	2.7	754
	5/25/05	377	(~12)	2,945	923	31	5.41	2.7	712
	8/24/05	468	(~15)	2,393	1,163	21	3.58	2.6	952
	3/28/06	684	(~22)	2,300	1,675	27	2.37	2.5	954
	9/25/06	865	(~28)	1,888	3,513	59	2.03	2.3	511
	12/20/2006	951	(~31)	1,018	3,625	303	2.67	2.1	939
	4/10/2007	1062	(~35)	1,431	4,100	878	15.85	1.9	959
	10/17/2007	1252	(~41)	508	3,775	980	31.21	1.8	611
Average of 3 monitor wells within test cell	3/31/04	-43		25,333	227	<25	0.4	3.0	1,057
	6/2/04	20	(~0.5)	12,667	482	<25	0.6	3.0	1,034
	9/1/04	111	(~3)	13,233	5,800	28	0.9	2.6	870
	11/17/04	188	(~6)	7,053	6,333	25	0.7	2.4	986
	2/9/05	272	(~9)	12,133	7,817	<25	2.3	2.5	838
	5/25/05	377	(~12)	8,950	7,033	<25	1.6	2.5	617
	8/24/05	468	(~15)	10,500	6,000	<25	0.9	2.6	1,195
	3/28/06	684	(~22)	5,833	7,267	<25	1.5	2.4	745
	9/25/06	865	(~28)	<25	2,123	4,567	12.2	1.2	675
	12/20/2006	951	(~31)	<25	430	3,533	89.6	1.0	983
	4/10/2007	1062	(~35)	34	310	3,067	60.2	1.0	1,187
	10/17/2007	1252	(~41)	5	67	1,020	28.6	1.0	734

- Concentrations shown as "<" indicate that all wells measured were less than the indicated method detection limit.
- Where concentrations in one or more of the wells used to calculate the average were reported to be below the detection limit, a value of ½ of the detection limit was used in calculating the average.
- Data from duplicate samples collected on any given day were averaged before being used in the calculations.
- Data shown from December 20, 2006 (Day 951) through the end of Phase II on October 17, 2007 (Day 1252) are after the addition of buffered EOS to the test cell.

7.4.2 Test Cell Injection and Monitor Wells.

The average TCE concentrations in four injection wells and three monitor wells in the test cell showed large changes as a result of the EOS® injection. **Figure 7-11** shows the change in concentrations of TCE, *cis*-DCE and VC in one of the injection wells (17PSI-10) that was routinely monitored throughout the pilot test. The data show a rapid drop in TCE concentration and concomitant increase in the *cis*-DCE concentration immediately after the introduction of EOS® to the aquifer. However, after the initial changes, it appears that the concentrations of these constituents do not change substantially in this well for the balance of the 28 months (through Day 865) that comprised Phase I. Some VC (41 µg/L) was detected on Day 188 and the amount detected increased slowly to 96 µg/L by Day 865 (see **Table IV-1** in **Appendix IV**). But, compared to the amount of TCE reduced and *cis*-DCE produced, this relatively small amount of VC suggested absence of conditions supporting complete biodegradation.

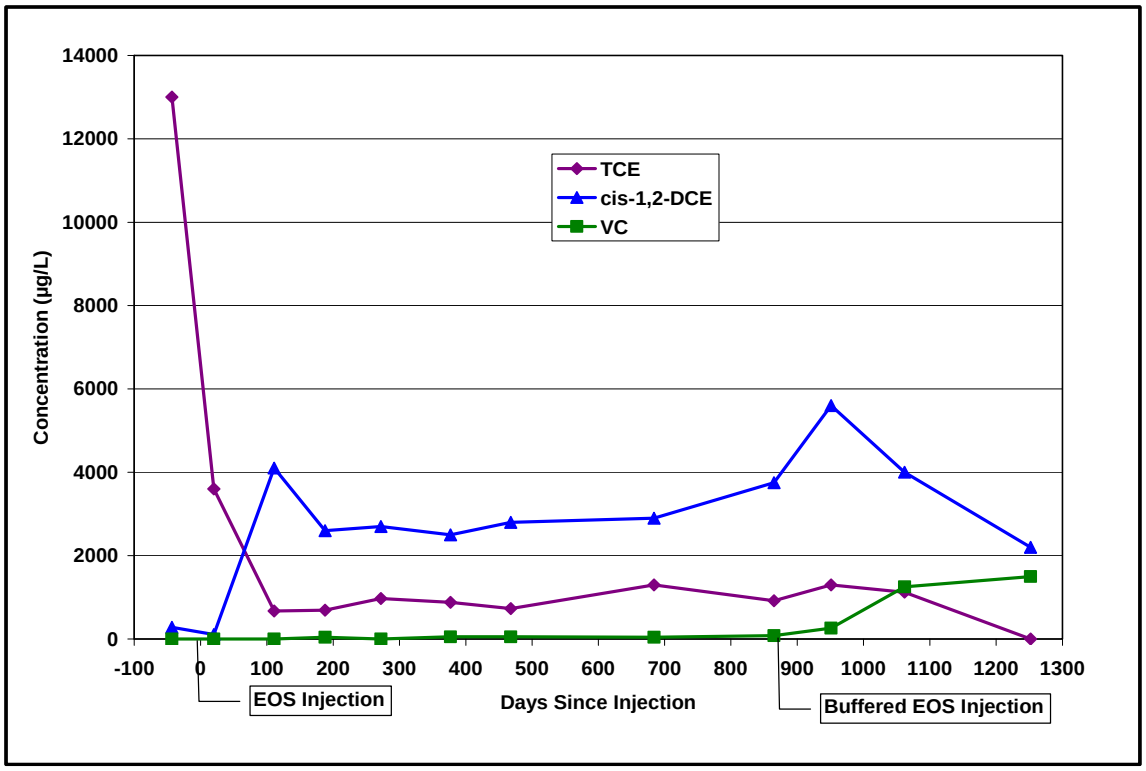


Figure 7-11. Concentrations of TCE and Biodegradation Daughter Products in Injection Well 17PSI-10

Figure 7-12 shows that a similar pattern emerges for the concentrations of the target chloroethenes when the average of all four injection wells is graphed. After the initial large drop, the average TCE concentration continued to slowly decline over the first 865 days with a slow increase in the concentration of *cis*-DCE over the same period. There was a

noticeable increase in *cis*-DCE (up to as much as 4,200 µg/L in 17PSI-13) around Day 865 , but relatively little VC (only as much as 96 µg/L in 17PSI-10) was detected (see **Table IV-1** and **Appendix IV**) at the same time.

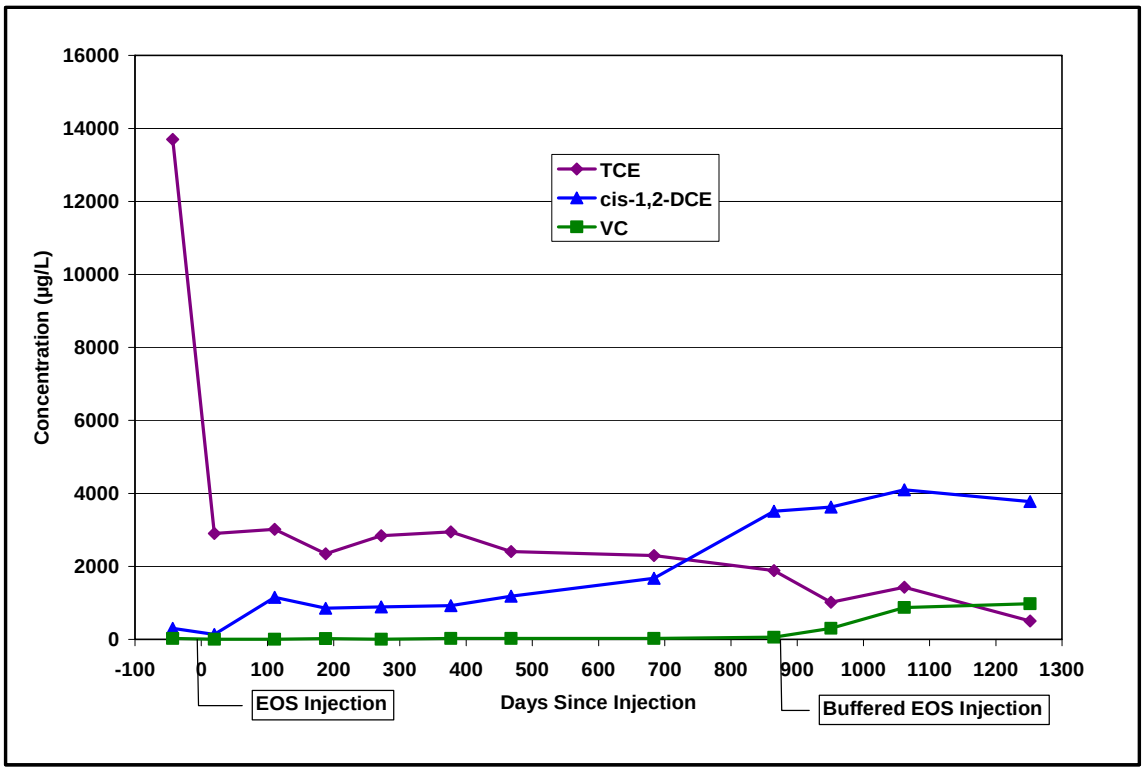


Figure 7-12. Average Concentration of TCE and Biodegradation Daughter Products in Four Injection Wells

Figures 7-13a, 7-13b and 7-13c show the changes in TCE and daughter products in the three monitor wells located in the test cell. Results are presented as micromolar concentrations of each constituent. The injection of EOS® on Day 0 resulted in a rapid decrease of TCE and measureable formation of *cis*-DCE as soon as 3 months after the addition of substrate. The performance varied in the three wells with the conversion from TCE to *cis*-DCE most pronounced in 17PS-03. **Figure 7-14** shows the changes in concentrations of TCE and daughter products in 17PS-03.

TCE concentrations were reduced by 86% and 99% in the injection and monitor wells, respectively, over the 28 months Phase I monitoring period. The concentrations of *cis*-DCE increased 11-fold and 9-fold in the same sets of wells over the same period. However, for most of the Phase I monitoring period, there is relatively little formation of either VC or ethene.

As discussed earlier in Section 7.2.7.1, the apparent inability to degrade *cis*-DCE further to VC and ethene was presumed to be a result of lowered pH inhibiting bioactivity of *Dehalococcoides spp*. and/or other dehalorespiring microorganisms in the aquifer. This

prompted base managers to experiment with several approaches to adjust the pH upward and stimulate the further biodegradation. As was shown in **Table 7-7**, the introduction of several different buffering agents into monitor wells 17PS-02 and 17PS-03 did not have a long-lasting effect on the pH in those wells. However, there may have been a transient effect since the results of groundwater performance monitoring on Day 862 clearly showed that TCE was removed, *cis*-DCE had decreased, and a substantial amount of VC and ethene had been formed. This sampling event is before the injection of buffered EOS® that began on Day 866 that marked the beginning of Phase II.

The addition of buffered EOS® resulted in a pronounced stimulation of the reductive dechlorination process in Phase II. As illustrated by the results from Day 951 through Day 1252 on **Figures 7-11** and **7-12**, there were substantial increases in both VC and ethene in the four injection wells that were monitored after injection of buffered EOS® on Day 866. In the three monitor wells, the influence of the buffered EOS® substrate was similar (**Figures 7-13a, b, c** and **Figure 7-14**). These changes support the hypothesis that appropriate microorganisms were present in the aquifer, but the decrease in pH inhibited their bioactivity. Once the pH pressure was relieved, biodegradation and complete conversion to ethene could proceed.

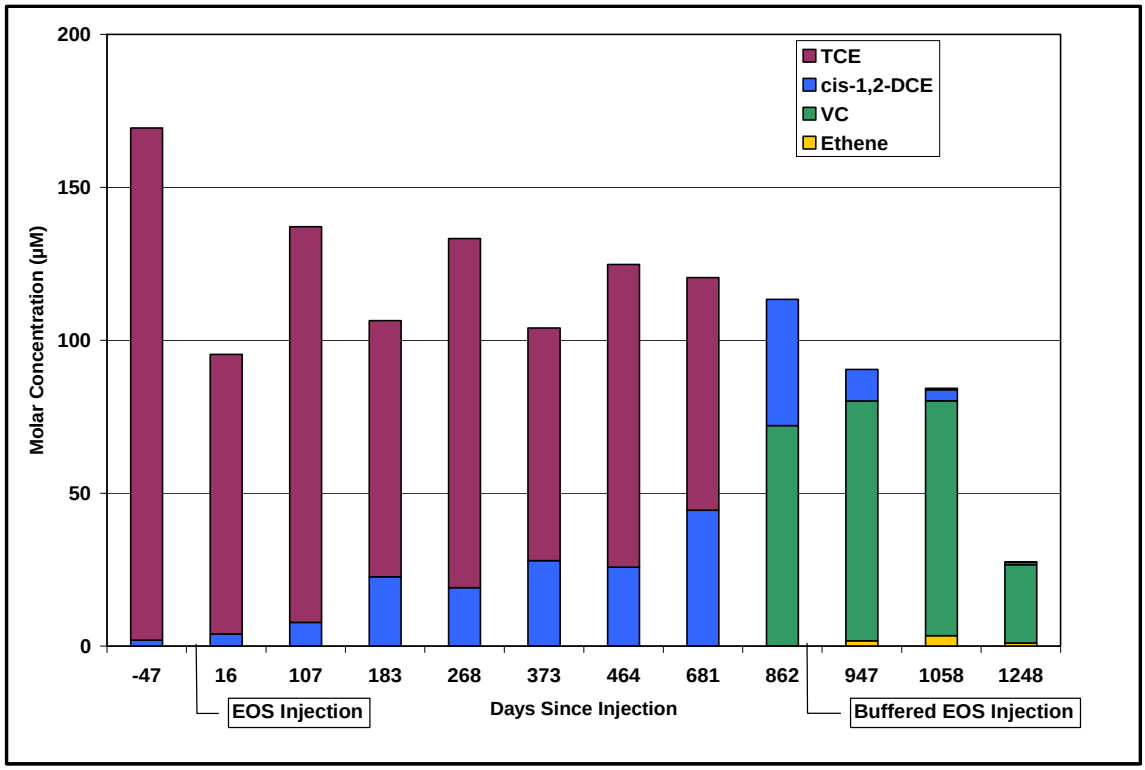


Figure 7-13a. Micromolar Concentrations of TCE and Biodegradation Daughter Products in Test Cell Monitor Well 17PS-01

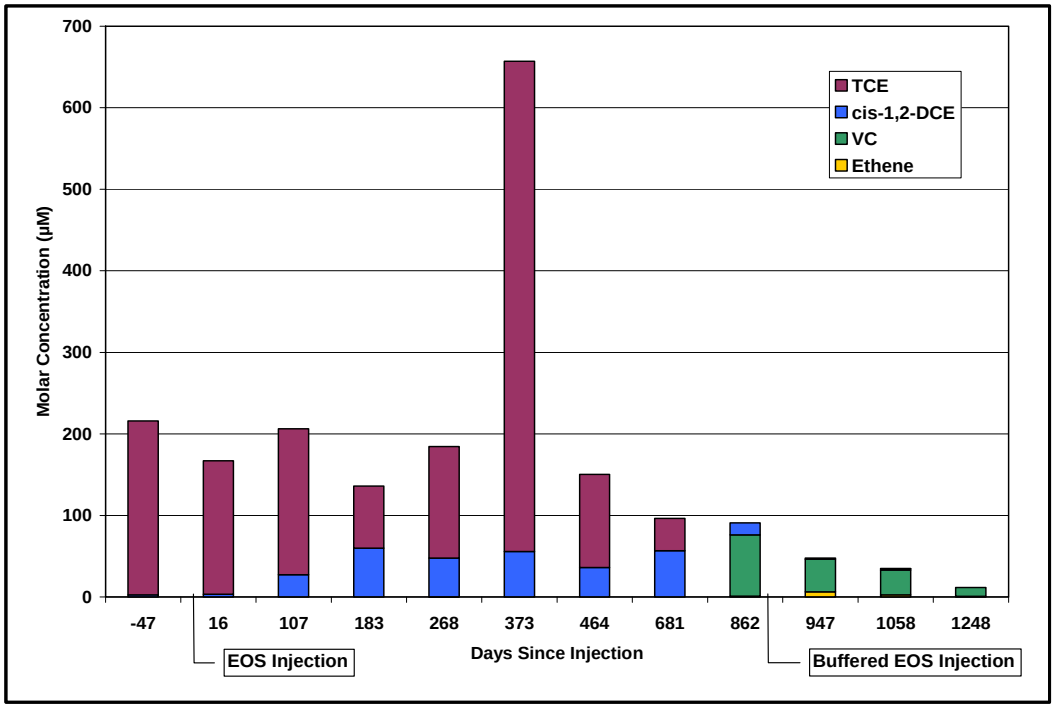


Figure 7-13b. Micromolar Concentrations of TCE and Biodegradation Daughter Products in Test Cell Monitor Well 17PS-02

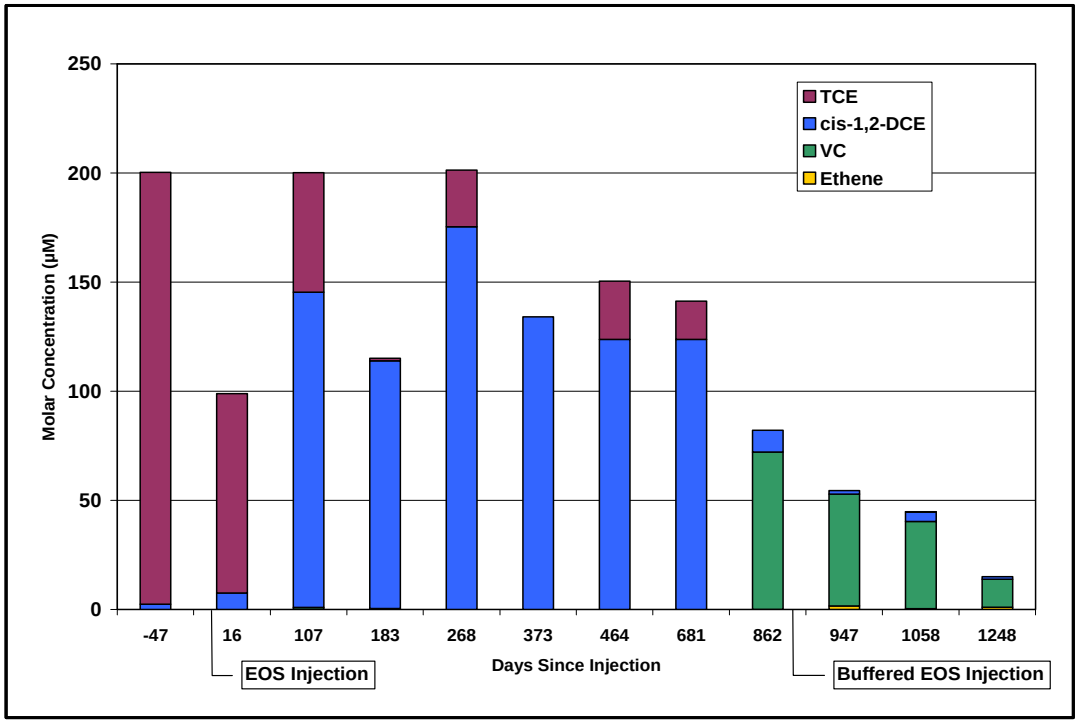


Figure 7-13c. Micromolar Concentrations of TCE and Biodegradation Daughter Products in Test Cell Monitor Well 17PS-03

Over the 41-month monitoring period, the average total concentration of target chlorinated VOCs (i.e., the sum of PCE, TCE, DCE and VC) decreased from 198 µM to 17 µM, a decline of 91%. This exceeds the performance criterion that a minimum of 50% of the TCE be converted to non-toxic end products (**Table 3-1**).

The average ethene concentration increased from 0.02 to 1.02 µM, indicating significant conversion to non-toxic end products. However, production of 1 µM ethene is much less than would be expected from destruction of 181 µM CVOCs. The reason for the poor mass balance is unknown, but may be associated with further conversion of ethene and/or volatilization.

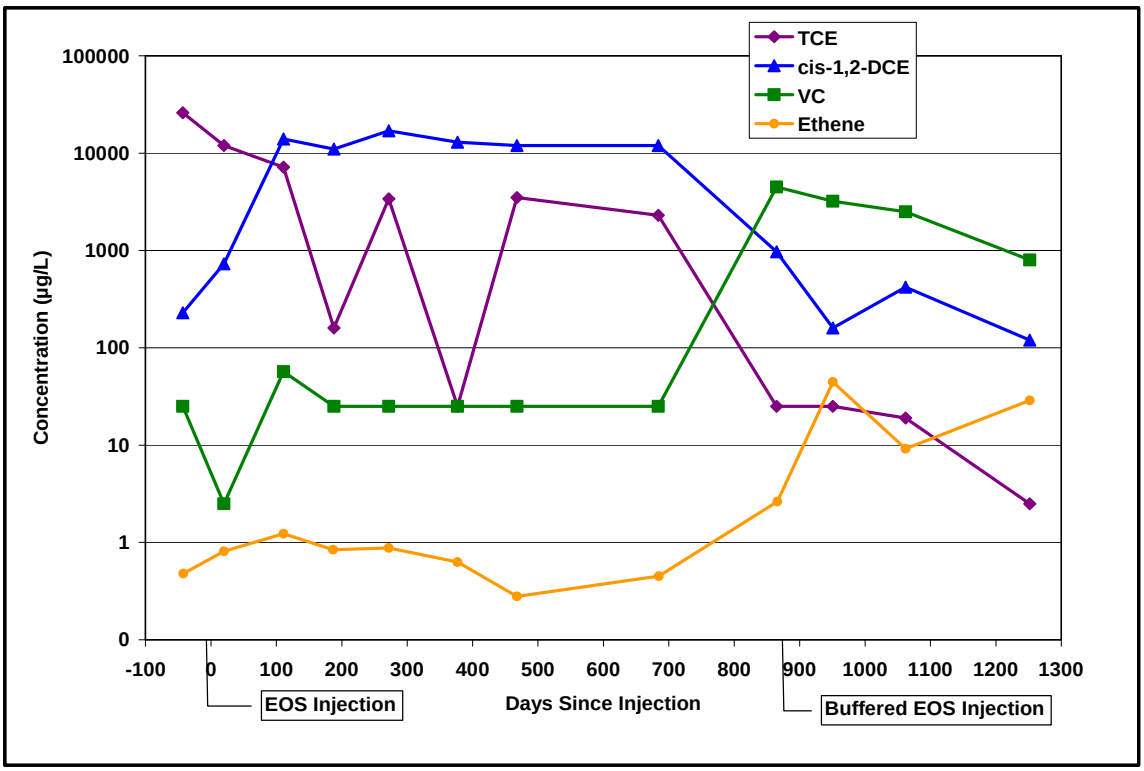


Figure 7-14. Changes in Concentration of TCE and Biodegradation Daughter Products in Monitor Well 17PS-03

The average TCE concentration in the three monitor wells within the pilot test cell declined by over 99.9% from an average of 25,333 µg/L to 7 µg/L. This reduction is significantly greater than the minimum 90% reduction (α=0.0025) specified in the performance criteria (**Table 3-1**).

7.4.3 Chlorine Number Evaluation.

The analytical results for TCE and its daughter products are summarized in **Table 7-9.** To help interpret the results, the groundwater concentrations were converted to molar

concentrations and the chlorine number (Cl#) for each well was calculated for each sampling event. Monitoring the change in Cl# over time is an effective tool for evaluating the progress of reductive dechlorination processes. Groundwater containing only TCE would have a Cl# = 3.0. However, if half of the TCE is reduced to *cis/trans*-DCE, the Cl# would decline to 2.5. Cl# for the biodegradation of TCE is calculated as:

$$Cl\# = \frac{4\,[PCE] + 3\,[TCE] + 2\,[cis/trans\text{-}DCE] + [VC]}{[PCE] + [TCE] + [cis/trans\text{-}DCE] + [VC] + [Ethene]}$$

where [ ] indicates concentration in moles per liter. The average chlorine numbers for the three background wells, the four injection wells and the three monitor wells in the treatment cell are shown in **Table 7-9. Figure 7-15** plots the average background Cl # along with the individual Cl #s calculated from the three monitor wells located in the test cell.

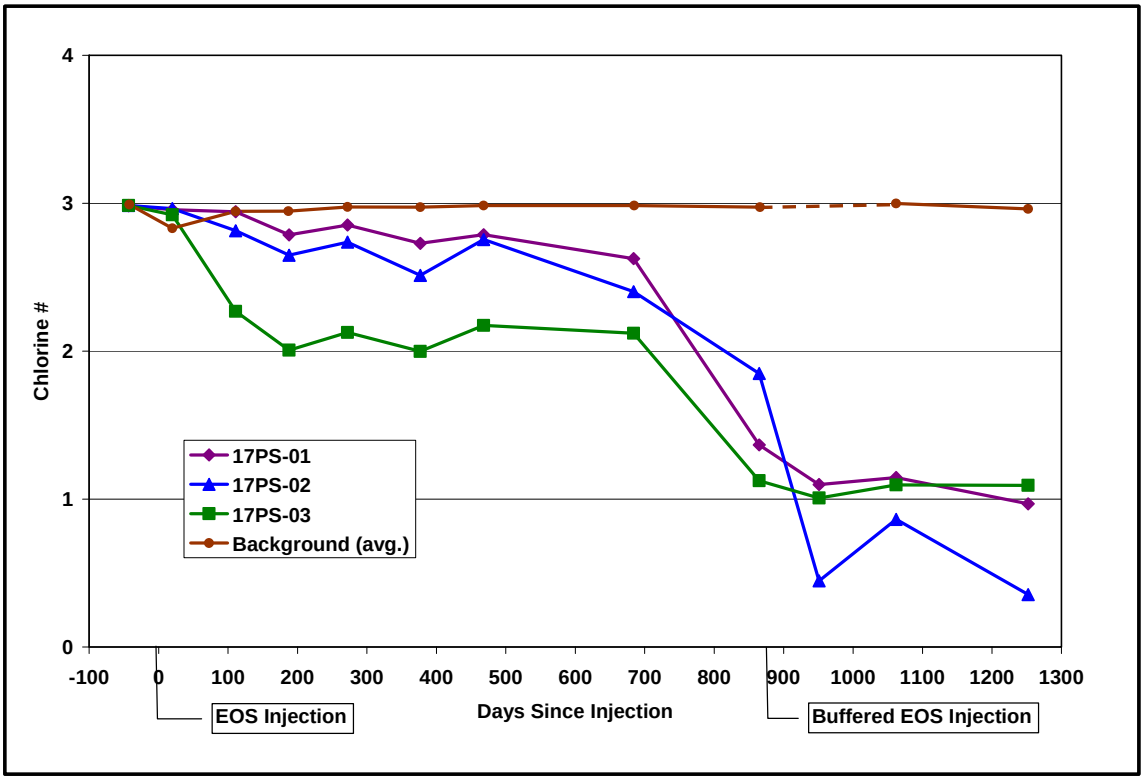


Figure 7-15. Changes in Chlorine Number (Cl #) in Background and Test Cell Monitor Wells

The chlorine numbers show the same changes discussed above relative to the groundwater concentrations of the target chloroethenes, and further illustrate the slowing of biodegradation after a relatively rapid initial conversion of TCE to *cis*-DCE. The Cl# in each of the three monitor wells in the test cell stayed between 3 and 2 (reflecting some conversion of TCE to *cis*-DCE) for the Phase I period from injection through Day 685.

The addition of buffered EOS® on Day 866 reduced the pH inhibition in the treatment cell, enhancing conversion of *cis*-DCE to VC and ethene. At the end of the 41-month monitoring period, the Cl# varied between 0.4 and 1.1 in these three wells indicating VC and ethene were the primary chlorinated aliphatic hydrocarbons present.

The Cl# for each of the four injection wells showed a similar pattern. After the addition of buffered EOS®, the average Cl# dropped to 1.8 with the final numbers ranging from 2.0 to 1.4 on Day 1252, the last day of monitoring. The average Cl# in the test cell monitor wells at the end of the study was 1.0, whereas the three background wells across the easement remained near 3.0.

7.4.4 Contaminant Migration

The orientation of the pilot test plot presumed groundwater flow direction was from west to east across the utility line easement. This was based on site wide groundwater maps and topographic changes in the land surface. Initial testing at the site indicated that there was a relatively flat gradient across the site and groundwater flow velocity was slow (see Sections 5.2.1 and 5.2.2). In accordance with the Technology Demonstration Plan, a Geoprobe® sampling event was scheduled six months after initial injection of substrate to assess the impact of the treatment plot on surrounding areas of the site.

Between November 8 to 11, 2004, twelve temporary wells were installed at locations surrounding the pilot treatment cell. The wells were designated 17PSTW-4 through 17PSTW-15 as shown on **Figure 7-16.** The locations were approximately 20, 30 and 50 feet from the center of the pilot test cell. At each location, a Geoprobe® boring was advanced to a total depth of 16 ft bgs and a section of 5-ft long 1-inch diameter PVC screen was temporarily placed in the hole to allow collection of groundwater samples using a peristaltic pump. The temporary screen interval of 11 to 16 ft bgs corresponded to approximately the middle portion of the pilot test injection and monitor well screen intervals of 8 to 18 ft bgs (see **Figure 5-3**). Groundwater samples were collected from each temporary well and analyzed for the full suite of performance monitoring parameters. The VOC results from the 12 borings were combined with the VOC results from the injection and monitor wells collected during the routine November 16, 2004 groundwater sampling event and chlorine numbers were calculated for TCE and its daughter products at each location. The results are shown on **Figure 7-16.** The data set from the Geoprobe® sampling event is provided in **Table IV-3** in **Appendix IV.**

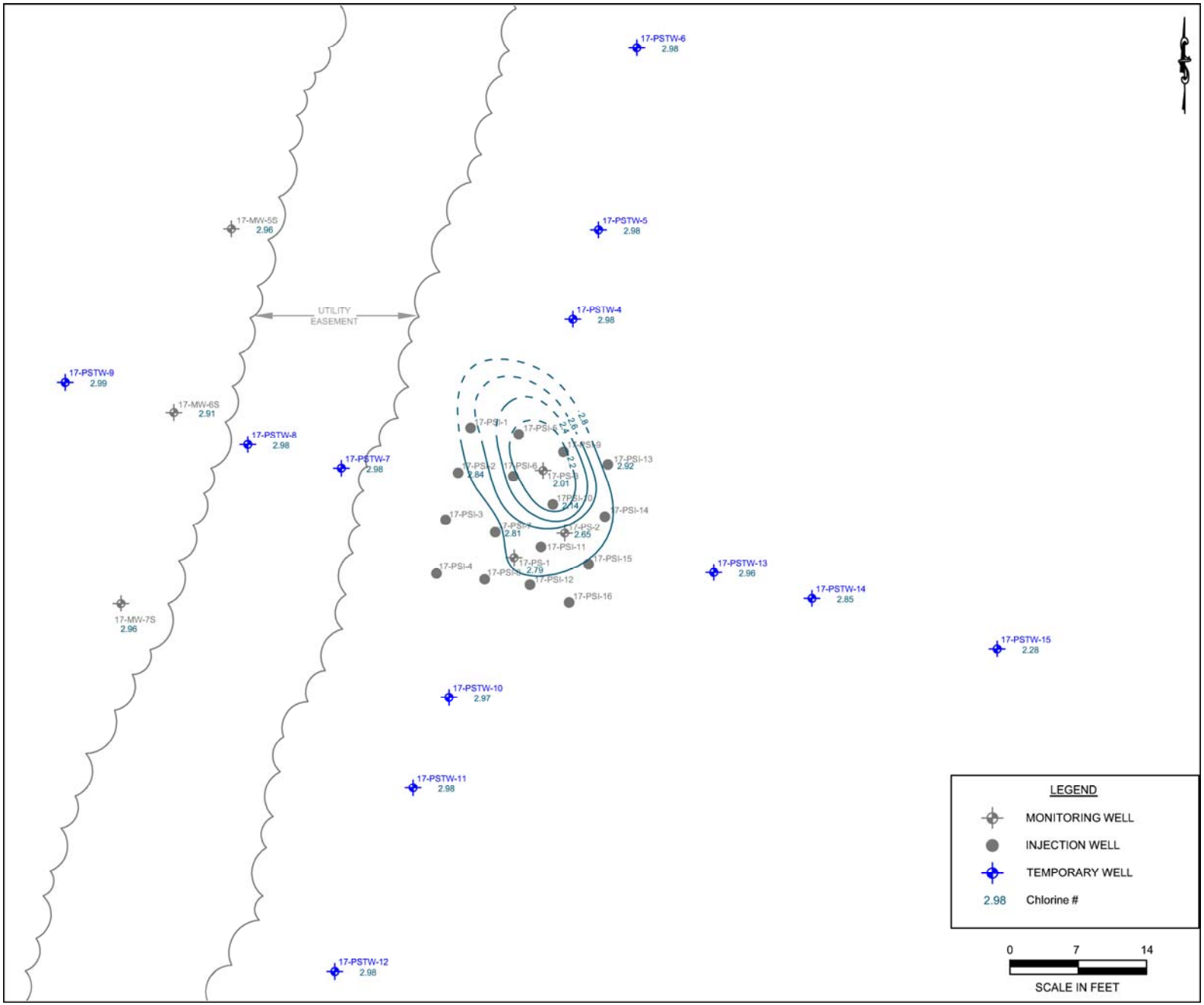


Figure 7-16. Chlorine Number Map from Groundwater Sampling Event Six Months after Injection of Substrate

The beginning effect of adding emulsified oil substrate on enhanced reductive dechlorination in the pilot test cell was observed compared to surrounding, untreated areas of the site. The groundwater flow velocity beneath the treatment cell is very slow (see Sections 7.1.1 and 7.1.2) and the direction is variable. In general, outside of the treatment cell, TOC (avg. = <1.0 mg/L), D.O. (avg. = 0.52 mg/L), ORP (avg. = +48.4 mV), sulfate (avg. = 157 mg/L), and pH (avg. = 5.7 S.U.) were all in ranges that would be considered less than conducive for anaerobic reductive dechlorination to occur (**Table IV-3** in **Appendix IV)**.

As discussed in Section 7.4.3, a Cl# closer to 3.0 reflects little to no formation of *cis/trans*-DCE while Cl# closer to 2.0 suggests biodegradation of almost all the TCE to *cis/trans*-DCE. As shown on **Figure 7-16**, the Cl# in groundwater collected from 11 of the 12 Geoprobe® borings emplaced 20 to 50 ft away from the edges of the pilot treatment cell had Cl# greater than 2.9. Conversely, of the groundwater samples collected from the injection and monitor wells in the treatment cell during the November 2004 (6 months post-injection) performance monitoring event, only 17PSI-13 was above Cl#2.9. The Cl# in the other three injection wells ranged from Cl# 2.14 to 2.84 and the Cl# in the three monitor wells in the treatment cell ranged from Cl# 2.01 to 2.79. These results indicate that biodegradation of TCE was beginning in the treatment cell by six months after injection, but had little impact on TCE biodegradation outside of the immediate area of the treatment cell. This result was not unexpected given the very low groundwater velocity at the site. Based on the absence of any clear indication of groundwater flow direction and detectable impact in any one direction away from the treatment cell, no additional monitor wells outside of the treatment cell that could be characterized as "downgradient monitor wells" were installed.

7.4.5 Chloride

As chlorinated solvents are biodegraded, chloride atoms are released resulting in increased chloride concentrations. However, background concentrations of chloride are often too high to observe a significant increase in chloride due to biodegradation. **Table 7-9** summarizes the average chloride concentrations observed across the site. Pre-injection chloride concentrations were measured and averaged 226 mg/L in the background wells and 639 to 1,057 mg/L in the injection and monitor wells in the treatment cell, respectively. The higher chloride concentrations to the south and east are presumably associated with chloride introduced when the area floods during large storms.

During the 28 months of Phase I and the additional 13 months in Phase II there was little change in the chloride concentrations in any of the three well groupings. The average chloride concentration in the background wells ranged from 115 to 232 mg/L (avg. = 249 ±156 mg/L) throughout the entire 41-month performance monitoring period; the average chloride concentrations in the injection wells ranged from 511 to 982 mg/L (avg. = 790 ± 174 mg/L) and from 617 to 1195 mg/L (avg. = 909 ± 194 mg/L) in the test cell monitor wells. The absence of change in chloride concentrations as a result of EOS® and buffered EOS® addition appears to be due to the inability to measure the change compared to the starting, native chloride concentrations. Further, although there was strong evidence that

the addition of buffered EOS® in Phase II enhanced reductive dechlorination, the chloride concentrations in the test cell did not change appreciably during the additional year of monitoring in Phase II.

7.4.6 Mass Flux Evaluation

Passive flux meters (PFM) were used to monitor changes in TCE and *cis*-DCE mass flux as a result of emulsified oil treatment. The PFM sorbent canisters developed by Dr. Mike Annable and Dr. Kirk Hatfield at the University of Florida were suspended in the bottom 8 to 9 ft of the three background monitor wells (17MW-5S, 17MW-6S and 17MW-7S) and three treatment cell monitor wells (17PS-01, 17PS-02 and 17PS-03) (**Figure 7-17)**. The PFM were initially installed on April 2, 2004, prior to emulsified oil treatment, and remained suspended in the wells for 35 days, prior to removal and laboratory analysis at the University of Florida. At the end of Phase II, PFMs were deployed again in the same background and treatment cell monitor wells, and remained undisturbed for 34 days prior to removal and laboratory analysis. The mass flux of TCE and *cis*-DCE entering each well over the *in situ* absorption period was calculated according to the method developed by Hatfield et al. (2004) and Annable et al. (2005). Computed Darcy velocity, TCE and *cis*-DCE flux profiles are provided in data and figures in **Appendix VI** for May 2004 (before treatment) and November 2007 (after 41 months of treatment).

Figure 7-17. Photograph of Installing a Mass Flux Canister into a Monitor Well in the Test Cell

Prior to emulsified oil treatment, Darcy velocities ranged from 0.3 to 3.9 cm/d across the 8 to 9 ft vertical intervals of the six wells evaluated. The vertically averaged Darcy velocity calculated for each well is provided in **Table 7-10** and shown to be relatively consistent across the site, ranging between 1.07 and 1.92 cm/d. The graphs of the data (**Appendix VI**) suggest higher permeability and greater mass flux of TCE at depths between 10 and 16 ft bgs. Vertical averages of TCE mass flux in the three background

wells across the easement ranged from 122 to 596 mg/m^2/d, which is somewhat higher than the vertically averaged TCE flux measured in the three treatment cell monitor wells prior to EOS® injection (81.3 to 102 mg/m^2/d) (**Table 7-10**). Since the Darcy velocity in the wells was similar, the difference is due to the higher TCE concentration in the three background wells (~76,000 g/L) than in the three treatment cell wells (~25,000 g/L)(**Table 7-9** and **Table IV-1** in **Appendix IV**). By contrast, the average starting concentration of *cis*-DCE in the background wells was 390 µg/L, which was very similar to 227 µg/L in the treatment cell wells. Consequently, the vertical averages of *cis*-DCE mass flux (0.76 to 6.77 mg/m^2/d) in the background wells was similar that of the treatment cell wells (1.69 to 3.48 mg/m^2/d).

Table 7-10
Vertically Averaged Darcy Velocity and Mass Flux in Monitor Wells
Before and 41 Months After Treatment with
Emulsified Oil and Buffered-Emulsified Oil Substrates
SWMU 17, Naval Weapons Station
Charleston, SC

Well ID	Darcy Velocity cm/day		TCE Flux mg/m^2/day		*cis*-DCE Flux mg/m^2/day	
	May-04	Nov-07	May-04	Nov-07	May-04	Nov-07
	Background Monitor Wells					
17MW-5S	1.61	1.82	122.	183.	0.76	52.7
17MW-6S	1.07	0.92	154.	70.7	6.77	86.0
17MW-7S	1.33	0.96	596.	95.8	3.56	101.
	Test Cell Monitor Wells					
17PS-01	1.32	5.18	93.0	1.5	3.48	0.0
17PS-02	1.83	2.48	81.3	0.6	1.98	0.0
17PS-03	1.92	2.79	102.	1.1	1.69	0.0

Data from before and after treatment are summarized in **Table 7-10.** The vertically averaged Darcy velocity in background wells 17MW-5S, 6S and 7S ranged from 0.92 to 1.82 cm/d which is comparable with the pre-treatment baseline velocities in May 2004. The corresponding TCE flux through these background wells ranged from an average of 71 to 183 mg/m^2/d; two out of three of these values are slightly lower than those observed in May 2004, and reflect apparent natural reductions in TCE concentrations that had occurred in these wells approximately 41 months after the first PFMs were deployed. Interestingly, there was a measureable increase in the mass flux of *cis*-DCE from the background wells. This suggests some ongoing natural biodegradation of TCE to *cis*-DCE although the changes in Cl# in these wells suggested that the conversion was minimal.

The vertically averaged Darcy velocities in test cell monitor wells 17PS-01, 02 and 03 ranged from 2.48 to 5.18 cm/d, which was approximately 1.5 to 3.9 times higher than those calculated before any injections of substrate occurred. There was little change in the Darcy velocity in the background wells away from the test cell, but the velocity appears to have increased slightly in the treatment grid. This indicates that EOS® and buffered EOS® injection did not significantly reduce the overall groundwater velocity through the test cell.

After 41 months of treatment, there was less than 10 µg/L TCE and less than 120 µg/L of *cis*-DCE in the three test cell monitor wells (see **Table IV-1** in **Appendix IV**). Thus, it was expected that mass flux would be relatively low. Graphic comparisons of vertically averaged TCE and *cis*-DCE mass flux results presented in **Table 7-10** are shown in **Figures 7-18a** and **7-18b,** respectively. The average TCE mass flux for the three wells within the test cell was reduced by over 98%. This reduction in mass flux is significant at the 99% level ($\alpha<0.01$) and exceeds the minimum reduction of 75% specified in the performance criteria (**Table 3-1**). The three well average *cis*-DCE mass flux in the test cell was also reduced by 100%, as no mass flux of *cis*-DCE was measureable in the treatment cell monitor wells at the end of the study. These results agree strongly with the Cl# evaluation in demonstrating the effectiveness of the emulsified oil treatment in promoting biodegradation of chloroethenes and reducing mass flux of TCE and *cis*-DCE over the 41-month performance monitoring period.

The pilot test cell was approximately 20 ft (6.1 m) wide by 10 ft (3.05 m) deep with a total treatment cross-sectional area perpendicular to flow of 18.6 m^2. Prior to treatment, the total mass flux through the pilot test area was 0.63 kg/yr (4.76 mole/yr) of TCE and 0.02 kg/yr (0.17 mole/yr) of *cis*-DCE. Following treatment, the total mass flux was reduced to 0.01 kg/yr (0.055 mole/yr) of TCE and below detection for *cis*-DCE.

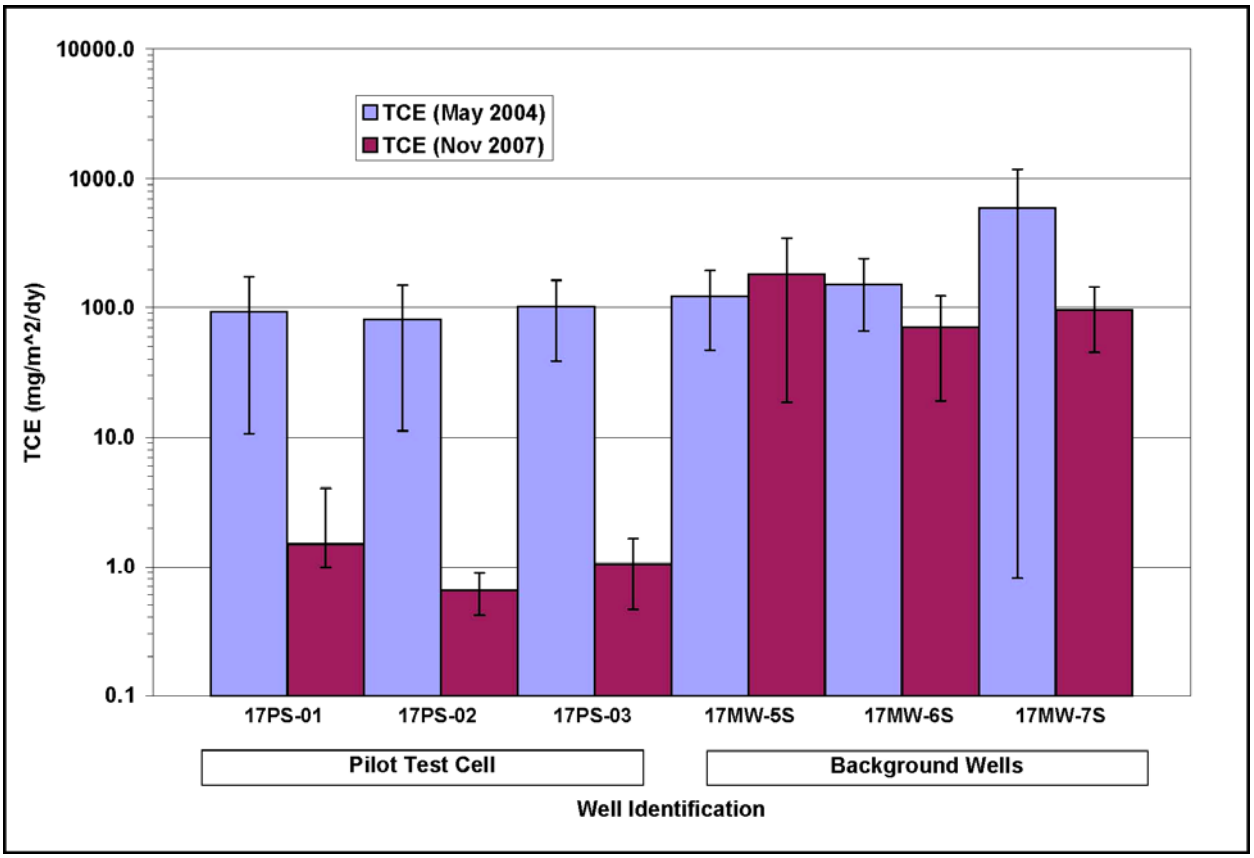


Figure 7-18a. Vertically Averaged Mass Flux of Trichloroethene before Injection and after 41 Months of Exposure to Emulsified Oil and Buffered-EOS®. (Error bars indicate range of mass flux measurements within individual wells.)

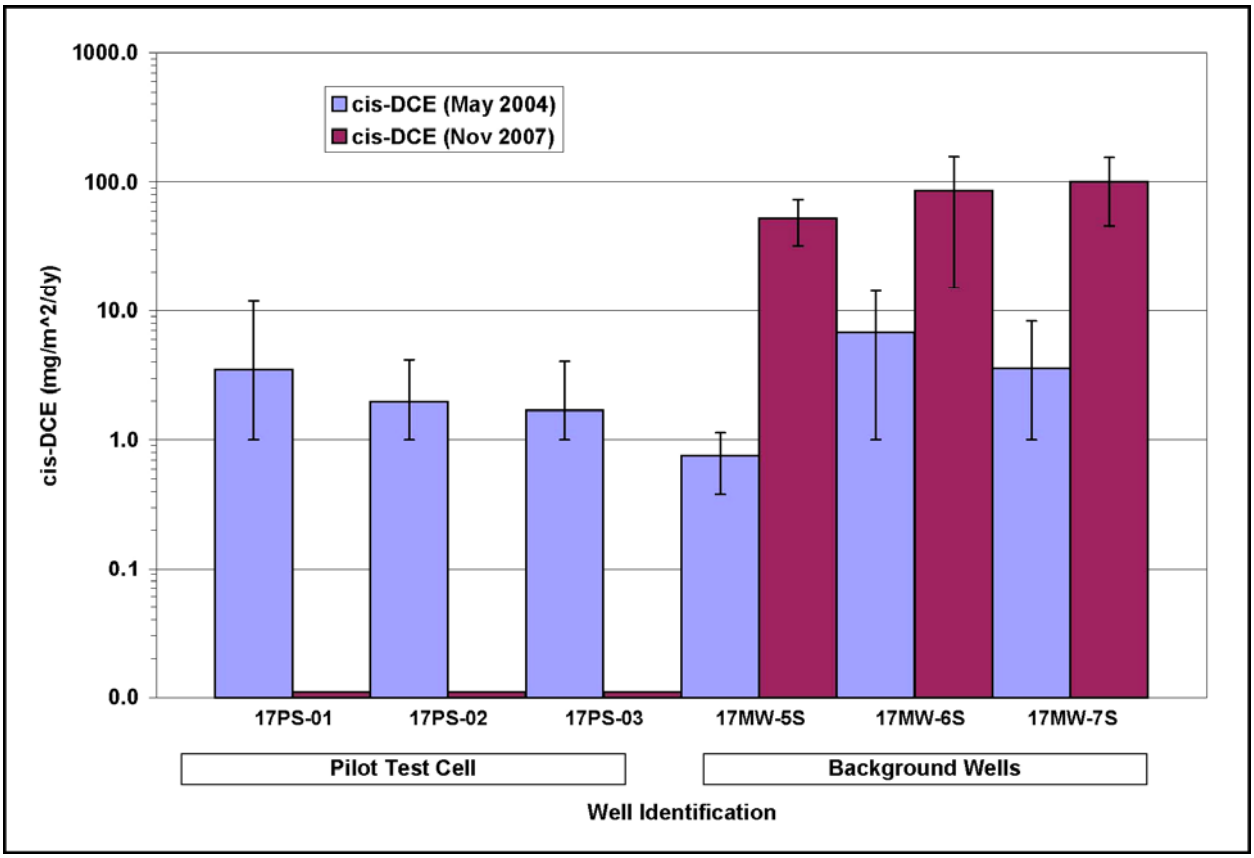


Figure 7-18b. Vertically Averaged Mass Flux of *cis*-1,2-Dichloroethene before Injection and after 41 Months of Exposure to Emulsified Oil and Buffered-EOS®. (Error bars indicate range of mass flux measurements within individual wells.)

7.5 Trichloroethene Biodegradation in Soil

The concentrations of target chlorinated VOCs (CVOCs) in soil were measured from varying depths in 12 soil borings installed in the treatment test cell in March 2004, approximately one to two months prior to the injection of substrate. The complete set of VOC results is provided in **Table IV-5** in **Appendix IV**. **Table 7-11** shows the TCE concentrations in soil before treatment as represented by the samples collected in March 2004. Before Phase I was begun, TCE was the predominant CVOC in the soil with an average concentration of 7,520 µg/kg (n = 30) throughout the vertical profile. Concentrations of *cis*-DCE were mostly below the method reporting limits that ranged from 220 to 280 µg/kg, but an average *cis*-DCE concentration was calculated as 170 µg/kg. No VC was reported in any of the pre-treatment soil samples.

The target CVOCs were measured again in soil at the completion of the 41-month performance monitoring period. The complete set of VOC results is provided in **Table IV-5** in **Appendix IV** and the TCE results are shown on **Table 7-11** as the samples collected in October 2007. Five borings were installed (17PSSB-17 through 17PBBB-21) and 16 soil samples (n = 16) from varying depths below the groundwater table were collected and analyzed. The results showed a significant decrease in the concentration of TCE with concomitant increases in *cis*-DCE and VC. **Table 7-11** also provides summaries of the average concentrations of TCE and its daughter products before and after treatment. The average concentrations of the target CVOCs after

treatment were calculated as 303 µg/kg of TCE, 149 µg/kg of *cis*-DCE and 228 µg/kg of VC. The results demonstrate the effectiveness of the emulsified oil substrate for promoting anaerobic reductive dechlorination of chlorinated ethenes. The average TCE concentration was reduced by approximately 96% by EOS® treatment. This reduction in average TCE concentration is significant at the 99.99% level ($\alpha<0.0001$) and exceeds the minimum reduction of 80% specified in the performance criteria (**Table 3-1**).

The regulatory standard for TCE concentrations in soil is 53 µg/kg (**Table 1-1**). After 41 months of treatment, TCE concentrations were less than the standard in 10 of 16 (62.5%) soil samples. This number of samples exceeding regulatory standards does not meet the performance criterion established for this project of achieving regulatory levels in 90% of the samples (**Table 3-1**).

TCE was the predominant contaminant in soil, but other halogenated hydrocarbons were also detected throughout the soil profile before treatment. These included PCE, 1,1-DCE, 1,1,2,2-PCA, 1,1,2-TCA, and chloroform. The average concentrations of total CAHs (including TCE) was 7,564 µg/kg before treatment and only 678 µg/kg after 41 months (**Table IV-5** in **Appendix IV**). These results suggest the effectiveness of emulsified oil substrate treatment on a variety of halogenated hydrocarbons.

Table 7-11
Chlorinated VOC Concentrations in Soil Before and After Treatment with Emulsified Oil Substrate
SWMU 17, Naval Weapons Station
Charleston, SC

	Trichloroethene (µg/kg) with Depth Before Treatment with Substrate											
	17PSI-01	**17PSI-02**	**17PSI-03**	**17PSI-04**	**17PSI-06**	**17PSI-08**	**17PSI-09**	**17PSI-13**	**17PSI-14**	**17PSI-15**	**17PSI-16a**	**17PSI-16**
Depth (ft bgs)	**3/1/2004**	**3/25/2004**	**3/25/2004**	**3/1/2004**	**3/25/2004**	**3/24/2004**	**3/25/2004**	**3/1/2004**	**3/24/2004**	**3/24/2004**	**3/1/2004**	**3/24/2004**
0-4	390											
4-5											11,000	
5-6	8,100			14,000								
6-7								5,400			9,200	11,000
7-8												
8-9		9,900			9,000							13,000
9-10	4,000				9,100			3,100				
10-11			10,000		5,300	5,000				6,500		
11-12					9,800							
12-13				8,200	9,000				7,200			
13-14					7,200							
14-15				16,000	5,800							
15-16					5,900						4,800	
16-17					8,700		3,200	<5				
17-18					5,900							

	Trichloroethene (µg/kg) With Depth After 41 Months of Treatment				
	17PSSB-17	**17PSSB-18**	**17PSSB-19**	**17PSSB-20**	**17PSSB-21**
Depth (ft bgs)	**10/18/2007**	**10/18/2007**	**10/18/2007**	**10/18/2007**	**10/18/2007**
0-4					
4-5					
5-6					
6-7					
7-8					
8-9			12		490
9-10		3,100			
10-11	<4.8		<4.7	<7.7	
11-12					
12-13	23		210	43	650
13-14					
14-15	13	210	<5.1	<4.9	4
15-16					
16-17			90		
17-18					

Average* Chlorinated VOCs (µg/kg) Before Treatment			
TCE	***cis*-DCE**	**VC**	**Total CAHs****
7,520 ± 3660	173 ± 231	<250	7,564 ± 3700

Average CVOCs (µg/kg) After 41 Months of Treatment			
TCE	***cis*-DCE**	**VC**	**Total CAHs***
303 ± 770	149 ± 153	228 ± 210	678 ± 835

* Averages calculated using 1/2 the detection limit where concentrations were reported as below detection.

**Total CAHs include TCE; *cis*-1,2-DCE; 1,1-DCE; 1,1,2,2-PCA; 1,1,2-TCA; chloroform; and dichlorofluoromethane.

7.6 Soil Gas Assessment

The biodegradation of organic substrate and the formation of anaerobic conditions can lead to the depletion of oxygen and formation of soil gasses such as hydrogen sulfide (H_2S) and carbon monoxide (CO) and methane. As described in Section 5.1.2, to assess the formation of these gasses in the treatment cell, a 4-gas analyzer was used to measure these parameters and compare concentrations in the two soil gas monitoring wells 17PSG-1 and 17PSG-2 emplaced at the site. The data are presented in **Table IV-4** in **Appendix IV.**

The percent O_2 in the headspace of the three background wells and 17PSG-2 located upgradient of the test cell generally varied between 18.3 and 20.9 %. There were occasional detections of low concentrations of CO up to 12 ppm, some slight indications of possible methane, but no H_2S. Overall, there was little evidence of these gasses generated naturally in the aquifer.

The headspace of the injection and monitor wells were all reported to contain reduced percent O_2, elevated LEL often approaching 100 %, measurable CO and easily detectable H_2S (both by meter and olfactory detection by sampling personnel). The concentrations varied from sampling event to sampling event, likely depending both on generation of the gasses, groundwater fluctuations, and sampling methodology (e.g., time allowed after removing well cap before taking measurement). No trend was apparent with regard to changes in concentration over time, but clearly the addition of substrate resulted in anaerobic conditions favorable for the formation of these gasses in groundwater.

Soil gas monitoring well 17PSG-1 was located in the middle of the test cell. The well was constructed with the screen interval in the unsaturated zone above the aquifer. The soil gas measurements collected from this well showed the percent O_2 ranging from 16.3 to 20.1 % during the pilot test, some presence of methane approaching 20% of the LEL (during Phase II), less than 8 ppm CO and no detectable H_2S. These results closely resemble the natural background conditions and suggest that gasses generated in groundwater are not readily detected in the vadose zone.

7.7 Microbial Evaluation

An initial population count in soil and groundwater was performed before treatment commenced. Soil from Geoprobe® boring 17PSI-7 (10–16 ft bgs) installed March 25, 2004, was composited and shipped to both SiREM (Guelph, ONT, CN) and Microbial Insights, Inc. for enumeration of *Dehalococcoides spp*. (DHC) population. The results indicated that the DHC population in soil was below detection. On April 1, 2004, groundwater from future injection well 17PSI-7, installed in the same soil boring, was collected and also shipped to SiREM and Microbial Insights. The results from SiREM indicated that the DHC population was below detection; Microbial Insights reported 2.92E+00 genomes/mL. The analytical reports are provided in **Appendix VII**.

The first performance monitoring assessment of the microbial activity in soil was conducted in February 2005 (Day 273). Soil samples were collected from Geoprobe® MacroCore sleeves

from different depths in four borings and submitted to Microbial Insights for analysis. Phospholipid fatty acid (PLFA) analysis was used to evaluate both the viability of the microbiological community in soil in the test cell and the relative composition of the community with regard to the on-going treatment. The cell count results are included in **Table 7-12;** population census data are provided along with the analytical report in **Appendix VII. T**he results showed the microbial community structures varied considerably among the samples. The estimated viable biomass ranged from 1.62×10^6 to 3.09×10^8 cells/g. The four samples with more diverse microbial communities contained measurable proportions of "anaerobic" biomarkers including sulfate-reducing bacteria and terminally-branched saturated PLFA. The data suggest that conditions in location 17PSSB-5 (10-12') are considerably more anaerobic than conditions in other locations.

The first attempt to enumerate individual dechlorinating species and associated enzyme activity in soil and groundwater was conducted in August 2005, approximately 469 days after injection of substrate. This work was performed as part of the initial characterization of sites matrices for the laboratory treatability study described above in Section 6.2. Tillotson (2007) composited groundwater and soil matrices and submitted samples to Microbial Insights, Inc. (Rockford, TN) for analysis of DHC, *Dehalobacter spp*. (DHB), *Desulfuromonas spp*. (DSM) and populations exhibiting TCE reductase (TCE-R-Dase)[3], BAV1 VC reductase (BAV1-R-Dase)[4] and VC reductase (VC R-Dase) activity. The results are shown on **Table 7-12**. After 15 months exposure to substrate, there appears to be little difference in the populations of DHC, DHB and DSM in groundwater from background and treated portions of the site. Similarly, there is little difference in enzyme activity. The population of DHB in groundwater is three orders of magnitude higher than DHC both in and out of the test cell. The cell counts in soil are generally higher than in groundwater, indicating the presence of DHC, DHB and DSM in the site matrices. There is little evidence of active stimulation of DHC by exposure to the substrate and little evidence of enzyme activity.

At the end of the entire 41-month performance monitoring period, both soil and groundwater samples were collected and sent to Microbial Insights for microbial analyses. Groundwater samples from one background monitor well (17MW-6S), two injection wells (17PSI-7 and 17PSI-10), and one treatment cell monitor well (17PS-02) were analyzed for the presence of DHC, DHB, and populations exhibiting TCE-R-Dase, BAV1-R-Dase and VC R-Dase activity. The results are shown on **Table 7-12** and the analytical report is provided in **Appendix VII**.

The background well contained few DHC (82.1 cells/mL), a relatively large DHB population (23,200 cells/mL), some low level of TCE reductase, but virtually no VC reductase. This was consistent with the historical observations at the site suggesting some natural degradation of TCE to *cis*-DCE, but little biodegradation beyond that step.

[3] Functional gene for strains 195 and FL2, that encodes for the TCE reductive dehalogenase (TCE R-Dase) which catalyzes the dechorination of TCE to VC (Microbial Insights, Inc.).

[4] Functional gene found within the DHC strain BAV1 which encodes for the reductive dehalogenase that catalyzes the direct dechlorination of VC (Microbial Insights, Inc.).

Within the treatment cell, addition of buffered EOS® resulted in a 100,000x to 1,000,000x increase in DHC levels in both injection and monitor wells. TCE R-dase levels increased concurrent with the increase in DHC. However, BAV1 VC R-dase and VC R-dase were below detection in all groundwater samples from the pilot test cell. The high levels of DHC and low levels of VC R-dase may explain the temporary accumulation of VC and only slow production of ethene observed during the pilot test.

Four soil samples were also analyzed at the end of the 41-month study for DHC population size. The samples were collected via Geoprobe® Macro-Core® sampling tubes from different depths in the pilot test cell. As shown in **Table 7-12**, the data suggest that the DHC cell density increases with depth achieving a population size of 3.87×10^6 DHC cells/gram between 12 and 14 ft bgs. No TCE R-Dase, BAV1 VC R-Dase, or VC R-Dase census data were collected. Bioaugmentation with a culture of DHC containing known VC R-dase activity could improve the *in situ* biodegradation capacity of the aquifer.

TABLE 7-12
Summary of Microbial Analyses
SWMU 17, Naval Weapons Station,
Charleston, South Carolina

Microbial Census in Groundwater Samples									
Well ID	**Days Since Injection**	**Sample Date**	**PLFA**	**DHC**	**DHB**	**DSM**	**TCE R-Dase**	**BAV1 VC R-Dase**	**VC R-Dase**
			Background Locations						
				(cells/mL)	**(cells/mL)**	**(cells/mL)**	**(cells/mL)**	**(cells/mL)**	**(cells/mL)**
17MW-5S & 17MW-7S	469	8/25/02005	-	5.30E+01	1.42E+04	7.74E-02	<4.13E-01	1.92E+00	-
17-MW-6S	1252	10/17/2007	-	8.21E+01	2.32E+04		1.51E+01	<5E-01	<5E-01
			Treatment Cell Locations						
17PSI-7	-43	3/31/04	-	BDL & 2.92E+00	-	-	-	-	-
17PSTW-18 & 19 & 20 (composite)	469	8/25/2005	-	2.03E+00	2.17E+03	1.95E-02	1.35E+00	1.04E+00	-
17-PSI-7	1252	10/17/2007	-	1.78E+05	<2.22E+00	-	1.92E+04	<1.11E+00	<1.11E+00
17-PSI-10	1252	10/17/2007	-	1.28E+06	<2.5E+00	-	1.18E+05	<1.25E+00	<1.25E+00
17-PS-2	1252	10/17/2007	-	1.46E+05	<2E+00	-	1.18E+04	<1E+00	<1E+00
Microbial Census in Soil Samples									
Sample ID	Days Since Injection	Sample Date	PLFA (cells/g)	DHC (cells/g)	DHB (cells/g)	DSM (cells/g)	TCE R-Dase (cells/g)	BAV1 VC R-Dase (cells/g)	VC R-Dase (cells/g)
			Background Locations						
17MW-5S & 17MW-7S	469	8/25/2005	-	3.10E+03	2.28E+04	7.10E+00	< 9.78E+02	3.14E+02	NA
			Treatment Cell Locations						
17PSI-7 (10-16)	-49	3/25/2004		BDL & BDL	-	-	-	-	-
17PSSB-1 (10-12)	273	2/10/2005	3.09E+08	-	-	-	-	-	-
17PSSB-4 (10-12)	274	2/11/2005	5.05E+06	-	-	-	-	-	-
17PSSB-4(16-18)	274	2/11/2005	1.62E+06	-	-	-	-	-	-
17PSSB-5 (10-12)	274	2/11/2005	2.21E+07	-	-	-	-	-	-
17PSSB-6 (16-18)	274	2/11/2005	2.87E+06	-	-	-	-	-	-
17PSTW-18 & 19 & 20	469	8/25/2005	-	< 9.71E+02	1.60E+05	1.47E+02	< 9.71E+02	< 9.71E+02	-
17PSSB-18 (9-11)	1253	10/18/2007	-	<9.19E+02	-	-	-	-	-
17PSSB-19 (10-12)	1253	10/18/2007	-	1.02E+03	-	-	-	-	-
17PSSB-20 (10-12)	1253	10/18/2007	-	4.75E+04	-	-	-	-	-
17PSSB-19 (14-16)	1253	10/18/2007	-	3.87E+06	-	-	-	-	-

Empty cells were not analyzed.
Data presented for Day 469 obtained from samples processed by Tillotson (2007).
DHC = *Dehalococcoides spp.* DHB = *Dehalobacter spp.* DSM = *Desulfuromonas spp*. PFLA = Phospholipid Fatty Acids

8.0 Performance Assessment

Emulsified edible oils can be very effective as a long-lasting, natural time-release, organic substrate used to quickly stimulate biodegradation of recalcitrant organic compounds in groundwater to less toxic forms. Two field demonstration pilot tests, funded by the ESTCP, were conducted to evaluate the effectiveness of emulsified oil substrate (EOS®) for enhancing the biodegradation of perchlorate and chlorinated VOCs. Each pilot test had different injection design layouts [permeable reactive barrier (PRB) vs. grid], contaminants, and aquifer characteristics. The pilot test results were evaluated for the substrate's deployment, distribution, contact time, and longevity in the aquifer; changes in native aquifer chemistry; and the effect on the target contaminants.

The results and evaluation of the use of an EOS® PRB to treat groundwater contaminated with perchlorate, 1,1,1-TCA and TCE at the first demonstration site in this project are presented in a technical report (ESTCP, 2006b) and report addendum (ESTCP, 2008). The results and evaluation of the use of an EOS® grid to treat groundwater contaminated with TCE at the second demonstration site in this project (i.e., SWMU 17 at Charleston NWS) are presented in this report. The key performance assessment parameters are summarized below.

8.1 Treatment Design Layout

The technology demonstration conducted at the Charleston NWS described in this Technical Report evaluated the effectiveness of the emulsified oil process for area treatment of TCE. A highly contaminated portion of SWMU 17 was chosen to demonstrate the approach. The site was historically used for surface disposal of solid waste, oils, rubble, paint cans, some engine oil and missile components. The full extent of the SWMU is much larger than the area selected for the demonstration (Section 4.1).

Before embarking on the treatment design, Solutions-IES evaluated the site conditions to better understand the subsurface geology, hydrogeology, contaminant profile and site-specific biogeochemistry and increase the potential for success. Based on the baseline characterization, the pilot study design consisted of a grid of 16 temporary injection/recirculation wells installed approximately 5-ft OC across a 20 x 20 ft test cell located in the southern part of SWMU 17. The contamination was generally between 8 and 18 ft bgs in a relatively tight, silty to clayey sand zone. For this reason, the plan took into consideration ways of maximizing the distribution of emulsified oil substrate throughout the treatment zone which comprised 148 yd^3 of aquifer material.

The amount of emulsified oil injected into the subsurface was determined based on the configuration of the treatment zone, concentrations of the target compounds, the concentrations of various biodegradation and geochemical parameters, and the geologic and hydrogeologic conditions. The design tools supplied by the emulsified oil vendor, EOS Remediation, Inc., recommended injecting 165 gallons (1,260 lb) of substrate into the aquifer to provide sufficient reducing power for the design life of 18 months (Section 6.1).

8.2 Injection Methods and Substrate Distribution

8.2.1 Injection Designs

Solutions-IES considered three options for injecting of emulsified oil substrate:

1) High pressure injection through direct push rods outfitted with a special nozzle for delivering substrate into the aquifer as the rod is advanced or withdrawn.

2) Application of dilute substrate through temporary injection wells followed by injection of potable water to push substrate away from the injection points.

3) Injection of substrate, diluted with site-matrix groundwater obtained from the formation, via temporary injection wells using the recovery/extraction of groundwater for diluent to aid with drawing the substrate through the formation.

The Technology Demonstration Plan described option 3 as the preferred means of injecting emulsified oil substrate at this site (see Section 6.1). For Phase I, it was decided that this approach would provide the best distribution of substrate throughout the silty to clayey sand lithology. Injection pressures were less than 2 psi during the injection process and proved sufficient to inject the full design volume of emulsified oil substrate. Approximately 684 gallons of dilute EOS® (~4 parts water:1 part EOS® concentrate) were injected. The total volume of EOS® concentrate was 165 gallons (1,260 lbs). This amount was spread throughout the 148 yd^3 of the treatment zone by recirculating water for 84.5 hours after all the EOS® had been injected. Although the substrate was successfully distributed, it was apparent that recirculation in the low permeability environment was complicated and time consuming.

After the EOS® was distributed, soil and groundwater sampling was performed periodically to evaluate the distribution of the substrate away from the injection points. Water table mounding was observed during the injection process, but the natural gradient was quickly re-established after the injection process was completed. There was some reduction in hydraulic conductivity in the treatment cell after the injection of emulsified oil substrate, but this appeared to have little measureable effect on the relatively slow groundwater flow velocity through the treatment cell.

In Phase II, 326 gallons (3,030 lbs) of buffered EOS® diluted with 850 gallons of water were injected into the treatment zone (Section 6.4). In this case, injection option 1 was used because there was concern that the alkaline solids in the blended substrate might necessitate additional pressure to inject. The process of low pressure direct injection of buffered EOS® through the Geoprobe® injection tool was relatively easy to accomplish. However, there was substantial difficulty injecting this amount of material into the treatment zone presumably because of the relatively low permeability throughout the vertical profile. During injection, groundwater mounding was noticeable and substrate breakout was observed around the Geoprobe® rod and onto the ground surface. This head buildup dissipated over time allowing continued injection to proceed. To allow for

this, the total process was performed in two mobilizations approximately one month apart to allow the aquifer to recover between injection events.

8.2.2 Distribution of Substrate

The most obvious indicator of the successful distribution of substrate is discoloration of groundwater as the emulsion moves from the injection wells to nearby monitor wells, and dramatic increases in dissolved TOC. Eighteen hours after stopping the injections, samples from the three monitor wells situated approximately 2.5 ft from surrounding injection wells were not milky, but the TOC concentrations ranged from 10.5 to 150 mg/L (see Section 7.2.1). By 20 days post-injection, the TOC in groundwater had increased to as much as 63 mg/L in the monitor wells. The concentrations of VFAs including acetic, propionic and butyric acids in monitor well 17PS-02 in the middle of the test cell also increased soon after injection. Together, these data indicate that more soluble components of EOS® can spread effectively during injection and *in situ* biodegradation.

Micron-sized droplets of buffered EOS® were effectively distributed throughout the target treatment zone by direct-push injection. Substantial increases in pH and TOC were observed in monitor wells shortly after injection. Three months after buffered EOS® injection, soil samples collected from 8 to 16 ft bgs throughout the test cell showed that the soil pH had increased from pH 4.9-5.3 to pH 6.4-7.7, a range more favorable for reductive dechlorination.

Injection of buffered EOS® resulted in a significant decline in the apparent permeability of the injection and monitor wells. This decline in permeability occurred at the same time as a globular residue formed at the top of the water column in the treatment cell wells. This material was presumed to be a combination of oily material from the buffered EOS® and excessive biological growth in the organic carbon-rich environment provided by the pH-neutral product at the air-water interface. The presence of this material appears to have interfered with the specific capacity measurements taken after the injection of buffered EOS®. This led to erroneously low calculations of hydraulic conductivity and groundwater flow velocity when compared to velocities calculated by the mass flux canisters. The material could be removed by pumping and did not interfere with collection of groundwater samples from deeper in the water column.

8.3 Performance Monitoring

The Technology Demonstration Plan called for comprehensive monitoring to last approximately 18 months. The evaluation of the data during that period showed initial changes to the aquifer geochemistry toward conditions more favorable for anaerobic reductive dechlorination of TCE. However, there was evidence that further biodegradation of TCE and *cis*-DCE was being limited, presumably by a decrease in pH in groundwater beneath the pilot test cell. The impact of this phenomenon warranted additional study and the project was extended to allow for laboratory testing to evaluate means of overcoming the problems and one additional year to demonstrate the proposed solution in the field. The results of the first 28 months (Phase I) and the last 13 months (Phase II) of field evaluation were discussed in Section 7.0 of this report.

8.3.1 Substrate Effectiveness for Enhanced Reductive Dechlorination

The use of emulsified oil for groundwater remediation is a patented, two-step process to enhance the anaerobic biodegradation of chlorinated solvents. In Step 1, as the oil emulsion substrate slowly biodegrades over time, it provides a continuous source of dissolved organic carbon; (i.e., fermentation products) to support anaerobic biodegradation of the target contaminants. Degradation of the oil results in removal of oxygen and production short-chain volatile fatty acids (e.g., acetic, propionic and butyric acid) and hydrogen. It also results in the decrease of competing electron acceptors including nitrate, sulfate and ferric iron.

In the second step, the hydrogen and acetate generated are used by specialized microbial communities to degrade the TCE. At the demonstration site, the biotransformation of TCE to *cis*-DCE suggested an active population of *Dehalobacter spp*. (DHB) in the aquifer, although the enumeration of DHB showed the population was below detection in the treatment cell at the end of the performance monitoring period. Before treatment, there was little indication of background *Dehalococcoides spp*. (DHC) activity, and the addition of substrate resulted in only marginal formation of VC and ethene. *Dehalococcoides spp*. is sensitive to acidic pH conditions with little activity documented near or below pH 5.5. The addition of buffered EOS® during Phase II resulted in an increase in pH and a large increase in conversion of TCE and *cis*-DCE to VC. However, further conversion of VC to ethene was slow. At the end of Phase II, the DHC population density was 4 to 5 orders-of-magnitude greater in the treated soil and groundwater compared to the untreated background matrices. However, no organisms were detected with the enzymes BAV1 VC R-dase or VC R-dase that are known to be capable of rapid reduction of VC to ethene. The slow conversion of VC to ethene is believed to be due to absence of organisms capable of rapid VC degradation. VC degradation would likely be enhanced by bioaugmentation with cultures capable of rapid conversion of VC to ethene.

As early as six months after the Phase I injection of EOS® substrate, data were obtained that showed the beginning of enhanced reductive dechlorination in the treatment cell compared to the surrounding environment (see Section 7.4.4) By 28 months, the TCE concentrations were routinely 76 to 86% lower throughout the test cell groundwater than in the background groundwater. After the pH was adjusted, the concentrations of TCE were further reduced to less than 96 to >99% of the background concentrations (Section 7.4.2). The chlorine number calculations show that conversion of TCE to *cis*-DCE, VC and ethene was enhanced after the addition of buffer (see Section 7.4.3). The mass flux measurements also showed that applying the substrate in a grid formation could effectively reduce the mass flux of contaminants moving through the treated zone (see Section 7.4.6).

8.3.2 Substrate Longevity

The demonstration successfully documented changes to the aquifer geochemistry that favored anaerobic reductive dechlorination. The addition of emulsified oil substrate immediately increased the dissolved TOC and also the organic carbon bound to the aquifer sediments (Section 7.2). The small amount of lactate in the EOS® concentrate was available for immediate and short-term stimulation of the aquifer microorganisms. Fermentation of the soybean oil was then responsible for formation of more soluble VFAs and hydrogen that could be used in the subsequent reductive dechlorination process (Section 7.2.2).

Three drums (165 gal; 1,260 lbs) of EOS® concentrate provided for elevated TOC in groundwater for the entire 28 months of Phase I. After the initial increase in concentrations, the TOC in groundwater generally declined over time. After 377 days (~12 months) the average TOC concentration was still 57.4 mg/L, but by 468 days (~15 months), the concentration had dropped to 9.6 mg/L. The TOC in soil nine months after injection was elevated compared to pre-injection concentrations of native background TOC. These observations support the hypothesis that even after prolonged exposure to bioactivity there is residual TOC is sorbed to the aquifer sediments. However, this reserve organic carbon may not be apparent by simply measuring TOC in groundwater.

The treatment grid was then rejuvenated with an additional 330 gal (3,030 lbs) of buffered EOS® and monitored for an additional 13 months (Phase II). The presence and effectiveness of this second injection beyond 13 months was not tested. The availability of excess TOC was evident by the level of methane production throughout the entire 41-month pilot study.

8.3.3 Geochemical Changes to the Aquifer

Geochemical changes to the aquifer that occurred as a result of the introduction of substrate are discussed in Section 7.3. Dissolved oxygen decreased very soon after injection of substrate and stayed low during the course of the study. There was an immediate reduction in ORP in the treatment grid from mostly positive to negative, but there was some rebound and fluctuations in ORP observed over the course of the project. The ORP in the pilot test monitor wells stayed more consistently below 0 mV than the ORP in the injection wells. After buffered EOS® was added, the ORP in the pilot test monitor wells steadily decreased approaching -160 mV. It is possible that some of the inability to achieve high rates of reductive dechlorination may have also been a result of not reaching optimal ORP during Phase I of the pilot study. Methane and H_2S were formed as noted in the headspace of the wells, but were not measurable in the vadose zone via the soil gas monitoring points. The increasing concentrations of dissolved methane in groundwater during the pilot test suggests that lower ORPs are being achieved than have been measured.

Nitrate was not present in the aquifer and was not an issue during this study. Sulfate was not extraordinarily high in the aquifer and the addition of emulsified oil quickly reduced the concentrations to below 20 mg/L where they remained for the balance of the study. Dissolved iron concentrations increased substantially after the injection of substrate. This

is another indicator of the creation of a strongly reducing environment. The addition of buffered EOS® resulted in a drop in dissolved iron, presumably due to precipitation of $FeCO_3$.

8.3.4 Effect of pH

Carbon addition to an aquifer can result in fatty acid buildup as the biodegradation of soybean oil fatty acids results in the formation of short-chain keto acids. In turn, these compounds can be further degraded to H_2 and acetic acid and carbonic acid.

Complex Organics -→ VFAs →H_2 + Acetic Acid + Carbonic Acid.

Bacteria then can use these end-products for reductive dechlorination, releasing up 3 moles of hydrochloric acid (HCl) for each mole of TCE reduced to ethene. In an already low-pH aquifer, this can exacerbate the decline in pH and slow bioactivity. The actual decline in pH will depend on the background alkalinity of the aquifer.

The optimum pH for the reductive dechlorination of PCE by DHC is above pH 6.0. Below pH 6.0 some inhibition occurs; below pH 5.5 reductive dechlorination may stop. As discussed in Section 8.3.1 above, it appears that aquifer pH in the pilot test cell decreased to below pH 5.5 resulting in cessation or slowing of reductive dechlorination.

By testing the acid demand in the laboratory and evaluating several alkaline materials for their ability to adjust the pH, a buffered EOS® blend was developed that could be injected into the aquifer to offer long-term pH adjustment and additional substrate. The blend was used in Phase II and was shown to effectively re-adjust the pH toward neutrality. This increase in pH was effective in stimulating rapid biodegradation of TCE and *cis*-DCE with significant conversion to ethene. However, complete conversion of TCE to non-toxic end products may have been slowed by the absence of microorganisms with the ability to rapidly and completely convert VC to ethene.

9.0 Cost Assessment

9.1 Cost Drivers

The primary cost drivers of the emulsified oil treatment technology are associated with the following:

1. The spatial arrangement and construction of the injection points;
2. Site conditions that determine the amount of substrate to inject; and
3. Site hydrogeology that affects the injection design and the amount of labor and equipment hours required to inject the substrate.

These costs are influenced by the subsurface lithology, and both horizontal and vertical extent of contamination. The performance of an emulsified oil substrate design for stimulating remediation of chlorinated solvents is strongly affected by the ability to distribute the emulsion throughout the treatment zone, the presence of microorganisms capable of contaminant biodegradation, contact time between the contaminants, bacteria and emulsion, and the rate of biodegradation of the target contaminants that can be achieved *in situ*. The length of time that the substrate remains effective in the aquifer controls the need for future re-injection and replenishment. The potential impacts of these conditions are discussed in the following sections.

9.1.1 Contamination Type and Levels

The emulsified oil technology has the potential for remediating many types of groundwater contamination including chlorinated VOCs and perchlorate. Although the microbial pathways may vary, the contaminants serve as the electron acceptor while the substrate functions as the electron donor. Competing electron acceptors for CVOC degradation include DO, nitrate, iron(III) and sulfate. Competing electron acceptors for perchlorate degradation are primarily DO and nitrate. These electron acceptors must be consumed before the desired reduction of the target contaminant can proceed effectively. Although these conditions are important, contaminant concentration has relatively little impact on the design and amount of substrate needed at many sites. In source zones with DNAPL, concentrations will have more relevance than in the dissolved plume found downgradient.

9.1.2 Plume Size and Depth

Obviously, the total cost to treat large areas is greater than for small areas. However, costs per unit volume to treat a large area can be significantly lower due to economies of scale during injection and the relatively lower design, permitting and monitoring costs. Deeper contamination zones are somewhat more expensive to treat due to the higher costs for injection wells. However, other costs are not significantly impacted.

9.1.3 Injection Network

Injection costs depend on the method used to install injection points, labor for injection, the flow rate per point, and the number of points injected at one time. Emulsified oils can be injected through direct-push points, temporary injection wells, or conventional monitor wells. The effect of injection point spacing on cost is primarily a trade-off between well installation, labor and substrate costs. If the intent of the injection is to “smear” the entire zone between the wells with

substrate during the injection process, wider spacing of the injection points will reduce injection well installation costs, but may increase the time/labor required for injection. If less than total coverage is acceptable, labor and equipment costs may be adjusted accordingly. Similarly, the well installation costs are affected by the geology and depth to groundwater, while the labor costs are determined by the time required for fluid injection. In a high permeability aquifer, fluid injection will be easier and will take less time. Often, multiple wells can be injected simultaneously by manifolding pumps and delivery lines or using commercially available dosing equipment to reduce the time required to complete the injections.

9.1.4 Substrate Costs

The amount of emulsified oil substrate required at a specific site will depend on two different factors:

1. The mass of contaminant and competing electron acceptors to be degraded, and
2. The oil retention by the aquifer material.

Material costs for anaerobic bioremediation using emulsified oils are generally higher than for soluble substrates such as carbohydrates and lactate. However, as shown in **Table 9-1**, it takes 26 times as many moles of lactate to obtain the same reducing equivalents as one mole of emulsified oil substrate. Consequently, total costs for emulsified oil are generally lower because of the additional amount of lactate required and the additional labor associated with repeated lactate additions to replenish spent substrate. The greater longevity of oil in the subsurface generally results in lower total costs because of the much less frequent substrate injection.

Table 9-1
Relative Amount of Electrons Produced by Degradation of Various Substrates

	Moles e^- Released	
	per mole	per gram
Acetate	8	0.13
Lactate	12	0.13
Glucose	24	0.13
Soybean Oil	313	0.36
Canola Oil	319	0.36

9.1.5 Emulsified Oil Distribution

To be most effective, emulsified oil substrate should be distributed vertically and horizontally throughout the treatment zone. If the emulsified oil is not effectively distributed, contact between contaminated soil and groundwater may be delayed as either soluble components of the substrate migrate away from the injection zone or contaminated groundwater migrates to the injection zone. For optimum contaminant removal, emulsified oil treatments should be designed to achieve the highest contact efficiency that can be cost-effectively achieved. Modeling studies by Clayton and Borden (2008) showed that injecting more oil with more water while using more closely spaced wells, will improve emulsion distribution. However, injecting more oil with more water and more wells will increase costs.

Because subsurface conditions can widely vary among sites, Borden et al. (2008a, 2008b), with funding from ESTCP, created a spreadsheet based design tool (Design Tool) to assist engineers and project scientists plan emulsified oil injection systems. The Design Tool can be applied to injection-only systems for distributing emulsified oils in barriers and area treatments. It allows users to quickly compare the relative costs of different injection alternatives and identify a design that is best suited to the site-specific conditions. The relative costs and performance of different injection alternatives can be evaluated using the Design Tool to identify a design that is best suited to the site-specific conditions.

9.1.6 Maximum Oil Retention

Maximum oil retention (OR_M) is one of the most important factors controlling system performance and costs, but also one of the most poorly known. Common practice is to select an oil retention value from a table of previously measured values for different aquifer materials (i.e., sand, clay, silty sand, etc.). However, there is tremendous variation in OR_M between different materials. Consequently, it would be very easy for the estimated value to differ from the actual value at the site by a factor of 2 to 4. Given the importance of this parameter, whenever possible, OR_M should be directly measured on field or lab samples so site-specific values can be used in the design.

9.1.7 Emulsified Oil Biodegradation

Contact time is an important variable in determining substrate volumes, especially for a PRB. At the Maryland demonstration site in this project, an emulsified oil permeable reactive barrier was installed to intercept groundwater contaminated with perchlorate, 1,1,1-TCA and TCE (ESTCP, 2006 and 2008). Perchlorate was degraded very quickly upon contact with the substrate and the required contact time for essentially complete perchlorate degradation was only a few weeks. By contrast, the required contact time for high levels of TCA and TCE degradation was estimated to be between three and six months. However, there is currently no reliable method to estimate the required contact time for source area treatment. For area treatment, estimated costs increase approximately linearly with target contact efficiency (Weispfenning and Borden, 2008; Borden et al, 2008a).

Little is known about the factors controlling substrate consumption in area treatment and how this influences performance over time. In source areas, contaminant biodegradation rates are often limited by slow mass transfer and maintaining high biodegradation rates may not be critical. However, maintaining high biodegradation rates could possibly reduce the required operating life of the source area treatment, reducing costs. If the edible oil emulsion is biodegraded too rapidly or depleted by high groundwater flow, then more frequent injection will be required to maintain performance, thus increasing overall project costs. Operating experience at other sites indicates that a single emulsion injection will be effective in stimulating biodegradation for three to five years. Increasing the time period between re-injections from two to five years for area treatment can be expected to significantly reduce costs. Increasing substrate longevity beyond five years has only a modest impact on life-cycle costs.

9.1.8 Absence of Appropriate Microorganisms

Available information indicates that the indigenous microbial population may not be capable of complete reductive dechlorination of PCE and TCE to ethene at all sites. The pilot study at SWMU 17 showed that TCE dehalorespiring bacteria were present in the aquifer and that the addition of substrate could stimulate microbial growth and result in biodegradation of TCE to *cis*-DCE. However, as the pH decreased in the aquifer, the ability to continue reductive dechlorination diminished. Re-establishing pH neutral conditions re-started the reductive dechlorination process resulting in almost complete removal of TCE and *cis*-DCE. However, VC was formed and only slowly disappeared, likely a result of the apparent absence of VC reductase enzymes in the environment.

Additional information on aquifer bioaugmentation can be found in ESTCP (2005). At sites where the required microorganisms are not present, commercially available bioaugmentation cultures may be added to the aquifer for improved treatment. The percentage of costs associated with bioaugmentation is often small compared to the overall project costs. For this reason, pre-design testing for the presence of appropriate dehalorespiring populations is warranted and can be valuable for predicting project success. Bioaugmentation should be considered if there is doubt.

9.2 Cost Analysis

A cost analysis was performed to (1) document actual pilot test costs and determine a treatment cost per unit volume, and (2) compare scaled-up emulsified oil bioremediation costs with other conventional source remediation approaches.

9.2.1 Charleston NWS Pilot Test Costs

Throughout the course of this demonstration, expenditures were tracked to evaluate the cost-effectiveness of enhanced bioremediation using emulsified oils as a remedial approach for source zones and to help provide cost information for scale-up of the technology. Costs associated with labor, equipment, subcontracted labor and purchased services such as drillers and analytical laboratories, were gathered to provide a basis for comparing the use of emulsified oils to other technologies frequently employed to remediate chlorinated solvent contamination in groundwater.

The pilot study demonstration was comprised of two injection phases (see **Section 6.1 and 6.4).** The site characterization and performance monitoring portions of the total costs were shared between the two phases. Some activities were outside the scope of a typical site characterization such as the MIP evaluation, grain-size analysis, treatability study and mass flux analysis. The monitoring lasted 41 months, comprising 13 events. This is longer than a typical pilot test might be run. Combined, these additional items served to increase the cost of the demonstration, but also improved the quality of the data obtained and depth of the evaluation.

Table 9-2 details the project's major cost elements. The cost of four years of project management, preparing the Technology Demonstration Plan for the site, technology transfer activities, preparation of the emulsified oil protocol for ESTCP (ESTCP, 2006a) and the technical report itself are not included. Project coordination, permitting, design, labor, travel,

equipment, materials, subcontractors, an in-depth treatability study, and performance monitoring activities including laboratory charges are included. The unit costs for injection have been separated to better represent the two phases of the project. Unit costs are based on the volume of the 20 ft x 20 ft x 10 ft treatment zone which is 4,000 ft^3 or 148 yd^3.

Substantial effort was expended to characterize the site before selecting the location of the pilot test area. The costs for these activities totaled almost $50,000 and included permitting, well installations, the grain size evaluation of lithology, MIP testing, and soil and groundwater preliminary contaminant profiling. The installation of the 16-well injection grid (**Section 5.2)** cost approximately $38,000 and the cost for purchase and installation of the original emulsified oil product in Phase I was another $27,000. The combined cost to install the treatment system, and manage the injection of substrate using the temporary injection/recovery recirculation approach was $65,000 which calculates to $16/$ft^3$ or $439/$yd^3$.

Phase II was initiated to test the treatability study findings that raising the pH of the aquifer would stimulate further bioremediation. A buffered EOS® product was used to add additional electron donor and buffer simultaneously. The substrate was injected in 19 locations across the treatment cell directly through the Geoprobe® injection tool (**Section 6.4**). Just under three times as much material was introduced into the aquifer as in Phase I and the unit cost of the substrate was slightly higher because of the blend of emulsified oil concentrate with alkaline buffering agent. Nonetheless, as shown in **Table 9-2**, the cost for purchase and application of the buffered EOS® substrate was slightly less at approximately $48,000 which calculates to $12/$ft^3$ or $325/$yd^3$.

Performance monitoring was performed almost quarterly for the duration of the 41-month study. The total cost for monitoring was $128,000 or approximately $9,900 per event.

Table 9-2
Costs for the Pilot Study

Task	Unit	Unit Cost	Quantity	Cost	Unit Costs for Injection
PHASE I CAPITAL COSTS					
Site Characterization and Design					
Design, planning, reporting, H&S	LS			$15,000	
Site Characterization (labor and equip.; incl. MIPs)	LS			$14,547	
Analytical laboratory	total			$8,280	
Install six 2-inch PVC MWs to 20 ft bgs	per well	$1,875	6	$11,250	
SUBTOTAL				**$49,077**	
Injection Grid					
Site prep and mobilization	LS			$7,316	
Install 16 1-inch. PVC Geoprobe inj. wells to 18 ft bgs	per well	$1,688	16	$27,000	
Oversight of injection well install (1 staff; incl. travel,	per	$1,200	3	$3,600	

Task	Unit	Unit Cost	Quantity	Cost	Unit Costs for Injection
etc)	day				
SUBTOTAL				**$37,916**	
Substrate Injection/Recirculation/Startup Testing					
Electron donor substrate (EOS®) + shipping	lbs	$2.45	1,260	$3,087	
Injection labor (2 staff; incl. travel, lodging, per diem)	per day	$3,800	5	$19,000	
Injection equipment (pumps, valves, etc.)	per day	$1,000	5	$ 5,000	
SUBTOTAL				**$27,087**	**$16/ft^3 $439/yd^3**
TOTAL PHASE I CAPITAL COSTS				**$114,080**	
PHASE II CAPITAL COSTS					
Laboratory Treatability Study				$43,081	
Substrate Direct Injection/Startup Testing					
Buffered EOS® + shipping	lb	$3.45	3,030	$10,453	
Injection oversight (2 staff; incl. travel, lodging, per diem)	per day	$3,165	5	$15,823	
Injection equipment (includes Geoprobe driller)	per day	$4,368	5	$21,840	
SUBTOTAL				**$48,116**	**$12/ft^3 $325/yd^3**
TOTAL PHASE II CAPITAL COSTS				**$91,197**	
MONITORING COSTS					
Specialized characterization and monitoring					
Mass flux (2 events)	LS			**$15,000**	
Soil properties					
Labor and equipment	per day	$500	5	**$2,500**	
Analytical laboratory	total			**$28,615**	
SUBTOTAL				**$46,115**	
Performance monitoring					
Labor (incl. travel, lodging, per diem)	event	$5,516	13	**$71,708**	
Equipment	event	$1,649	13	**$21,441**	
Analytical laboratory	event	$2,701	13	**$35,107**	
SUBTOTAL				**$128,256**	
TOTAL MONITORING COSTS				**$174,371**	
TOTAL PROJECT COST				**$379,648**	

The general distribution of project funds by major category is shown in **Figure 9-1**. Project management, Technology Demonstration Plan development, reporting costs and technology transfer costs are not shown. The total cost of the pilot test demonstration at SWMU 17 at Charleston NWS was $380,000 (**Table 9-2**). The largest portion of the total cost (~34%) was due to the extended performance monitoring of both phases that comprised 41 months of the demonstration. Phase I installation and injection was 16% of the total cost and Phase II represented 10 % of the total. Only 4% of the total cost for the pilot study was the cost of substrate and shipping.

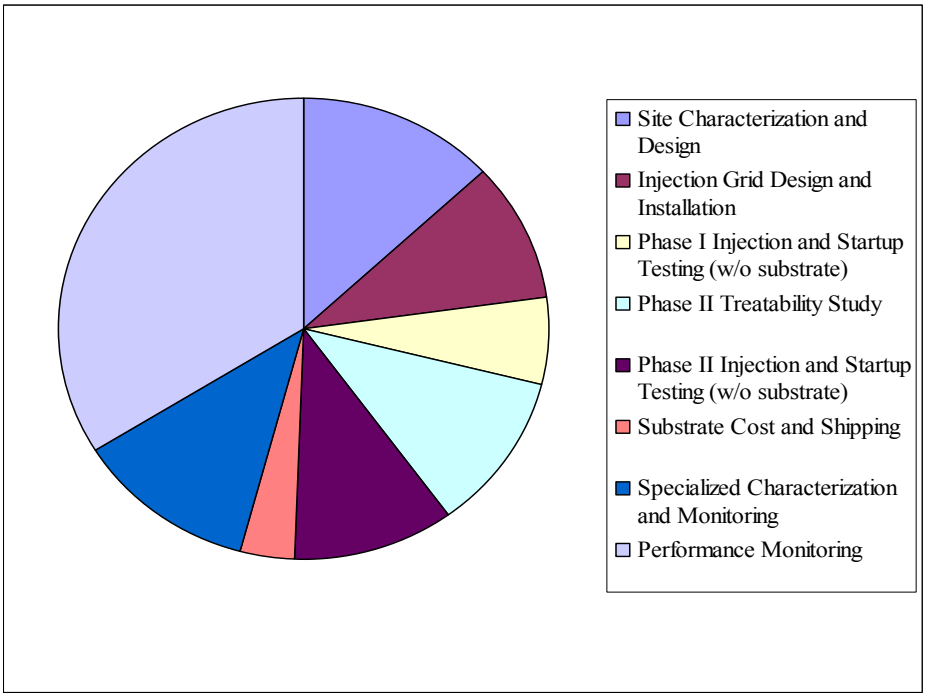


Figure 9-1. Project Expenditures by Major Category

9.2.2 Cost Comparisons and Sensitivity Analysis

Capital and life-cycle costs directly relate to the size of the treatment area, but are relatively insensitive to site conditions. Intuitively, project personnel might assume that total costs will be higher for large, wide, deep sites. However, unit costs will be higher also for smaller sites due to the proportionately higher fixed costs associated with planning, design and monitoring. The Design Tool was utilized in developing the cost comparisons presented in this section (Borden et al., 2008b). A sensitivity analysis is presented to illustrate how areal extent and depth of the contamination zone can impact costs. Additional factors such as contaminant concentrations, injection well spacing, proposed radius of influence of substrate around each injection well, site hydrogeology and substrate costs were kept constant except as noted.

9.2.2.1 Emulsified Oil Bioremediation Sensitivity Analysis

A base case condition was developed to represent a typical site comprised of silty sands throughout the treatment interval using the hydrogeological conditions found at SWMU 17. The Design Tool was used to prepare the estimates. Site conditions derived from the site

characterization activities were used (see **Section 5.2)**. The following parameters were used in the base case scenario:

- Treatment zone thickness = 25 ft
- Hydraulic conductivity (K) = 7 ft/day
- Hydraulic gradient = 0.002
- Effective porosity = 0.24
- Injection rate = 0.25 – 0.30 gpm
- Maximum soil retention = 0.0085 lb oil/ lbs soil

These conditions were used in a variety of hypothetical scenarios constructed by varying the size of the treatment area and depth. The outputs of the Design Tool were then compared. The treatment scenarios are shown in **Table 9-3**.

TABLE 9-3
Treatment Design Scenarios Used for Sensitivity Analysis

Scenario	Name	Source Area Dimensions	Depth to Top of Injection Zone	Treatment Zone Thickness	Well Installation/ Injection Method/Rate
1	Base Case Area (0.06 Acre)	50 ft x 50 ft	10 ft bgs	25 ft	25 DPT injection wells 10-ft OC*; Inj. rate = 0.25 – 0.3 gpm
2	Base Case with Lower Oil Retention (.005 lb oil/lb soil)	50 ft x 50 ft	10 ft bgs	25 ft	25 DPT injection wells 10-ft OC*; Inj. rate = 0.25 – 0.3 gpm
3	Small Source Area	25 ft x 25 ft	10 ft bgs	25 ft	16 DPT injection wells 7-8 ft OC*; Inj. rate = 0.25 – 0.3 gpm
4	Mid-Size Area (0.25 Acre)	100 ft x 100 ft	10 ft bgs	25 ft	100 DPT injection wells 10-ft OC*; Inj. rate = 0.25 – 0.3 gpm
5	Deep Groundwater	50 ft x 50 ft	105 ft bgs	25 ft	25 HSA wells 10-ft OC**; Inj. Rate = 1.0 gpm
6	Deeper Groundwater; Narrow Saturated Thickness	50 ft x 50 ft	40 ft bgs	10 ft	25 HSA wells 10-ft OC**; Inj. Rate = 1.0 gpm
7	Large Saturated Thickness	50 ft x 50 ft	10 ft bgs	50 ft	25 HSA wells 10-ft OC** ; Inj. Rate = 1.0 gpm

Scenario	Name	Source Area Dimensions	Depth to Top of Injection Zone	Treatment Zone Thickness	Well Installation/ Injection Method/Rate
8	Large Source Area (0.5 Acre)	100 ft x 200 ft	10 ft bgs	25 ft	200 DPT injection wells 10-ft OC*; Inj. rate = 0.25 – 0.3 gpm
9	Full-scale with Buffered EOS® (0.5 Acre)	100 ft x 200 ft	8 ft bgs	10 ft	200 DPT injection wells 10-ft OC*; Inj. rate = 0.25 – 0.3 gpm

*Substrate injected via 1-inch diameter temporary injection wells manifolded together.
** Substrate injected via 2-inch diameter deep injection wells, installed by hollow-stem auger, and manifolded together during injection.

Table 9-4 shows the costs calculated for each of the scenarios. The Design Tool output summaries are provided in **Appendix VIII**. The fixed costs for the basic scenario was generally maintained at $65,000 for each scenario. However, some additional fixed costs were added to larger sites with either substantially greater numbers of direct push wells or much deeper wells installed by conventional drilling. The fixed costs include project management, design, permitting, preparation of a work plan to guide the installation and monitoring activities, and some additional time for mobilization and installation of injection equipment. No costs for baseline site characterization are included; it is presumed that this has been completed before design begins.

For Scenarios 1, 2, 3, 4, 8 and 9, the injection grid was designed with 1-inch diameter injection wells installed 10 feet on-center (OC) at an average cost of $1,420 per well. The exception is Scenario 3 where the source area is relatively small and the wells are spaced more closely between 7.5 and 8.0-ft OC. The deep groundwater (Scenario 5), the limited saturated thickness (Scenario 6), and the large saturated thickness (Scenario 7) scenarios assume conventional hollow-stem auger drilling methods which incur higher costs. These scenarios also require a different injection process through the deeper wells. In every scenario, the well spacing is equal to the row spacing (1:1). The cost analysis assumes that injection through the 1-inch injection wells can be maintained at 0.25 to 0.3 gpm while injection through the conventional injection wells can achieve 1.0 gpm.

TABLE 9-4
Cost Estimates for Various Treatment Scenarios Using Emulsified Oil

Scenario – Name (volume)	Design/ Permitting /Mgmt	Well Installation. Cost (# injection wells)	Substrate Cost (# lbs of oil)	Labor for Injection	Total Cost to Implement	Unit Cost ($/ft^3)	Performance Monitoring ($/yr)	Net Present Value (7 yrs)
1 - Base Source Area (62,500 ft^3)	$65,000	$35,500 (25 DPT wells)	$29,155 (7,140 lbs)	$14,900	$144,555	$2.31/ft^3	$12,900/yr	$288,379

Scenario – Name (volume)	Design/ Permitting /Mgmt	Well Installation. Cost (# injection wells)	Substrate Cost (# lbs of oil)	Labor for Injection	Total Cost to Implement	Unit Cost ($/ft^3)	Performance Monitoring ($/yr)	Net Present Value (7 yrs)
2 - Base Area; Lower Oil Retention (62,500 ft^3)	$65,000	$35,500 (25 DPT wells)	$17,150 (4,200 lbs)	$14,900	$132,550	$2.12/ft^3	$12,900/yr	$266,112
3 – Sm. Source Area; Sm. Volume (15,625 ft^3)	$65,000	$22,720 (16 DPT wells)	$7,289 (1785 lbs)	$5,960	$100,969	$6.46/ft^3	$8,575/yr	$185,718
4 – Mid-Size Area; Lg. Volume (250,000 ft^3)	$68,750	$142,000 (100 DPT wells)	$116,620 (28,560 lbs)	$59,600	$386,970	$1.53/ft^3	$34,300/yr	$819,785
5 – Base Area; Deep Ground-water (62,500 ft^3)	$73,500	$106,625 (25 HSA wells)	$29,155 (7,140 lbs)	$5,790	$215,070	$3.44/ft^3	$12,900/yr	$373,572
6 – Base Area; Limited Sat'd Thickness (25,000 ft^3)	$73,500	$56,625 (25 HSA wells)	$11,662 (2,856 lbs)	$8,190	$149,977	$6.00/ft^3	$12,900/yr	$284,892
7- Base Area; Lg. Saturated Thickness (125,000 ft^3)	$73,500	$62,875 (25 HSA wells)	$58,310 (14,280 lbs)	$9,650	$204,335	$1.63/ft^3	$12,900/yr	$381,709
8- Lg. Area; Lg. Volume (500,000 ft^3)	$71,750	$162,000 (200 DPT wells)	$233,240 (57,120 lbs)	$119,200	$586,190	$1.17/ft^3	$33,670/yr	$1,165,448
9- : Large Area; Large Vol; Buffered EOS (200,000 ft^3)	$71,750	$162,000 (200 DPT wells)	$197,064 (22,848 lbs)	$59,600	$490,414	$2.45/ft^3	$34,300/yr	$998,831

An average cost of $2.45/lb delivered for the emulsion concentrate was used in the first eight scenarios to match the cost used in Phase I of the pilot test. The substrate costs shown in the first eight scenarios in **Table 9-4** are per pound of oil and assume the concentrated emulsion is 60% soybean oil. Based on the findings presented in this report (**Section 7.0**), full scale application of the technology at SWMU 17 at the Charleston NWS would likely utilize the buffered EOS®

substrate. For comparison, a ninth scenario was developed to evaluate the potential costs of this approach. The cost of buffered EOS® used in this model was $3.45/lb delivered; the buffered EOS® contains 40% emulsified oil. The full-scale design cost estimate for SWMU 17 is discussed further in **Section 9.2.2.2**. Although the pilot study in this report suggested that bioaugmentation might be useful at the site, costs for bioaugmentation were not included in any of the scenarios.

Injection costs assume manifolding together and simultaneously injecting up to 10 wells (or a maximum of 50% of total number of wells) for 9 hours of injection per day at a labor cost of $1,490/day. Mass and volume scaling factors of 0.5 were utilized as described in the Design Tool (Borden et al., 2008a; Weispfenning and Borden, 2008). Concentrations of chlorinated ethene or ethane contaminants, sulfate and nitrate concentrations, and groundwater flow velocity were not included in the scenario analysis since these factors do not significantly affect area treatment costs (see **Section 9.1.1**).

Based on the SWMU 17 pilot test performance (**Section 7.0**), it appears that one injection of the buffered EOS® would have been sufficient to meet regulatory goals for remediation of SWMU 17. However, to be conservative for this cost analysis, it was assumed that a second injection would occur four years later to replenish the treatment zone and achieve final cleanup that would be monitored for an additional 3 years. Well rehabilitation costs for future injection events were assumed to be 25% of the initial well installation cost. Thus, the Net Present Value (NPV) calculations are based on 4% interest rate over the course of a 7-year project life and include projections for performance monitoring based on the size of the treatment area.

In general, unit costs are relatively insensitive to site conditions and vary between $1.17 and $3.44/ft^3 except for the smaller two sites (Scenario 3 and 6) where unit costs were $6.00 to $6.46/ft^3. Using the limited number of scenarios presented in **Table 9-4**, there was minimal correlation between treatment volume and cost per unit volume ($r^2 = .40$; $n = 9$). However, the size of the site does appear to have the greatest impact on total cost. For a small site, the total costs are lower while unit costs are higher due to the proportionately large contribution of up-front fixed costs.

9.2.2.2 Cost of Full-Scale Implementation at SWMU 17 at Charleston NWS

The pilot demonstration treated a 20 ft x 20 ft area with a vertical interval of 10 ft. Tetra Tech (2001) described SWMU 17 as encompassing an area measuring approximately 90 ft x 180 ft which is just under 0.5 acre. Scenario 9 in **Table 9-4** shows the cost estimate for the full-scale, 0.5-acre treatment of SWMU 17. Based on the results of the pilot study, it was presumed that injection of buffered EOS® substrate through manifolded 1-inch diameter injection wells or direct injection tooling would be the desired design. Unit costs for injection did not change, but the unit cost for buffered EOS® was set at $3.45/lb to match the cost used in the pilot test. Injection rates were maintained at 0.25 to 0.30 gpm, but the injection well spacing was increased from 5-ft OC used in the pilot study to 10-ft OC to more cost-effectively address the larger area. Based on these conditions, the cost to implement the emulsified oil technology over the 0.5 acre area was estimated to be approximately $490,000. The NPV for a 7-year project was approximately $999,000.

9.2.2.3 Cost Comparisons with Other Technologies

The pilot study demonstrated the effectiveness of the emulsified oil treatment approach for potentially achieving regulatory goals for the site. However, other technologies could be applied to this same location. The following sections discuss other applicable technologies and provide a comparison of costs for the emulsified oil technology with other *in situ* bioremediation (ISB) approaches, *in situ* chemical oxidation (ISCO), and *in situ* low temperature thermal treatment (ISLTT).

McDade et al. (2005) conducted a detailed evaluation of remediation costs for several technologies. They conducted a review of peer-reviewed literature, conference proceedings, state and federal government agency reports, internet databases, and technical surveys to acquire cost and performance data at 36 full-scale and pilot-scale sites. Eleven sites used enhanced ISB with unspecified substrate although some sites might have included vegetable oil applications. Thirteen of these sites used ISCO and six employed ISLTT. None of the costs presented included monitoring. A comparison of the estimated cost/yd^3 for these three technologies and the emulsified oil technology estimates calculated in the nine scenarios in **Table 9-4** are shown in **Figure 9-2**.

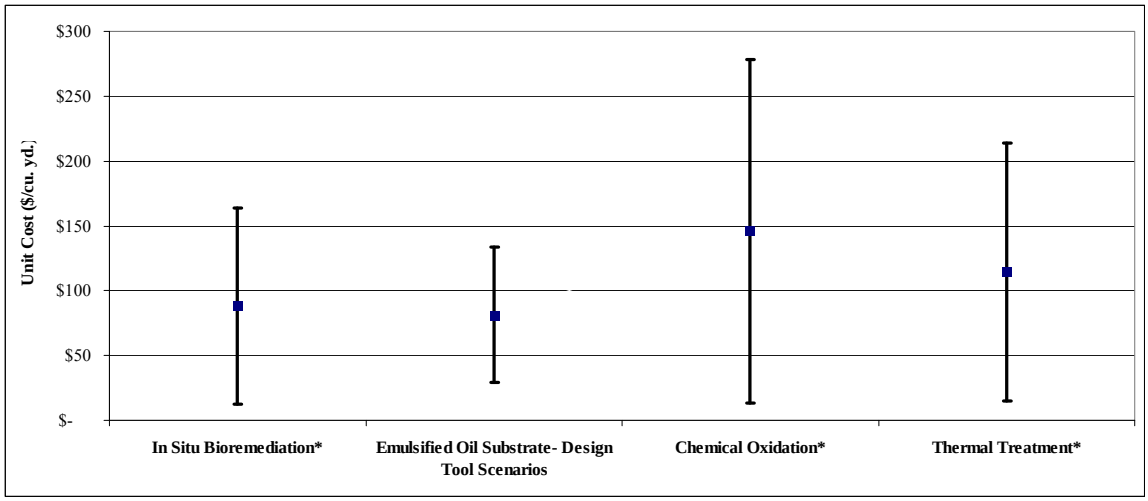


Figure 9-2. Unit Cost Comparison of *In Situ* Technologies

In situ Chemical Oxidation (ISCO)

The use of ISCO to treat small source areas is an effective way of aggressively destroying chlorinated solvents and dense non-aqueous phase liquid (DNAPL) source areas. Strong oxidants such as permanganate (MnO_4^-), Fenton's Reagent (H_2O_2/Fe^{2+}), and sodium persulfate are injected to chemically destroy the contaminants (Huling and Pivetz, 2006). Successful application of ISCO requires knowledge of oxidation processes for free-phase and residual DNAPLs, the stability and reactivity of oxidants during transport in the subsurface, the subsurface effects on oxidant fate and DNAPL destruction, and the potential for coupling ISCO with pre-and post-ISCO remedial methods (Siegrist, 2005). ISCO can be applied through Geoprobe® tooling and is very effective in the short term. Current limitations of ISCO include

the difficulty of bringing reactants into contact with contaminants, particularly when the contaminants are located in low permeability matrices in which diffusion and mass transfer are minimal, and the non-beneficial reactions of oxidant sources with aquifer materials such as metal catalyzed decomposition of the oxidation of naturally occurring organic materials (Watts, 2006). ISCO applications are subject to contaminant rebound after the chemical dissipates in the treatment zone and contaminated groundwater re-populates the treated zone. ISCO treatment often requires several re-applications over a relatively short period of time. ISCO may also leave undesirable residual secondary water quality conditions such as elevated sodium, manganese or sulfate.

McDade et al. (2005) analyzed the cost of ISCO at 13 sites. The unit costs ranged from $24 to $518/yd^3. The mean unit cost was $146 ± $72/yd^3 (**Figure 9-2**). Increased total costs did not correlate strongly (r^2 = .13; n = 13) with increased treatment volume.

In situ Low Temperature Thermal Treatment (ISLTT)

ISLTT typically includes three types of treatment approaches: steam, three-phase and six-phase electrical resistance heating McDade et al. (2005). These approaches all provide an external source of energy to heat the aquifer and volatilize the VOCs. Where an unsaturated zone overlies the contaminated aquifer, soil vacuum extraction may be implemented to capture the vapors released by the heat. This process has been shown to be effective for remediating source areas.

McDade et al. (2005) analyzed the cost of ISLTT at six sites. The unit costs ranged from $32 to $300/yd^3. The mean unit cost was $114 ± $100/yd^3 (**Figure 9-2**). Increased total costs correlate strongly (r^2 = .97; n = 6) with increased treatment volume.

In Situ Bioremediation (ISB)

Advantages of ISB typically include complete mineralization of the contaminants *in situ* with little impact on site infrastructure, no secondary waste stream to treat, and lower capital and O&M costs (AFCEE et al., 2004). Typical soluble substrates, neat oil and emulsified oils are relatively inexpensive, innocuous, food-grade substrates. The disadvantages of soluble substrates have been discussed previously in this report (see **Section 1.1).** Nonetheless, they have been used effectively on many sites. McDade et al. (2005) analyzed the cost of ISB at 11 sites. The unit costs ranged from $2 to $225/yd^3. The mean unit cost was $85 ± $78/yd^3 (**Figure 9-2**). Increased total costs correlated with increased treatment volume more strongly (r^2 = .38; n = 11) than ISCO.

When properly prepared and injected, emulsified oils can be moved away from the injection point to impact large zones of contamination. Once the injection has stopped, the oil becomes immobile and slowly biodegraded in most aquifers. Unlike the soluble substrates, a single low-cost injection can provide sufficient carbon to drive anaerobic biodegradation for several years. This significantly lowers O&M costs compared with aqueous-phase injection of soluble carbon sources (e.g., lactate and carbohydrates). Emulsified oils also can be emplaced at larger depths and situations such as fractured bedrock.

The unit costs for nine scenarios developed from the site conditions observed at the Charleston NWS were analyzed separately from the ISB costs shown by McDade et al. (2005). The unit costs ranged from \$32 to \$174/yd^3. The mean unit cost of the nine scenarios was \$81 ± \$52/yd^3 (Fi**gure 9-2**). Increased total costs correlated moderately (r^2 = .42; n = 9) with increased treatment volume and was similar to the correlation calculated for other ISB approaches.

9.3 Cost Analysis Summary

The pilot study at Charleston NWS was effective in demonstrating the effectiveness of using emulsified oil substrate and buffered substrate for promoting *in situ* reductive dechlorination of TCE. However, the level of effort was indicative of an in-depth study beyond that which might be expected of a typical pilot study. Consequently, the unit costs were found to be higher than reported in the literature for similar applications of ISB and the ISB scenarios developed using the Design Tool. The study shows that mean unit costs to implement ISB and ISB with emulsified oil are generally less than ISCO and ISLTT, but there is substantial overlap and site-specificity that can influence the overall cost.

10.0 Implementation Issues

10.1 Environmental Checklist

All materials used in the formulation of emulsified oil substrate (EOS®) are Generally Recognized As Safe (GRAS) food-grade materials (21 CFR 184.1400). The SCDHEC required no warranty regarding the ingredients in the substrate. However, the manufacturer warrants the concentrated material contains no heavy metals, emulsifiers or other ingredients that, upon dilution and injection, would contravene typical groundwater standards of the state. Other states may have specific requirements unlike SCDHEC.

The requirements for an underground injection permit or project work plan vary by state. SCDHEC did not require a formal plan, but did request to review the Technology Demonstration Plan prior to any injections. SCDHEC closely monitored the installation and abandonment of permanent wells, temporary wells and soil borings at the pilot study site. No formal permit was required, but permission to install was needed from both the Bureau of Land & Waste Management and the Division of Waste Management.

Dig permits were required at the NWS and were provided by the base prior to implementation. For this project, investigation-derived waste (IDW) was managed by the base.

10.2 End-User Issues

Potential end users of the technology include a variety of agencies within the federal government (DoD, Department of Energy [DoE], USEPA), state and local governments, and private industry. Typical end user concerns often include:

1. Possible permeability losses due to injection of the emulsion;
2. Potential impact of elevated residual concentrations of daughter products;
3. Sorption of the contaminants to the oil versus degradation;
4. Secondary water quality issues (e.g., changes to color, taste and odor that might occur); and
5. Gas production.

These concerns were addressed during the pilot test demonstration. The project's results were discussed in detail in Section 7.0 and summarized in Section 8.0. A brief synopsis is provided below as they pertain to the end-user issues noted above:

1a. The use of a recirculation design was only minimally helpful in distributing EOS®, but was complicated by generally low aquifer permeability. Some localized permeability losses are observed in the immediate vicinity of the injection wells, but these did not influence the overall performance of the source area treatment. Groundwater mounding was noted during direct injection of substrate. Given time, these effects dissipated and overall temporary permeability losses did not appear to substantially impact groundwater flow through the area.

2a. Daughter products can accumulate if complete biodegradation is not occurring. This can be a potential issue with chlorinated solvents. The contact time

needed for complete dechlorination should be considered in the design. The pilot study was conducted in an area of SWMU 17 with starting concentrations of TCE approaching 20,000 µg/L. The overall site characterization data from SWMU 17 indicated that concentrations from 80,000 to 1,000,000 µg/L may be present. To achieve reduction in concentrations that might meet regulatory limits, extended contact times may be required.

2b. The aquifer beneath the pilot test cell was naturally slightly acidic. The pilot study showed that addition of substrate can further reduce the pH, inhibiting reductive dechlorination. Measuring the baseline alkalinity may provide forewarning of the potential for further decreases in pH. Using a substrate containing a buffering agent can help prevent the drop in pH while providing donor carbon to support reductive dechlorination.

2c. The data suggest that the *Dehalobacter spp.* and *Dehalococcoides spp.* are present in the aquifer at SWMU 17. However, the laboratory study indicated that bioaugmentation may enhance conversion of VC to ethene.

3a. Sorption of chlorinated solvents (e.g., TCE) into the oil is typically observed within the injection zone immediately after injection. However, within one month of injection, sorption is typically no longer evident and biodegradation is the predominant contaminant reduction pathway. This was observed at the NWS site as evidenced by the changes in molar concentrations of chlorinated ethanes/ ethenes and reductions in chlorine number.

4a. By-products of emulsified oil injection may include metals mobilized from the solid phase (e.g., iron, manganese), methane, dissolved organic carbon, taste, and odor. Typically, these impacts are limited to the reactive zone. In addition, it is generally believed that dissolved metals will be re-precipitated downgradient when background conditions are reached. Potential adverse impacts on downgradient receptors should be evaluated, especially when the receptor is located within 100 ft of the bioremediation system.

5a. Gases, such as methane and hydrogen sulfide, were produced and could be detected in the headspace of the injection and monitor wells in the treatment grid. However, there was little indication that these gases migrated into the vadose zone. At sites where subsurface structures are located in close vicinity to the injection zone, engineering solutions should be used to minimize the potential for vapor accumulation.

10.3 Additional Guidance Documents

The following guidance documents provide additional information about the use of emulsified oil substrate for the *in situ* bioremediation of chlorinated solvents in groundwater:

- Borden R.C. and M.T. Lieberman, 2008. Chapter 8: Passive Bioremediation of Perchlorate Using Emulsified Edible Oil. *In*: H. Stroo and C.H. Ward (eds.), *In Situ* Bioremediation of Perchlorate in Groundwater. SERDP/ESTCP Remediation Technology Monograph Series, Springer Science & Business Media, LLC. NYC, NY., pp: 155-176.
- Borden, R.C., M.T. Lieberman, C. Zawtocki and W.J. Beckwith, 2006. Protocol for Enhanced *In Situ* Bioremediation Using Emulsified Edible Oil. Environmental Security Technology Certification Program (ESTCP Project ER-0221), Arlington, VA.
- AFCEE, 2007. Protocol for *In Situ* Bioremediation of Chlorinated Solvents Using Edible Oil. Prepared by Solutions-IES, Inc.; Terra Systems, Inc.; and Parsons, Inc. Air Force Center for Environmental Excellence, Brooks Air Force Base, Texas, Version 1.2, July 2007.
- AFCEE (Air Force Center for Environmental Excellence), NFESC (Naval Facilities Engineering Service Center), and ESTCP (Environmental Security Technology Certification Program), 2004. Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents. Prepared by Parsons Infrastructure & Technology Group, Inc., Denver, CO.

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Borden R.C. and M.T. Lieberman, 2008. Chapter 8: Passive Bioremediation of Perchlorate Using Emulsified Edible Oil. *In*: H. Stroo and C.H. Ward (eds*.), In Situ* Bioremediation of Perchlorate in Groundwater. SERDP/ESTCP Remediation Technology Monograph Series, Springer Science & Business Media, LLC. NYC, NY., pp: 155-176.

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APPENDIX I

MEMBRANE INTERFACE PROBE DATA AND REPORT

COLUMBIA TECHNOLOGIES

SmartData Solutions™

Subsurface Characterization Using Membrane Interface Probe (MIP) and Soil Conductivity (SC) Technologies Naval Weapons Station, SWMU 17 North Charleston, South Carolina

PREPARED FOR

Solutions IES
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Raleigh, North Carolina 27609

PREPARED BY

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Introduction

Solutions IES (IES) contracted **COLUMBIA Technologies, LLC (COLUMBIA)** to conduct an investigation of subsurface contamination at the Naval Weapons Station, SWMU 17, located in North Charleston, South Carolina. This investigation involved delineating the depth and horizontal extent of contamination using Membrane Interface Probe (MIP) and Soil Conductivity (SC) technologies. The purpose of this investigation was to characterize subsurface soils in the vadose and saturated zones, and delineate the nature and extent of soil contamination.

The investigation was conducted on February 27, 2004. COLUMBIA personnel on-site during the investigation included Morgan Aycock, MIP Specialist and Randy Brand, Southeast Regional Manager.

Objectives

The objectives of the MIP/SC investigation were to:

1. Characterize subsurface soils in the vadose and saturated zones.
2. Delineate the lateral boundaries of the contaminant.
3. Delineate the vertical extent of contamination.

Equipment Description

The MIP/SC probe is approximately 12-inches (30 cm) in length and 1.5-inches (3.8 cm) in diameter. The probe is driven into the ground at the nominal rate of one foot per minute using a Geoprobe® or similar direct push rig.

Soil conductivity, the inverse of soil resistivity, is measured using a dipole arrangement. In this process, an alternating electrical current is transmitted through the soil from the center, isolated pin of the probe. This current is then passed back to the probe body. The voltage response of the imposed current to the soil is measured across these same two points. Conductivity is measured in Siemens/meter, and due to the low conductivity of earth materials, the SC probe uses milliSiemens/meter (mS/m). The probe is reasonably accurate in the range of 5

to 400 mS/m. In general, at a given location, lower conductivity values indicate larger particles such as sands, while higher conductivities are representative of finer sized particles such as silts and clays.

The MIP portion of the probe was developed and patented by Geoprobe Systems, Inc. The operating principle is based on heating the soil and/or water around a semi-permeable polymer membrane to 121°C, which allows volatile organic compounds (VOCs) to partition across this membrane. The MIP can be used in saturated or unsaturated soils, as water does not pass through the membrane. Using nitrogen as a carrier gas, which sweeps across the back of the membrane, the VOCs are carried to the installed detectors. It takes approximately 37 seconds for the nitrogen gas stream to travel through 100 feet of inert tubing and reach the detectors.

COLUMBIA utilizes three detectors: a Photo Ionization Detector (PID), a Flame Ionization Detector (FID) and an Electron Capture Detector (ECD), mounted on a laboratory grade Shimadzu Model 14A gas chromatograph. The output signal from the detectors is captured by a MIP data logging system installed on a MIP Field Computer or laptop computer. Conductivity, speed, detector data and temperature are displayed continuously in real time during each push of the probe. In addition, the data logs can be printed for display and analysis following the data logging run or exported to common spreadsheet software for further analysis using COLUMBIA's ***SmartData Solutions***^{tm} technology.

The PID detector consists of a special UV lamp mounted on a thermostat controlled, low volume, flow-through cell. The temperature is adjustable from ambient temperature to 250°C. The 10.2 electron volt (eV) UV lamp emits energy at a wavelength of 120 nanometers, which is sufficient to ionize most aromatics (benzene, toluene, xylene, etc.) and many other molecules (H_2S, hexane, ethanol) whose ionization potential is below 10.2 eV. The PID also emits a lower response for chlorinated compounds such as TCE and PCE. Methanol and water, which have ionization potentials greater than 10.2 eV, do not respond on the PID. Detection limits for aromatics are in the low picogram range. Since the PID is non-

destructive, it is often run first in series with other detectors for multiple analyses from a single injection. Use of the PID is mandated in several EPA methods (8021, TO-14 etc.) because of its sensitivity and selectivity.

The most commonly used GC detector is the FID, which responds linearly from its minimum detectable quantity of about 100 picograms. The FID response is very stable from day to day, and is not susceptible to contamination from dirty samples or column bleed. This detector responds to any molecule with a carbon-hydrogen bond, but poorly to compounds such as H_2S, CCl_4, or NH_3. The carrier gas effluent from the GC column is mixed with hydrogen and burned. Hydrogen supports a flame and ionizes the analyte molecules. A collector electrode attracts the negative ions to the electrometer amplifier, producing an analog signal, which is directed to the data system input.

The ECD detector consists of a sealed stainless steel cylinder containing radioactive Nickel-63. The Nickel-63 emits beta particles (electrons), which collide with the carrier gas molecules, ionizing them in the process. This forms a stable cloud of free electrons in the ECD cell. When electro-negative compounds (especially chlorinated, fluorinated or brominated molecules) such as carbon tetrachloride or TCE enter the cell, they immediately combine with the free electrons, temporarily reducing the number remaining in the electron cloud. The detector electronics, which maintain a constant current of about 1 nanoampere through the electron cloud, are forced to pulse at a faster rate to compensate for the decreased number of free electrons. The pulse rate is converted to an analog output, which is transmitted to the data system.

Performance Test

Prior to logging each MIP location, performance tests with specific compounds are conducted to evaluate the sensitivity of the particular probe, transfer line and detector suite to be used. Using neat benzene to test the PID, and neat TCE to test the ECD, the headspace vapors are introduced to the membrane of the probe for four seconds. To test the FID, butane is released on the membrane for four seconds. These

values are compared to predetermined values and recorded.

Investigation Methods

MIP/SC profiling was conducted at six locations on the property of SWMU 17. Drilling was completed using a Geoprobe® 5410 truck mounted rig. Termination of MIP logging was determined by IES's representative onsite. The results from each location are shown in Appendix A. Maps and 3D graphics of the site have been prepared for easier visualization of the subsurface.

MIP Log Interpretation

The MIP logs include six graphs. The first graph is conductivity and is measured in mS/M. In general, lower conductivities are indicative of coarser grained particles, such as sands, and higher conductivities indicate finer grained particles, such as silts and clays. The second graph is the rate of penetration (speed of the probe) and is measured in feet/min. This information can be used to determine how hard the subsurface is. The next three graphs are chemical data: PID, FID, and ECD, measured in microvolts (uV). These graphs are a linear scale, and give relative concentrations of contamination. The last graph displays the temperature of the probe as it is advanced in the subsurface. This graph can be useful to determine where the groundwater table is located.

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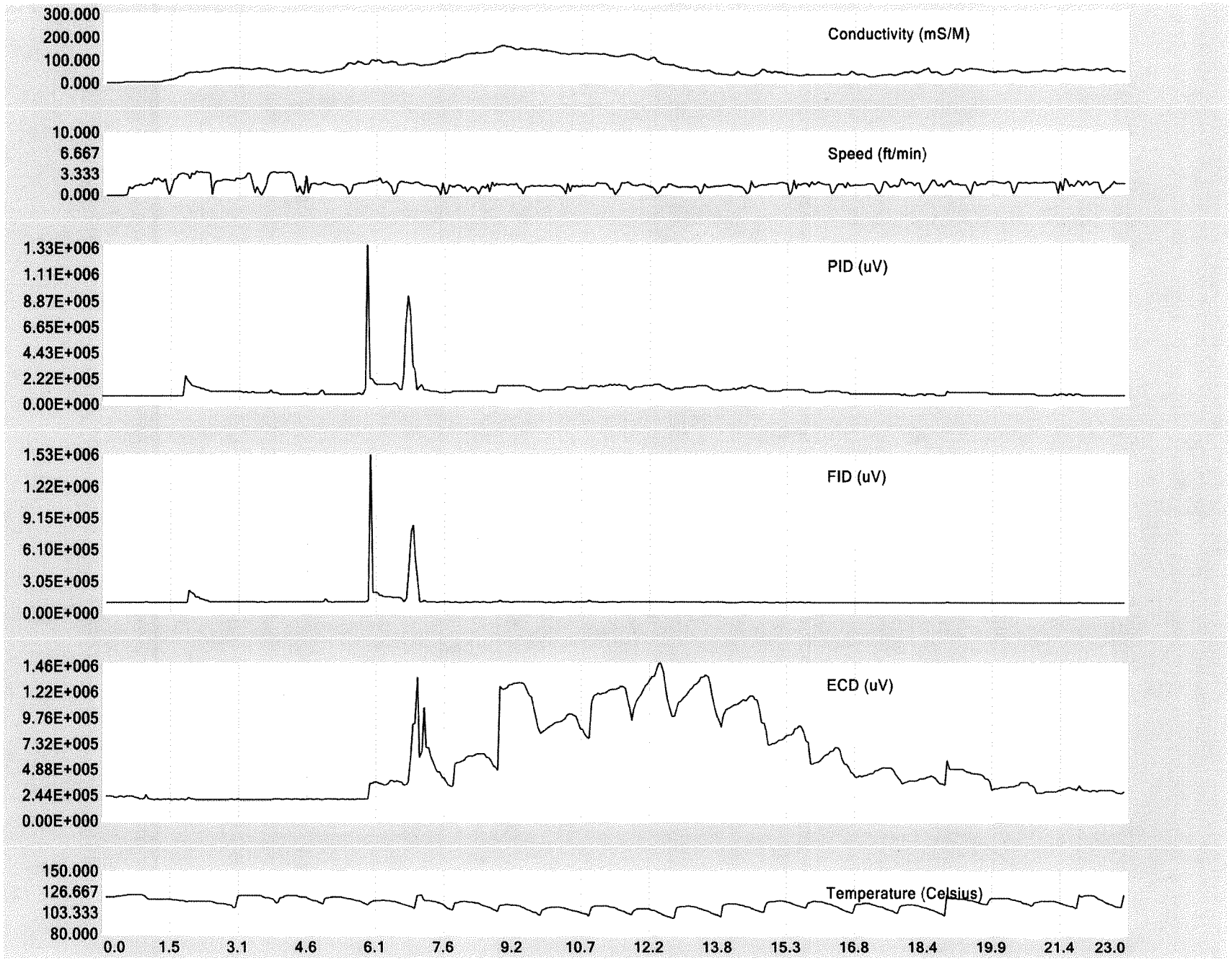

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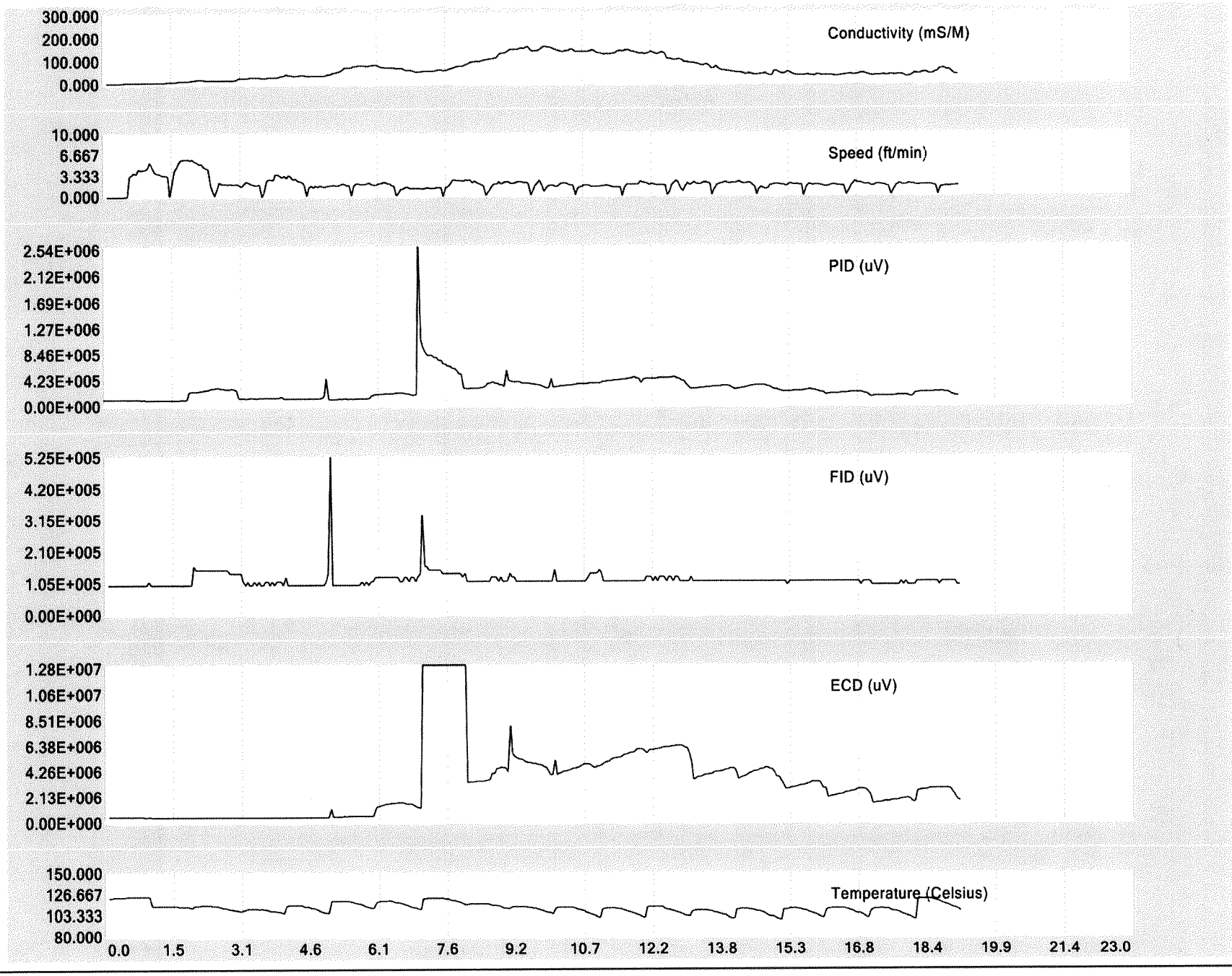

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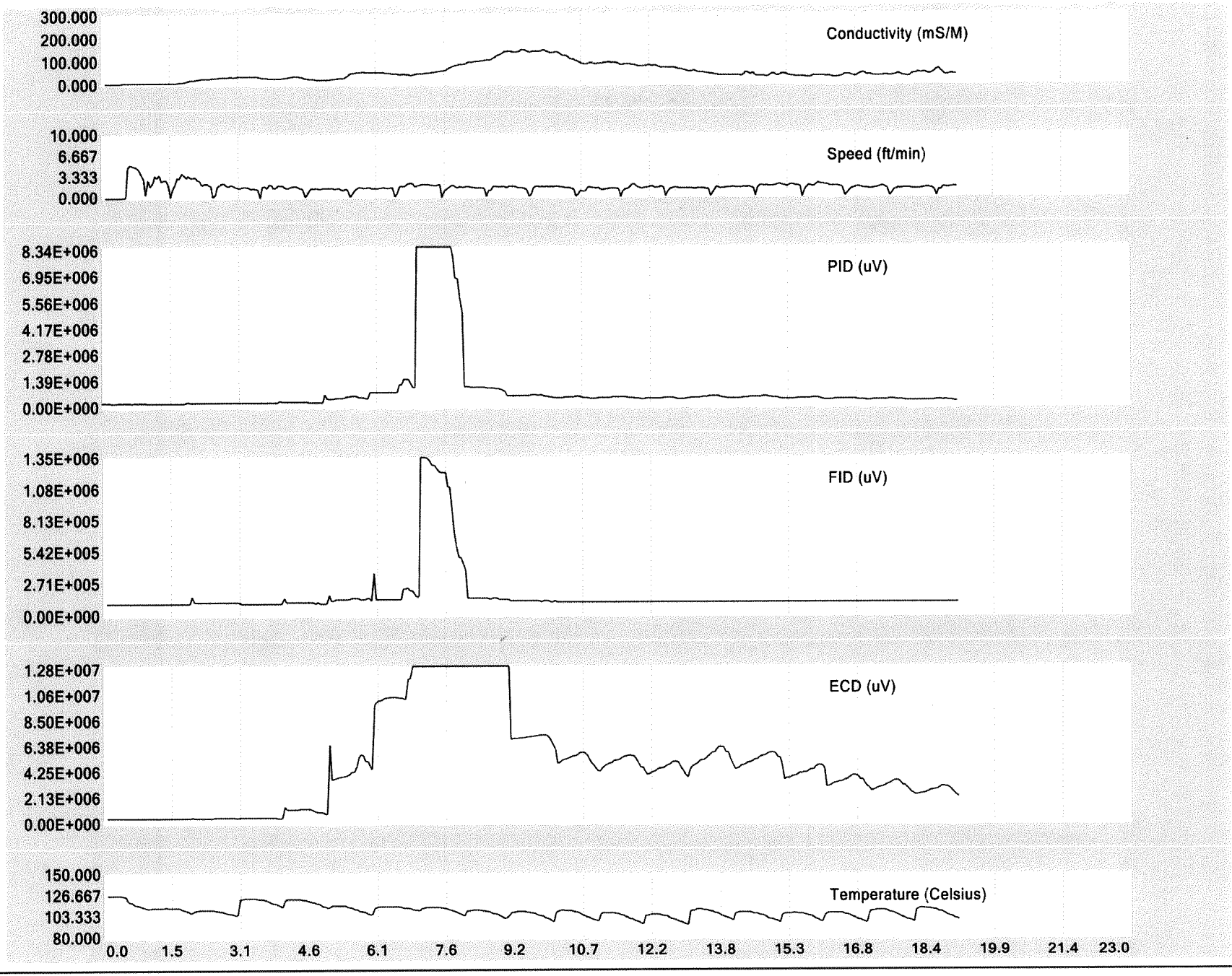

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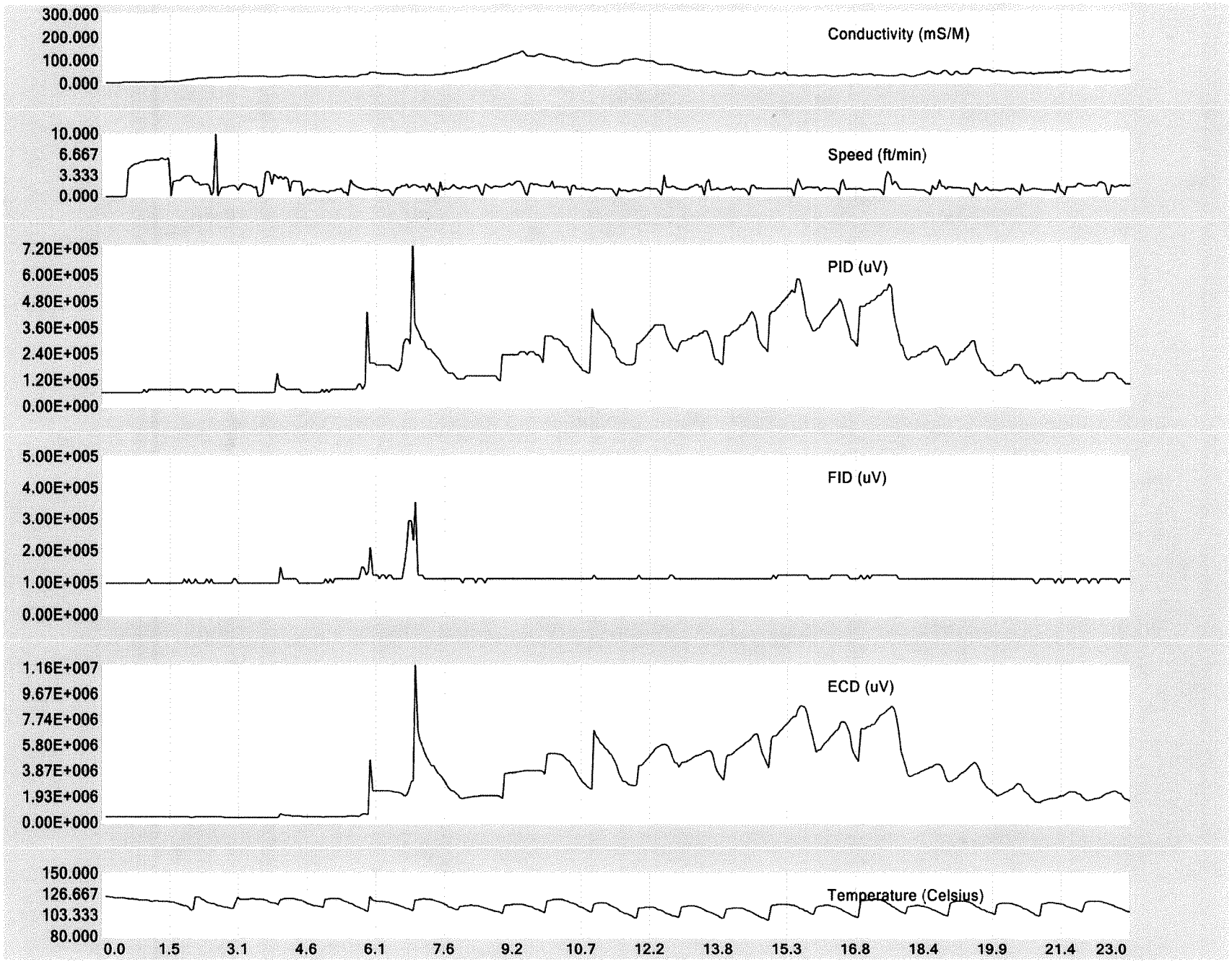

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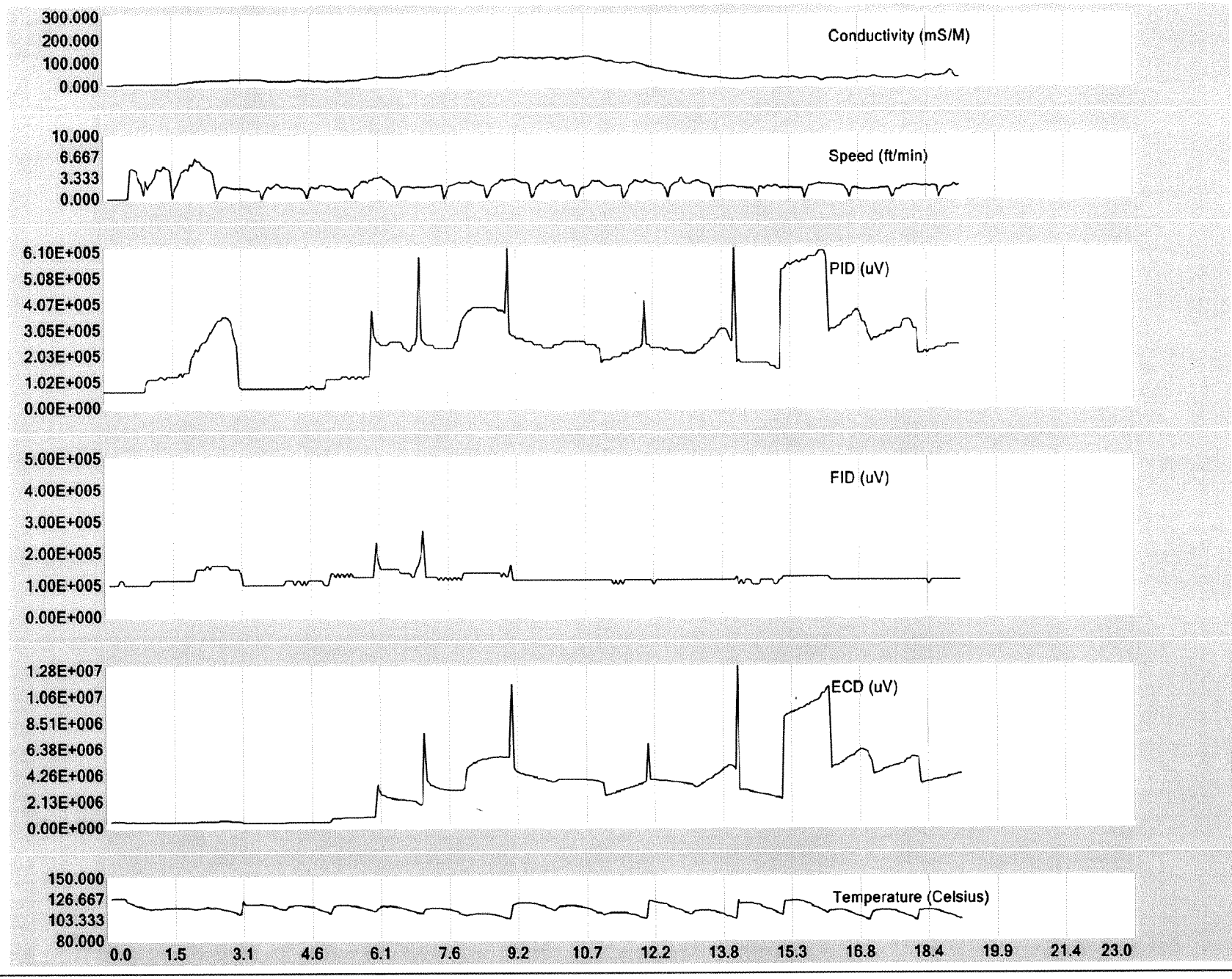

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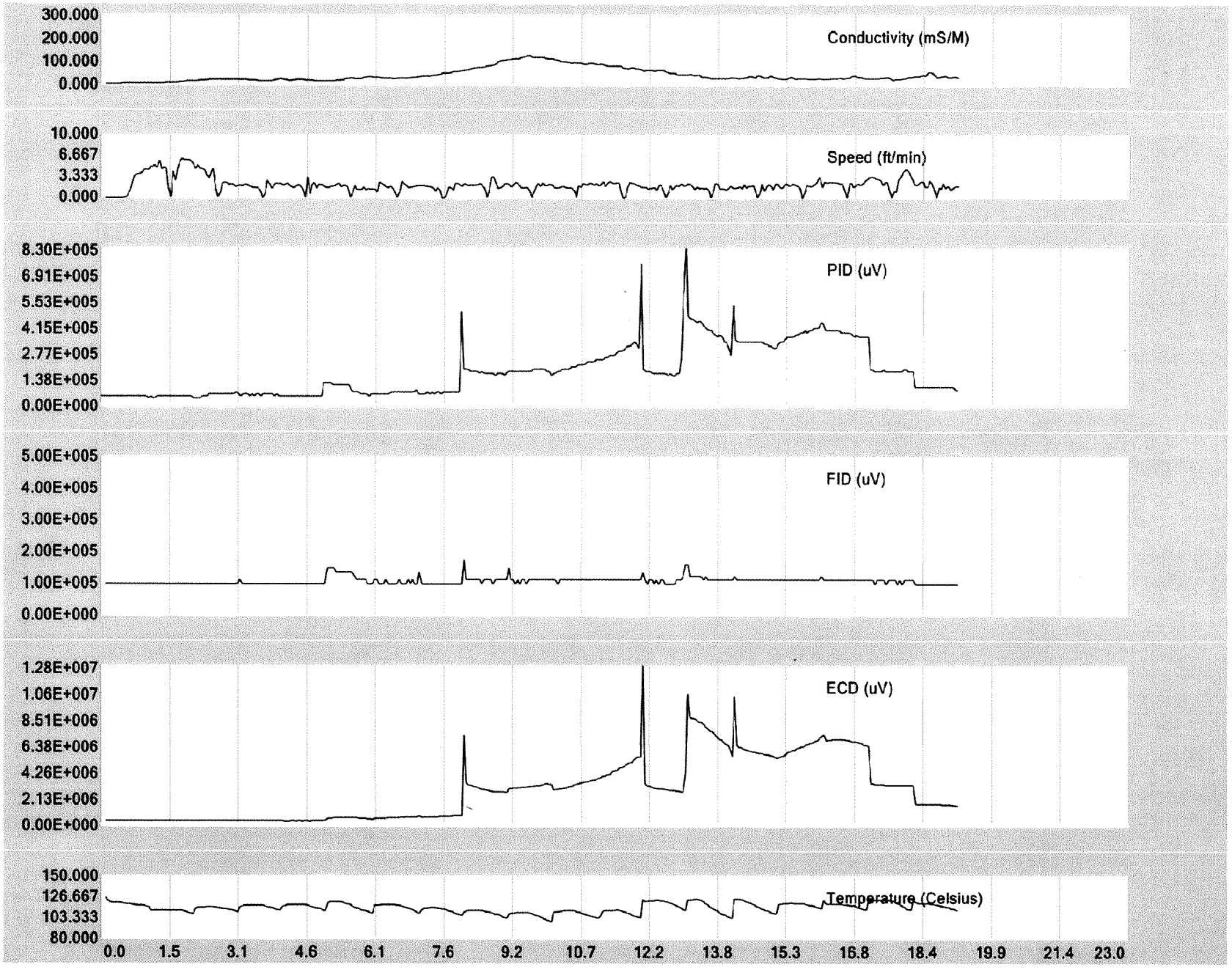

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APPENDIX II

TABLE II–1. PHOTOIONIZATION DETECTOR SOIL SCREENING RESULTS

Table II-1
Photoionization Detector Soil Pre-Screening Results
Charleston Naval Weapons Station, SWMU 17
Charleston, SC

Depth	March 25, 2004									March 24, 2004		March 1, 2004			
ft bgs	17-PSI-4	17PSI-7	17PSI-8	17PSI-11	17PSI-12	17PSI-13	17PSI-14	17PSI-15	17-PSI-16	17PSI-1	17PSI-2	17PSI-01	17PSI-04	17PSI-13	17PSI-16
0-1	1	4	16	18	23	6	11	23	40	1	16	2	2	19	8
1-2														20	3
2-3	1	1	10	18	28	7	23	12	46	25	21	0	18	21	15
3-4															
4-5	3	36	52	83	201	243	89	100	123	78	115	138	18	184	127
5-6													115		
6-7	10	73	202	105	245	197	136	204	107	94	156	159	NS	83	239
7-8															
8-9	35	58	118	121	107	134	NS	63	141	NS	162	64	160	163	153
9-10								28							
10-11	46	113	231	86	196	NS	NS	76	NS	NS	91	88	140	NS	137
11-12								86							
12-13	38	12	ns	81	57	NS	153	153	NS	25	82	40	40	94	NS
13-14								86						92	
14-15	8	61	ns	93	104	NS	84	51	NS	17	50	0	125	52	NS
15-16								18							
16-17	6	35	91	ns	46	NS	NS	29	NS	94	40	0	NS	NS	4
17-18								17							
18-19	7	1	31	ns	64	NS	35	7	NS	67	104	0	NS	NS	3
19-20	1														

Results are shown in parts per million (ppm)

APPENDIX III

HYDRAULIC CONDUCTIVITY MEASUREMENTS AND SPECIFIC CAPACITY METHOD

- **Table III-1. Hydraulic Conductivity From Specific Capacity Tests**

- **Field Estimation of Hydraulic Conductivity for Assessments of Natural Attenuation** (Wilson, et al. 1997. Paper from the Fourth International *In Situ* and On-Site Bioremediation Symposium, New Orleans, April 28 – May 1, 1997, Volume 2 Columbus Battelle Press, pp. 309-314.

FIELD ESTIMATION OF HYDRAULIC CONDUCTIVITY FOR ASSESSMENTS OF NATURAL ATTENUATION

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ABSTRACT: A Geoprobe is a sampling tool that drives hollow steel rods into the earth to serve as a temporary ground water monitoring well. The rods are threaded to allow them to be joined together, and the leading rod is slotted to admit the ground water being sampled. A simple technique was developed by EPA staff that uses a Geoprobe to estimate the hydraulic conductivity of the depth interval that provides the water sample. The approach can be used where ground water can be sampled by suction lift using a pump on the surface.

INTRODUCTION

Risk assessments of natural attenuation (intrinsic remediation) of organic contaminants in ground water often require an accurate estimate of the residence time of the contaminants along a flow path to a receptor. This is particularly true if first-order rate constants for depletion of the contaminant are used to estimate contaminant concentrations at the receptor or some point of compliance. Traditionally, the time of travel from one monitoring location to another is inferred from Darcy's law based on measured hydraulic gradients, the hydraulic conductivity of the interval in the aquifer sampled by the monitoring wells, and an estimate of effective porosity.

The Geoprobe and similar push technology is finding wide application as an alternative to conventional wells. The hydraulic conductivity of the interval yielding water to permanent monitoring wells can be estimated by pumping tests or slug tests conducted in the well. However, no equivalent test exists for the Geoprobe or other similar push technology.

MATERIALS AND METHODS

The test was developed using off-the-shelf Geoprobe tools and equipment.

Specific capacity refers to the flow of water yielded by a well at a particular drawdown. The test is usually done by pumping from a well at a fixed rate and monitoring the drop in the level of water in the well over time. We refer to the test devised for the Geoprobe tools as an ***inverse specific capacity*** because the drawdown is set at a predetermined level, and the yield at that predetermined level is measured.

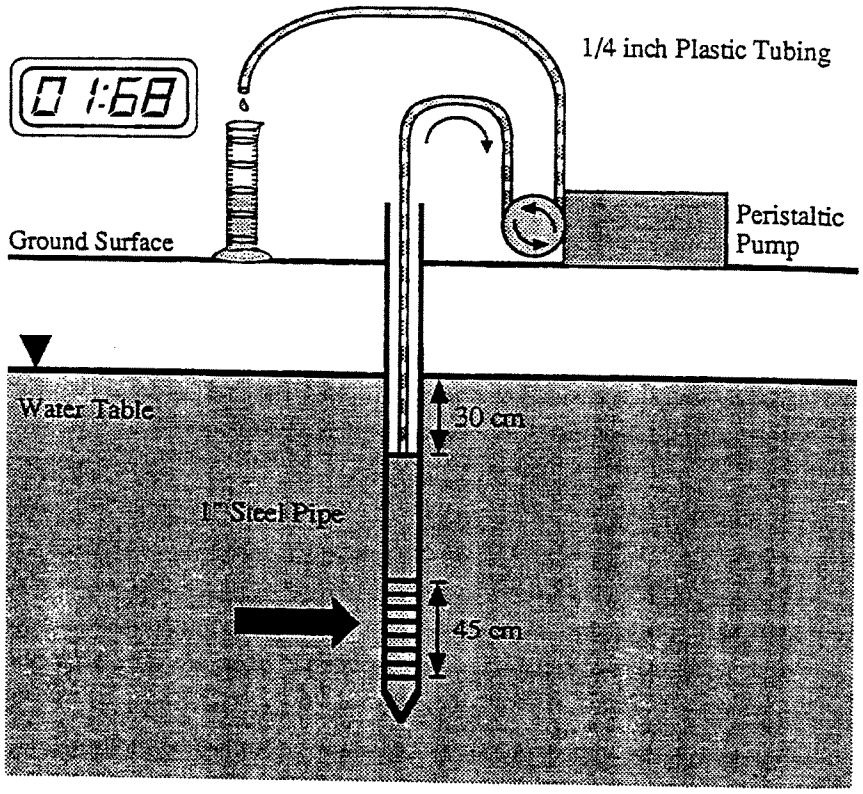

FIGURE 1. A test to measure the specific capacity of a Geoprobe well.

The tests were conducted as follows. A Geoprobe screened rod was driven to the depth to be sample. The rods were screened over an interval of 1.5 feet (45 cm) with 0.020 inch (0.51 mm) slots. A polyethylene tube was inserted to the bottom of the rods and pumped to remove all the sediment from the interior of the rods. Occasionally sediment entered the screen when the drawdown in the well exceeded 1.0 feet (30 cm). To remedy this, distilled water was poured into the rods during pumping of the sediment to prevent excessive drawdown. The water level inside the Geoprobe was allowed to come to equilibrium. A polyethylene tube was inserted in the well with the tip at an elevation of 1.0 foot (30 cm) or 0.5 foot (15 cm) below the static water level. Water was pumped from the tube at a rate that produced both water and air. This poised the level of water in the Geoprobe rods at the predetermined level. The well was pumped until the flow rate came to equilibrium, the time required to collect 100 ml was measured. If the yield was very slow, the yield in five minutes was measured. Inverse specific capacity was

calculated in milliliter per second per centimeter of drawdown. The specific capacity was multiplied by an empirical calibration factor of 0.03 to estimate hydraulic conductivity in centimeters per second. After the test for inverse specific capacity, the tube was lowered and ground water was sampled for routine parameters (FIGURE 1).

RESULTS AND DISCUSSION

Reproducibility. The reproducibility of the Geoprobe specific capacity test was evaluated at a site on the North Beach area of the U.S. Coast Guard Support Center at Elizabeth City, NC.

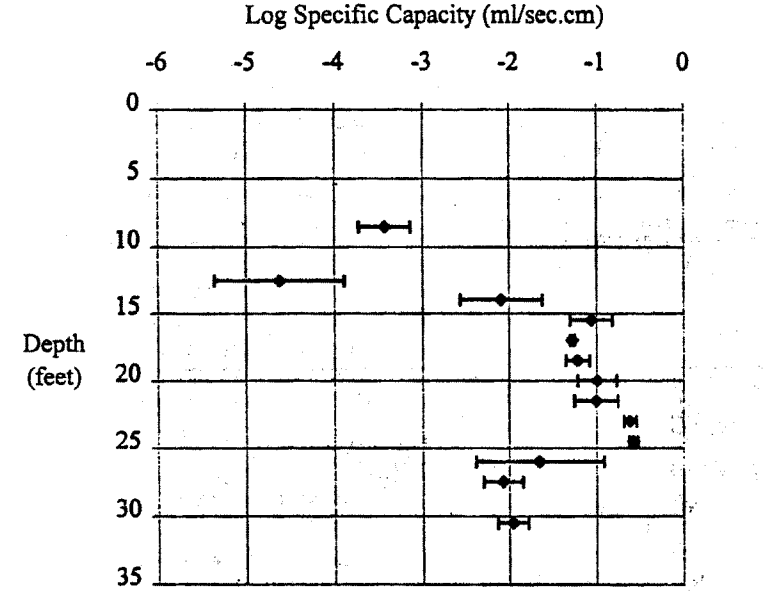

FIGURE 2. Reproducibility of the test for specific capacity using a Geoprobe. The diamonds are the logarithmic means of three independent tests. The bars are the standard deviation of the logarithms of the independent tests.

At the test site, the shallow sediments are clay and silt, transitioning to silty fine sand and fine sand at 15 feet (4.6 m) and back to silt at 25 feet (7.6 m). The water table was 4.0 feet (122 cm) below the surface in clay and silt. FIGURE 2 plots the mean of three tests conducted at thirteen separate depth intervals extending from the water table to the bottom of the first semi-confined aquifer. As expected, the specific capacity is low in the clay and silt extending to 15 feet (4.6 m) in depth, it is about two orders of magnitude higher in the silty fine sand and fine sand, and between one and two orders of magnitude lower in the deeper silty layer.

FIGURE 2. plots the standard deviation of the common logarithm of the means. In the interval of silty fine sand to fine sand, the widest standard deviation corresponds to a factor of 1.8, and the average of nine standard deviations corresponds to a factor of 1.4. The standard deviations are much wider in samples across the transition zones at 15 feet (4.6 m) and 26 feet (7.9 m). This may reflect natural heterogeneity in the aquifer, or more likely, error in the vertical position of the Geoprobe screen. In uniform material with specific capacities ranging from 0.000366 ml/sec.cm up to 0.232 ml/sec.cm, the standard deviation of tests in general corresponded to a factor of 2.0 or less. However, the standard deviation of the tests conducted at 12.5 feet (3.8 m) increased to a factor of 5.4. The specific capacity of this material was 0.0000237 ml/sec.cm. Apparently 0.000366 ml/sec.cm is the effective lower limit for reproducibility in the test. As discussed below, this corresponds to a hydraulic conductivity of 0.00001 cm/sec.

Calibration. The specific capacity of the Geoprobe wells was calibrated by comparing the specific capacity to the hydraulic conductivity of a conventional monitoring well 2.0 inches (5.1 cm) in diameter, or to the hydraulic conductivity of a core sample subjected to a permeameter test (TABLE 1).

TABLE 1. Empirical calibration factors that estimate hydraulic conductivity from the specific capacity of the Geoprobe well.

Location	Method	Hydraulic Conductivity (cm/sec)	Specific Capacity (ml/cm.sec)	Calibration Factor
Elizabeth City, NC	Pumping test in 2 inch well	0.0246	0.70	0.035
Elizabeth City, NC	Pumping test in 2 inch well	0.00244	0.081	0.030
Eglin AFB Florida	Slug test in 2 inch well	0.036	0.32	0.11
Eglin AFB Florida	Permeameter test on core	0.015	0.35	0.043
Plattsburgh AFB, NY	Permeameter test on core	0.0089	0.34	0.026
Pontotoc Co, OK	Permeameter test on core	0.0078	0.40	0.020
Pontotoc Co, OK	Permeameter test on core	0.000018	0.0044	0.004

The calibrations at two sites at Elizabeth City, NC were conducted by determining the average specific capacity of Geoprobe samples extending across the interval sampled by an adjacent permanent monitoring well. Data for a well at the U.S. Coast Guard Support Center in Elizabeth City, NC are illustrated in FIGURE 3. When a particular interval was not sampled by the Geoprobe, the specific capacity was estimated by linear interpolation from the adjacent samples. The permanent wells were 2.0 inches (5.1 cm) in diameter. They were pumped at a rate of 1.0 to 2.0 gallons (3.8 to 7.5 liters) per minute for twenty to thirty minutes. Drawdown in the permanent well was used to estimate transmissivity using the equation of Jacob as described in Appendix 16.D, page 1021 of Driscoll (1986). The calibration on material from Eglin AFB, FL was conducted by comparing the specific capacity of the Geoprobe wells to a permanent monitoring well that was 2.0 inches in diameter (5.1 cm) with a 5.0 foot (152 cm) screen. The 1.5 feet (45 cm) of screen in the Geoprobe rod was located at a depth adjacent to the center of the screen of the permanent monitoring well.

Core samples were selected from sites that were known to be uniform over the vertical interval sampled by the core. The calibrations on material from Plattsburgh AFB, NY and Eglin AFB, FL were conducted by packing core material from the same depth interval into a laboratory permeameter. The calibrations on material from Pontotoc Co. OK were conducted by collecting a core in plastic sleeve that was 1.5 inches (3.8 cm) in diameter, then conducting a permeameter test in the field. The elevation of the cored interval corresponded within 1.0 inch (2.5 cm) with the interval sampled by the Geoprobe.

In general the agreement between the empirical calibrations as listed in TABLE 1 is good. Five of the calibrations involving two permanent monitoring wells and three core samples produced empirical calibration factors that varied over a small range, from 0.043 to 0.020. The hydraulic conductivity of these materials varied from 0.0246 to 0.00244 cm/sec. At Eglin AFB, the Geoprobe yielded less water than was expected from a slug test on the neighboring permanent monitoring well. This may have resulted from the differences in the screened intervals. In the less permeable material from Pontotoc Co, OK, the Geoprobe well yielded ten times more water than would be expected from the permeameter test on the core sample. The result is outside the expected standard deviations as determined in FIGURE 2.

The lower range for effective calibration is probably 0.0001 cm/sec. Below that range the estimates should be considered accurate only within an order of magnitude. The upper limit for effective calibration is controlled by the rate at which the pump can pump water and air. The Masterflex pumps used at Kerr Research Center have a maximum rate of about 300 ml/minute. The lowest imposed drawdown that can be accurately measured is about 1.0 inch (2.5 cm), making the upper limit that can be measured about 0.1 cm/sec.

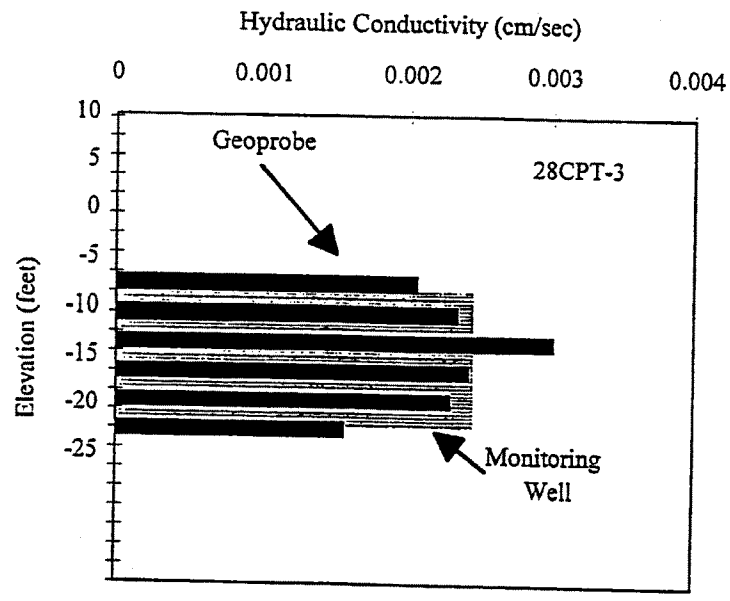

FIGURE 3. Correlation between hydraulic conductivity as determined by a pumping test in a permanent monitoring well and the specific capacity test in temporary Geoprobe well.

DISCLAIMER

The views expressed in this abstract are those of the individual authors and do not necessarily reflect the views and policies of the U.S. Environmental Protection Agency (EPA). Scientists in EPA's Office of Research and Development have prepared the EPA sections, and these sections have been reviewed in accordance with EPA's peer review and administrative review policies and apposed for presentation and publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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In Situ and On-Site Bioremediation: Volume 2

Explosives and Nitroaromatics
Composting of Contaminated Soils and Sludges
Natural Attenuation of Recalcitrant Compounds
Landfarming
Polycyclic Aromatic Hydrocarbons
Pesticides and Herbicides
Field Methods and Process Monitoring
PCBs and Chlorinated Aromatics
Fungal Technologies
Surfactant-Aided Bioremediation

Papers from the Fourth International
In Situ and On-Site Bioremediation Symposium
New Orleans, April 28 —May 1, 1997

Symposium Chairs
Bruce C. Alleman and Andrea Leeson
Battelle, Columbus, Ohio

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TABLE III-1
Hydraulic Conductivity from Specific Capacity Tests
Naval Weapons Station
Charleston, SC

	Pre-Injection		Phase I - Post EOS® Injection					Phase II - Post Buffered EOS®		
	3/25/04	4/2/04	5/13/04	6/2/04	9/1/04	11/15/04	2/8/05	4/10/07	9/20/07	10/17/2007
Well ID	ft/day	ft/day	ft/day	ft/day	ft/day	ft/day	ft/day	ft/day	ft/day	ft/day
17-PSI-1	0.54	---	---	---	---	---	---	---	---	
17-PSI-2	0.63	---	0.51	0.74	0.30	0.16	0.27	0.04	0.02	0.0028
17-PSI-3	0.25	---	---	---	---	---	---	---	---	
17-PSI-4	0.38	---	0.36	0.87		0.2	0.14		0.04	
17-PSI-5	0.55	---	0.39	0.66		0.26	0.19		0.07	
17-PSI-6	0.39	---	---	---	---	---	---	---	---	
17-PSI-7	0.43	---	0.37	1.01	0.33	0.12	0.19	0.05	0.07	
17-PSI-8	0.34	---	---	---	---	---	---	---	---	
17-PSI-9	0.41	---	---	---	---	---	---	---	---	
17-PSI-10	0.37	---	0.32	0.46	0.17	0.12	0.14	0.05	0.06	
17-PSI-11	0.26	---	---	---	---	---	---	---	---	
17-PSI-12	0.39	---	0.31	0.41		0.26	0.17		0.04	
17-PSI-13	0.19	---	0.17	0.36	0.14	0.08	0.14	0.05	0.03	
17-PSI-14	0.40	---	---	---	---	---	---	---	---	
17-PSI-15	0.53	---	0.45	0.61		0.28	0.19		0.07	
17-PSI-16	0.42	---	---	---	---	---	---	---	---	
17-PS-1	5.24	5.24	---	4.73	5.93	4.15	6.20	0.01	0.83	0.32
17-PS-2	7.36	7.36	---	7.57	6.17	6.31	6.17	0.02	0.02	0.057
17-PS-2 (after surging)	---	---	---	---	---	---	---	---	0.14	
17-PS-3	8.06	8.06	---	8.07	6.31	7.44	6.20	0.01	0.11	0.071
17-PS-3 (after surging)	---	---	---	---	---	---	---	---	0.34	
17-MW-5S	---	5.78	---	7.44	5..77	9.55	6.17	11.07	5.51	
17-MW-6S	5.78	0.39	---	7.44	6.00	8.92	6.06	8.86	7.92	
17-MW-7S (before surging)	0.39	0.39	---	---	---	---	---	---	---	
17-MW-7S	---	---	---	6.24	6.24	6.46	5.54	6.64	5.76	
17-MW-7S (after surging)	0.42	0.42	---	---	---	---	---	---	---	

APPENDIX IV

SUMMARIES OF ANALYTICAL DATA

- **Table IV-1. Summary of Chlorinated Aliphatic Hydrocarbons, Volatile Organic Compounds and Dissolved Hydrocarbon Gases in Groundwater**
- **Table IV-2. Summary of Groundwater Bio-Geochemistry Parameters**
- **Table IV-3. Results of Geoprobe Groundwater Sampling Event Six Months after Injection of EOS**
- **Table IV-4. Summary of Soil Gas Measurements**
- **Table IV-5. Results of Pre- and Post-Injection Soil Chlorinated Volatile Organic Compound Analyses**

TABLE IV-1
Summary of Chlorinated Aliphatic Hydrocarbons, Volatile Organic Compounds and Dissolved Hydrocarbon Gases in Groundwater
Naval Weapons Station
Charleston, South Carolina

Well ID Distance fron barrier)	Sample Date	Toluene (µg/L)	Benzene (µg/L)	Total Xylenes (µg/L)	Naphthalene (µg/L)	Dichloro- fluorometha (µg/L)	Methylene chloride (µg/L)	1,1,2,2- TCA (µg/L)	1,1,2- TCA (µg/L)	PCE (µg/L)	TCE (µg/L)	*cis*- 1,2-DCE (µg/L)	*trans*- 1,2-DCE (µg/L)	1,1-DCE (µg/L)	Vinyl Chloride (µg/L)	Chloro- form (µg/L)	Total CAHs (µg/L)	Methane (µg/L)	Ethane (µg/L)	Ethene (µg/L)
BACKGROUND MONITORING WELLS																				
17MW-5S	4/1/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	32,000	230	<50	<50	<50	300	32,530	102.1	0.05	0.45
	6/2/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	16,000	1,600	<50	<50	<50	160	17,760	147.1	0.08	0.78
	9/1/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	9,300	260	<50	<50	<50	<50	9,560	20.0	0.02	0.12
	11/16/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	31,000	930	<50	<50	<50	210	32,140	62.7	0.02	0.3
	2/9/05	<5.0	16	<10	<5.0	<5.0	<20	<5.0	18	<5.0	22,000	490	<5.0	<5.0	<5.0	130	22,638	79.3	0.04	0.69
	5/25/05	<20	31	<40	<20	<20	<80	<20	<20	<20	29,000	420	<20	<20	<20	98	29,518	126.9	0.05	1.0
	8/24/05	<20	<20	<40	<20	<20	<80	<20	<20	<20	25,000	280	<20	<20	<20	100	25,380	150.2	0.06	0.65
	3/29/06	<20	<20	<40	<20	<20	<80	<20	<20	<20	23,000	190	<20	<20	<20	88	23,278	134.5	0.04	0.56
	9/26/06	<20	25	<40	<20	<20	<80	<20	<20	<20	29,000	250	<20	<20	<20	140	29,390	134.0	0.04	0.59
	12/20/06	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	4/10/07	<5.0	23	<10	<5.0	14	<20	<5.0	<5.0	<5.0	1,500,000	190	<5.0	<5.0	17	140	1,500,347	224.6	0.06	7.89
	10/17/07	<5.0	12	<10	<5.0	<5.0	<20	<5.0	6	<5.0	27,000	340	<5.0	<5.0	<5.0	100	27,446	141.6	0.04	1.17
17MW-6S	4/1/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	46,000	330	<50	<50	<50	570	46,900	101.6	0.11	0.73
	6/2/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	16,000	6,600	<50	<50	<50	260	22,860	125.6	0.19	2.81
	9/1/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	31,000	3,900	<50	<50	<50	390	35,290	75.8	0.08	1.96
	11/17/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	34,000	2,500	<50	<50	<50	440	36,940	71.5	0.05	1.12
	2/9/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	40,000	1,400	<50	<50	<50	330	41,730	82.1	0.08	0.99
	5/25/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	37,000	1,200	<50	<50	<50	210	38,410	133.4	0.08	2.03
	8/24/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	35,000	630	<50	<50	<50	280	35,910	122.3	0.09	1.11
	3/29/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	30,000	470	<50	<50	<50	150	30,620	30.5	0.03	0.5
	9/26/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	32,000	980	<50	<50	<50	210	33,190	126.8	0.07	1.94
	12/20/06	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	4/10/07	<50	<50	<100	<50	<50	<200	<50	<50	<50	33,000	550	<50	<50	<50	150	33,700	79.3	0.05	1.23
	10/17/07	<50	<50	<100	<50	<50	<200	<50	<50	<50	29,000	710	<50	<50	<50	210	29,920	112.3	0.17	2.19
17MW-7S	4/1/04	<50	<50	<100	<50	<50	<200	<50	210	<50	150,000	610	<50	<50	<50	1,300	152,120	67.7	0.07	0.80
	6/2/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	38,000	2,000	<50	<50	<50	290	40,290	100.0	0.14	1.56
	9/1/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	110,000	2,100	<50	<50	<50	1,100	113,200	73.7	0.11	0.97
	11/17/04	<50	<50	<100	<50	<50	<200	<50	91	<50	88,000	2,700	<50	<50	<50	770	91,561	56.6	0.06	0.69
	2/9/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	130,000	1,400	<50	<50	<50	860	132,260	137.9	0.17	1.51
	5/25/05	<50	<50	<100	<50	<50	<200	<50	60	<50	110,000	1,600	<50	<50	<50	500	112,160	101.8	0.11	1.56
	8/24/05	<50	<50	<100	<50	<50	<200	<50	78	<50	110,000	780	<50	<50	<50	680	111,538	118.1	0.12	1.35
	3/29/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	79,000	680	<50	<50	<50	470	80,150	23.1	0.03	0.32
	9/26/06	<50	<50	<100	<50	<50	<200	<50	110	<50	85,000	1,500	<50	<50	<50	650	87,260	156.2	0.11	1.88
	12/20/06	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	4/10/07	<50	<50	<100	<50	<50	<200	<50	<50	<50	110,000	680	<50	<50	<50	730	111,410	93.3	0.08	1.36
	10/17/07	<50	<50	<100	<50	<50	<200	<50	110	<50	41,000	1,500	<50	<50	<50	290	42,900	81.7	0.05	1.3

Well ID Distance from barrier)	Sample Date	Toluene (µg/L)	Benzene (µg/L)	Total Xylenes (µg/L)	Naphthalene (µg/L)	Dichloro-fluoromethane (µg/L)	Methylene chloride (µg/L)	1,1,2,2-TCA (µg/L)	1,1,2-TCA (µg/L)	PCE (µg/L)	TCE (µg/L)	*cis*-1,2-DCE (µg/L)	*trans*-1,2-DCE (µg/L)	1,1-DCE (µg/L)	Vinyl Chloride (µg/L)	Chloro-form (µg/L)	Total CAHs (µg/L)	Methane (µg/L)	Ethane (µg/L)	Ethene (µg/L)
INJECTION WELLS																				
17PSI-02	3/31/04	<50	<50	<100	<50	<50	<200	<50.0	<50	<50	18,000	360	<50	<50	<50	210	18,570	53.2	0.11	1.36
	6/2/04	<5.0	28	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	3,000	150	<5.0	<5.0	<5.0	88	3,238	47.4	3.63	1.74
	9/1/04	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	3,600	210	<5.0	<5.0	<5.0	80	3,890	42.6	1.67	3.55
	11/17/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	3,300	340	<50	<50	<50	83	3,723	256.3	0.91	3.17
	2/9/05	<5.0	17	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	4,300	310	19	8.8	<5.0	59	4,697	429.6	0.78	1.23
	5/25/05	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	4,600	420	15	8.8	23	33	5,100	1135	1.45	4.82
	8/24/05	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	3,800	650	15	15	22	56	4,558	812.8	1.59	5.91
	3/28/06	<5.0	<5.0	<10	<5.0	<5.0	19	<5.0	<5.0	<5.0	3,700	1,600	10	9.7	25	120	5,465	1933.2	0.97	4.28
	9/25/06	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	3,200	3,100	16	18.0	50	110	6,494	1366.9	0.70	3.74
	12/20/06	<5.0	<5.0	<10	<5.0	<5.0	20	<5.0	<5.0	<5.0	470	1,000	25	5.5	52	<5.0	1,553	2135.8	0.15	0.57
	4/10/07	<5.0	<5.0	<10	<5.0	<5.0	33	<5.0	<5.0	<5.0	1,900	3,800	<5	15	180	<5	5,895	9433.9	0.53	4.20
	10/17/07	<5.0	<5.0	<10	<5.0	<5.0	20	<5.0	<5.0	<5.0	140	4,500	<5.0	<5.0	120	<5.0	4,760	5269.8	0.46	5.89
17PSI-07	3/31/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	14,000	410	<50	<50	<50	200.0	14,610	40.7	0.09	1.26
	6/2/04	<0.5	1.6	<1.0	<0.5	<0.5	<2.0	<0.5	4.5	<0.5	2,300	120	7.2	<1.0	7.5	49.0	2,488	53.7	2.61	2.66
	9/1/04	1.7	<0.5	2.5	0.59	2.8	7.3	1.9	6.4	<0.5	2,500	170	7.8	3.8	12.0	65.0	2,767	26.6	2.13	9.91
	11/17/04	<50	1.6	7.5	<50	1.1	9.7	1.7	5.1	<50	1,900	270	8.9	6.8	8.3	36.0	2,237	156.3	0.58	3.39
	2/9/05	<0.5	1.6	<1.0	<0.5	<0.5	17.0	1.3	5.7	<0.5	2,500	360	8.6	4.0	5.2	49	2,934	151.7	0.23	0.96
	5/25/05	<0.5	2	<1.0	<0.5	<0.5	13.0	1.7	5.0	1	2,700	560	15.0	12	19	34	3,348	1469.4	1.24	6.47
	8/24/05	<2.0	<2.0	<4.0	<2.0	<2.0	13	<2.0	4.1	<2.0	2,500	640	8.6	7.6	15	66	3,241	1816.0	0.96	4.41
	3/28/06	<2.0	<2.0	<4.0	<2.0	<2.0	13	<2.0	2.4	<2.0	2,400	1,100	9.7	15	22	80	3,629	2121.1	0.44	2.67
	9/25/06	<2.0	<2.0	<4.0	<2.0	<2.0	18	<2.0	6	<2.0	2,500	3,000	14	20	70	100	5,710	2684.9	0.29	1.56
	12/20/06	<2.0	<2.0	<4.0	<2.0	<2.0	15	<2.0	<2.0	<2.0	1,500	3,300	11	16	120	94	5,041	5509.0	0.48	3.05
	4/10/07	<2.0	<2.0	<4.0	<2.0	<2.0	12	<2.0	<2.0	<2.0	1,900	4,100	14	20	380	77	6,491	4086.0	0.29	7.69
	10/17/07	<2.0	<2.0	<4.0	<2.0	<2.0	2.6	<2.0	<2.0	<2.0	1,300	4,100	11	19	1100	28	6,558	5377.2	1.2	66.87
17PSI-10	3/31/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	13,000	280	<50	<50	<50	150	13,430	35.5	0.27	1.05
	6/2/04	<5.0	41	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	3,600	110	<5.0	<5.0	<5.0	30	3,740	16.9	2.85	2.11
	9/1/04	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	670	4,100	17	10	<5.0	45	4,842	20.1	0.28	0.54
	11/17/04	<5.0	17	<10	<5.0	<5.0	<20	<5.0	5.2	<5.0	690	2,600	18	10	41	59	3,423	27.2	0.15	0.37
	2/9/05	<5.0	20	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	970	2,700	18	10	<5.0	40	3,738	851.9	1.61	5.17
	5/25/05	>5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	880	2,500	37	10	52	<5.0	3,479	2626.4	1.05	3.68
	8/24/05	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	670	2,700	7.9	13	33	<5.0	3,424	1884.3	0.80	1.65
(duplicate)	8/24/05	<20	<20	<40	<20	<20	<80	<20	<20	<20	790	2,900	13.0	11	68	<20	3,782			
	3/28/06	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	1,300	2,900	8.5	9.1	42	<5.0	4,260	2152.8	0.27	1.38
	9/26/06	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	840	4,000	<5.0	16.0	67	100	5,023	4147.0	0.23	1.33
(duplicate)	9/26/06	<20	<20	<40	<20	<20	<80	<20	<20	<20	1,000	3,500	<20	14 J	96	75	4,671			
	12/20/06	<5.0	<5.0	<10	<5.0	<5.0	9.2	<5.0	<5.0	<5.0	1,300	5,600	12	15	260	80	7,267	5972.8	0.16	4.00
	4/10/07	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	350	3,400	11	11	1,300	52	5,124	9990.4	0.66	40.39
(duplicate)	4/10/07	<20	<20	<40	<20	<20	<80	<20	<20	<20	1,900	4,600	<20	<20	1,200	93	7,793			
	10/17/07	<5.0	<5.0	<10	<5.0	<5.0	9.2	<5.0	<5.0	<5.0	<5.0	2,200	<5.0	<5.0	1,500	<5.0	3,700	6651.4	0.45	44.65

Well ID Distance from barrier)	Sample Date	Toluene (µg/L)	Benzene (µg/L)	Total Xylenes (µg/L)	Naphthalene (µg/L)	Dichloro-fluoromethane (µg/L)	Methylene chloride (µg/L)	1,1,2,2-TCA (µg/L)	1,1,2-TCA (µg/L)	PCE (µg/L)	TCE (µg/L)	*cis*-1,2-DCE (µg/L)	*trans*-1,2-DCE (µg/L)	1,1-DCE (µg/L)	Vinyl Chloride (µg/L)	Chloro-form (µg/L)	Total CAHs (µg/L)	Methane (µg/L)	Ethane (µg/L)	Ethene (µg/L)
17PSI-13	3/31/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	9,800	170	<50	<50	<50	110	10,080	13.4	0.07	0.50
	6/2/04	<5.0	49	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	2,700	160	<5.0	<5.0	<5.0	28	2,888	17.5	3.77	2.35
	9/1/04	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	5,300	120	<5.0	<5.0	<5.0	46	5,466	14.3	1.13	5.76
	11/16/04	<5.0	24	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	3,500	210	<5.0	<5.0	<5.0	21	3,731	78.7	0.39	1.56
	2/9/05	<5.0	20	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	3,600	190	<5.0	<5.0	<5.0	22	3,812	534.5	1.87	8.58
	5/25/05	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	3,600	210	12	7.6	18	12	3,860	3441.6	1.17	6.68
	8/24/05	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	2,600	660	8.0	12	15	22	3,317	2550.7	0.28	2.33
	3/28/06	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	1,800	1,100	8.7	10	18	69	3,006	1105.7	0.09	1.13
	9/26/06	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	930	4,200	13	16	33	<5.0	5,192	5069.7	0.1	1.48
	12/20/06	<5.0	<5.0	<10	<5.0	<5.0	9.0	<5.0	<5.0	<5.0	800	4,600	12	18	780	<5.0	6,210	5540.8	0.23	3.04
	4/10/07	<5.0	<5.0	<10	<5.0	<5.0	11.0	<5.0	<5.0	<5.0	800	4,500	13	19	1700	46	7,078	7879.1	0.14	11.13
	10/17/07	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	590	4,300	10	18	1200	<5.0	6,118	9099.5	0.47	7.42
Average	3/31/04										0	0			0		0	0		0.00
	6/2/04										0	0			0		0	0		0.00
	9/1/04										0	0			0		0	0		0.00
	11/17/04										0	0			0		0	0		0.00
	2/9/05										0	0			0		0	0		0.00
	5/25/05										0	0			0		0	0		0.00
	8/24/05										0	0			0		0	0		0.00
	3/28/06										0	0			0		0	0		0.00
	9/26/06										0	0			0		0	0		0.00
	12/20/06										0	0			0		0	0		0.00
	4/10/07										0	0			0		0	0		0.0
	10/17/07										0	0			0		0	0		0.00
MONITORING WELLS																				
17PS-01	4/1/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	22,000	190	<50	<50	<50	400	22,590	27.2	0.08	0.43
	6/2/04	23	13	<10	<5.0	<5.0	<20	8.4	<5.0	<5.0	12,000	390	<5.0	<5.0	<5.0	110	12,508	25.8	0.45	0.56
	9/1/04	6.5	14	<10	<5.0	<5.0	<20	7.2	8.3	<5.0	17,000	750	17	<5.0	<5.0	170	17,953	37.7	0.92	0.87
	11/16/04	6.7	<5.0	<10	<5.0	<5.0	<20	<5.0	16.0	<5.0	11,000	2,200	27	15	<5.0	130	13,388	33.1	0.32	0.57
	2/9/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	15,000	1,900	<50	<50	<50	110	17,010	145.0	0.89	1.20
(duplicate)	2/9/05	<5.0	5.5	<10	<5.0	<5.0	<20	<5.0	11.0	<5.0	15,000	1,800	26	14	<5.0	150	17,001			
	5/25/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	10,000	2,700	<50	<50	<50	96	12,796	231.9	1.88	2.62
	8/24/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	13,000	2,500	<50	<50	<50	230	15,730	92.2	0.98	1.08
	3/29/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	10,000	4,300	<50	<50	<50	490	14,790	261.2	0.97	1.15
	9/26/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	<50	4,000	<50	<50	4500	<50	8,500	1232.6	2.12	2.49
	12/20/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	<50	1,000	<50	<50	4900	<50	5,900	7415.3	2.77	48.99
	4/10/07	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	62	350	<5.0	<5.0	4800	<5.0	5,212	11308.5	4.89	95.42
	10/17/07	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	10	79	<5.0	<5.0	1600	<5.0	1,689	7759.2	0.38	29.24

Well ID Distance from barrier)	Sample Date	Toluene (µg/L)	Benzene (µg/L)	Total Xylenes (µg/L)	Naphthalene (µg/L)	Dichloro-fluoromethane (µg/L)	Methylene chloride (µg/L)	1,1,2,2-TCA (µg/L)	1,1,2-TCA (µg/L)	PCE (µg/L)	TCE (µg/L)	*cis*-1,2-DCE (µg/L)	*trans*-1,2-DCE (µg/L)	1,1-DCE (µg/L)	Vinyl Chloride (µg/L)	Chloro-form (µg/L)	Total CAHs (µg/L)	Methane (µg/L)	Ethane (µg/L)	Ethene (µg/L)
17PS-02	4/1/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	28,000	260	<50	<50.0	<50	440	28,700	30.8	0.05	0.40
	6/2/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	15,000	320	<50	<50.0	<50	72	15,392	30.6	0.56	0.68
(duplicate)	6/2/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	13,000	330	<50	<50.0	<50	56	13,386			
	9/1/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	16,000	2,600	<50	<50.0	<50	190	18,790	36.7	0.56	0.73
(duplicate)	9/1/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	15,000	2,700	<50	<50.0	<50	190	17,890			
	11/16/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	13,000	5,100	<50	<50.0	<50	310	18,410	66.0	0.19	0.34
(duplicate)	11/16/04	<50	<50	<100	<50	<50	<200	<50	<50	<50	10,000	5,800	<50	<50.0	<50	290	16,090			
	2/9/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	18,000	4,600	<50	<50	<50	250	22,850	1144.8	1.62	4.91
	5/25/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	7,900	5,400	<50	<50	<50	150	13,450	1176.5	0.45	1.41
	8/24/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	15,000	3,500	<50	<50	<50	210	18,710	1681.8	0.88	1.21
	3/29/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	5,200	5,500	<50	<50	840	600	12,140	3639.3	0.34	3.03
(duplicate)	3/29/06	<20	<20	<40	<20	<20	<80	<20	<20	<20	4,700	4,900	<20	<20	700	390	10,690			
	9/26/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	<50	1,400	<50	<50	4700	<50	6,100	2133.3	0.14	31.39
	12/20/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	<50	130	<50	<50	2500	<50	2,630	9880.6	9.65	175.2
	4/10/07	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	21	160	<5.0	<5.0	1900	<5.0	2,081	8896.9	7.84	76.00
	10/17/07	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	<5	<5	<5.0	<5.0	660	<5.0	660	9148.4	0.44	27.73
17PS-03	4/1/04	<50	<50	<100	<50	<50.0	<200	<50	<50	<50	26,000	230	<50	<50	<50	330	26,560	36.0	0.09	0.48
	6/2/04	<5.0	25	<10	<5.0	<5.0	<20	6	<5.0	<5.0	12,000	730	<5.0	<5.0	<5.0	54	12,790	50.7	1.26	0.81
	9/1/04	<5.0	<5.0	<10	<5.0	<5.0	<20	11	12	<5.0	7,200	14,000	130	30	57	310	21,750	173.3	0.86	1.23
	11/16/04	<5.0	<5.0	<10	<5.0	<5.0	<20	<5	6	<5.0	160	11,000	73	29	25	150	11,443	2062.5	0.56	0.84
	2/9/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	3,400	17,000	<50	<50	<50	380	20,780	7737.5	0.42	0.88
	5/25/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	<50	13,000	85	<50	<50	<50	13,085	4425.3	0.17	0.63
	8/24/05	<50	<50	<100	<50	<50	<200	<50	<50	<50	3,500	12,000	<50	<50	<50	<50	15,500	3136.5	0.07	0.28
	3/29/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	2,300	12,000	<50	<50	<50	<50	14,300	3522.2	0.13	0.45
	9/26/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	<50	970	<50	<50	4,500	<50	5,470	4852.4	0.06	2.63
	12/20/06	<50	<50	<100	<50	<50	<200	<50	<50	<50	<50	160	<50	<50	3,200	<50	3,360	9839.1	2.16	44.6
	4/10/07	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	19	420	<5.0	<5.0	2,500	<5.0	2,939	4281.3	0.65	9.18
	10/17/07	<5.0	<5.0	<10	<5.0	<5.0	<20	<5.0	<5.0	<5.0	<5	120	<5.0	<5.0	800	<5.0	920	10127.1	0.09	28.79
Average	4/1/04										25,333	227			<50		25,950	31.3	0.07	0.44
	6/2/04										12,667	482			<50		13,229	35.7	0.76	0.68
	9/1/04										13,233	5,800			28		19,348	82.6	0.78	0.94
	11/16/04										7,553	6,217			26		14,414	720.5	0.36	0.58
	2/9/05										12,133	7,833			<50		20,213	3,009	0.98	2.33
	5/25/05										8,950	7,033			<50		13,110	1,945	0.83	1.55
	8/24/05										10,500	6,000			<50		16,647	1,637	0.64	0.86
	3/29/06										5,833	7,267			<50		13,743	2,474	0.48	1.54
	9/26/06										<50	2,123			4,567		6,690	2,739	0.77	12.17
	12/20/06										<50	430			3,533		3,963	9,045	4.86	89.57
	4/10/07										34	310			3,067		3,411	8,162	4.46	60.20
	10/17/07										<5	67			1,020		1,090	9,012	0.30	28.59

Notes:
NA denotes not analyzed.
J denotes estimated value between the Reporting Limit and the MDL

TABLE IV-2
Summary of Groundwater Bio-Geochemistry Parameters
Naval Weapons Station
Charleston, South Carolina

Well ID (Distance from Barrier	Days Since Injection 5/13/2004	Sample Date	Total Inorgan Carbon (mg/L)	Total Organic Carbon (mg/L)	Chloride (mg/L)	Nitrite (mg/L)	Bromide (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Sulfate (mg/L)	Dissolved Iron (mg/L)	Arsenic (mg/L)	Manganese (mg/L)	Sulfide (ppm)	Alkalinity (ppm)	Carbon Dioxide (ppm)	Dissolved Oxygen (mg/L)	ORP (mV)	pH	Temperature (°C)	Conductivity (mS/cm)
UPGRADIENT MONITORING WELLS																					
17MW-5S	-42	4/1/04	19.9	1.29	317.6	<0.5	0.8	<0.5	<0.5	19.1	3.0	NA	0.083	NA	NA	NA	3.01	154	7.3	16.8	1.14
	20	6/2/04	44.7	8.09	200.8	<0.5	0.6	<0.5	<0.5	4.4	14.0	NA	0.190	0.1	15	40	0.76	-82	6.07	20.6	1.54
	111	9/1/04	21.3	4.74	126.9/138.5	<0.5/<0.5	<0.5/<0.5	<0.5	<1.0	9.1	1.4	NA	<0.05	0	10	70	0.19	-43	5.21	23.3	0.41
	187	11/16/04	26.6	<1.0	241.6/242.7	<1.0/<1.0	0.9/0.8	<0.5/<0.5	<0.5/<0.5	23.1/21.0	15.0	NA	0.150	0	12	30	0.20	64	6.04	20.8	0.92
	271	2/8/05	14.6	1.22	178	<0.5	0.7	<0.5	<1.0	20.8	0.76	NA	0.096	0	20	45	0.21	18	5.38	17.7	0.77
	377	5/25/05	29.6	19.4	297	< 0.5	0.8	< 0.5	< 1.0	30.9	1.6	NA	0.130	0	25	70	0.48	-3	6.47	18.5	0.68
	468	8/24/05	49.6	2.71	201/217	<0.5/<0.5	0.9/1.0	<0.5/<0.5	<1.0/<1.0	20.8/20.7	7.8	NA	0.093	NA	<10	70	0.70	106	5.40	24.6	0.94
	685	3/29/06	12.2	1.88	172	<2	0.7	<0.5	<10	23.1	1.1	NA	0.084	<0.1	0	<100	0.62	69	5.96	20.4	0.78
	866	9/26/06	13.3	1.53	NA	NA	NA	NA	NA	NA	8.4	NA	0.087	0.0	55	55	1.44	61	1.24	24.7	0.62
	951	12/20/06	NA	NA	NA	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	1062	4/10/07	19.9	1.31	266.1	<0.5	0.7	<0.5	NA	18.6	8.6	NA	0.130	0.0	55	NM	0.52	76	5.45	16.8	1.05
	1252	10/17/07	4.7	5.80	989/900	<.5	2.8/2.8	<0.5/<0.5	NA	39.8/38.2	26.0	NA	0.460	NA	1.2	NA	0.90	-21	6.0	22.2	1.79
17MW-6S	-42	4/1/04	22.0	<1.0	240.5	<0.5	0.9	<0.5	<0.5	25.0	0.4	<0.010	0.069	NA	NA	NA	2.77	170	7.2	16.4	0.98
	20	6/2/04	61.3	15.1	154	<0.5	0.6	<0.5	<0.5	1.3	8.7	0.038	0.340	0	18	100	0.27	-110	6.33	20.1	1.42
	111	9/1/04	42.2	3.75	195.7	<0.5	0.7	<0.5	<1.0	17.7	7.7	0.015	0.210	0	25	100	0.14	-35	5.42	24.8	0.66
	187	11/16/04	43.0	3.63	221	<1.0	1.0	<0.5	<0.5	32.9	10.0	0.016	0.270	0	35	20	0.44	39	6.59	21.1	0.87
	271	2/8/05	21.2	1.91	287	<5.0	1.0	<0.5	<1.0	26.5	1.6	0.010	0.160	0	35	40	0.24	-4	5.52	17.8	1.20
	377	5/25/05	37.1	18.0	321	< 0.5	1.1	< 0.5	< 1.0	38.6	5.4	0.023	0.220	0	80	70	0.21	35	6.72	19.2	0.66
	468	8/24/05	56.0	2.42	351	< 0.5	1.8	< 0.5	< 1.0	34.3	6.9	<0.010	0.140	0	<10	70	0.25	106	5.29	25.1	1.13
	685	3/29/06	23.8	1.36	211	<1	1.1	<0.5	<10	34.6	3.5	0.011	0.150	<0.1	<50	120	0.62	91	6.14	20.3	0.87
	866	9/26/06	21.1	1.39	NA	NA	NA	NA	NA	NA	9.8	0.006	0.160	0.00	55	60	1.55	-50	5.77	24.9	0.71
	951	12/20/06	NA	NA	NA	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	1062	4/10/07	28.6	1.22	328	<0.5	1.2	<0.5	NA	40.0	6.4	0.017	0.280	0.00	55	NA	0.69	5	6.03	17.4	1.43
	1252	10/17/07	0.66	5.40	459	<0.5	1.5	<0.5	NA	28.6	11.0	0.002	0.350	NA	12.0	NA	0.50	-21	6.0	23.1	1.46
17MW-7S	-42	4/1/04	26.9	1.64	121.8/120.7	<0.5/<0.5	0.9/0.9	<0.5	<0.5	31.6	2.7	NA	0.059	NA	NA	NA	NM	170	7.7	15.7	0.70
	20	6/2/04	62.2	17.8	90.1/90.5	<0.5/<0.5	0.5/0.6	<0.5	<0.5	<0.5/<0.5	<0.5	NA	0.530	0	<10	25	0.43	-110	6.54	20.3	1.27
	111	9/1/04	34.8	3.38	103.5	<0.5	<0.5	<0.5	<1.0	15.9	10.0	NA	0.094	0	15.0	50	0.15	-24	5.62	24.7	0.60
	187	11/16/04	32.3	3.20	123	<0.5	0.8	<0.5	<0.5	26.6	0.2	NA	0.160	0	40	25	1.03	36	6.85	20.9	0.71
	271	2/8/05	16.2	1.29	158	<0.5	0.9	<0.5	<1.0	21.9	5.9	NA	0.080	0	18	160	0.61	32	5.38	18.0	0.83
	377	5/25/05	33.9	23.9	1.0	<0.5/<0.5	1.0/1.0	<0.5/<0.5	<1.0/<1.0	34.4/34.5	9.1	NA	0.120	0	50	70	0.30	41	6.58	18.7	0.57
	468	8/24/05	36.5	3.70	137	< 0.5	1.0	< 0.5	< 1.0	25.3	10.0	NA	0.071	0	<10	80	0.39	85	5.53	24.2	0.82
	685	3/29/06	19.5	1.85	125	<0.5	1.0	<0.5	<10	35.7	1.9	NA	0.084	<0.1	<50	120	0.41	115	5.9	19.4	0.66
	866	9/26/06	22.4	1.98	NA	NA	NA	NA	NA	NA	8.7	NA	0.120	0.0	50	70	0.71	-14	5.54	25.0	0.57
	951	12/20/06	NA	NA	NA	NA	NA	NA	NA	NA		NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	1062	4/10/07	26.8	1.55	256	<0.5	1.2	<0.5	NA	28.9	6.6	NA	0.110	0.0	50	NA	0.51	76	5.41	17.8	1.14
	1252	10/17/07	0.72	5.40	622	<0.5	2.1	<0.5	NA	94.7	13.0	NA	0.380	NA	48	NA	0.40	-18	5.90	23.4	0.78

Well ID (Distance from Barrier	Days Since Injection 5/13/2004	Sample Date	Total Inorganic Carbon (mg/L)	Total Organic Carbon (mg/L)	Chloride (mg/L)	Nitrite (mg/L)	Bromide (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Sulfate (mg/L)	Dissolved Iron (mg/L)	Arsenic (mg/L)	Manganese (mg/L)	Sulfide (ppm)	Alkalinity (ppm)	Carbon Dioxide (ppm)	Dissolved Oxygen (mg/L)	ORP (mV)	pH	Temperature (°C)	Conductivity (mS/cm)
INJECTION WELLS																					
17PSI-02	-43	3/31/04	17.3	<1.0	654.2/661.2	**	1.6/1.6	<0.5	<0.5	91.5	33	NA	0.390	NA	NA	NA	1.48	97	5.60	16.0	2.40
	20	6/2/04	55.6	46.2	655.7	<5	1.2	<0.5	<0.5	18.0	150	NA	0.570	1.0	<10	300	0.39	-82	5.44	20.3	6.63
	111	9/1/04	77.4	1180	782.9	<5.0	<0.5	<0.5	<1.0	<0.5	160	NA	0.510	2.5	<10	1000	0.42	-45	4.85	22.9	1.21
	188	11/17/04	74.6	1190	523	<5.0	1.2	<0.5	1.3	<0.5	210	NA	0.530	0.1	120	NA	0.14	42	4.92	19.6	3.02
	271	2/8/05	78.8	754	548/549	<5.0/<5.0	1.5/1.5	1.0/1.0	1.4/<1.0	0.95	210	NA	0.550	0.4	<10	600	0.44	39	4.90	16.6	2.79
	377	5/25/05	93.0	1010	518	<5.0	1.6	< 0.5	9.0	< 0.5	210	NA	0.660	0.1	<10	1250	0.19	34	5.08	18.5	1.90
	468	8/24/05	85.8	876	694.9	<5.0	1.6	< 0.5	< 1.0	< 0.5	180	NA	0.630	NA	0	750	0.35	-3	4.70	22.5	2.99
	684	3/28/06	50.5	960	769	<10	2.3	<0.5	<10	<0.5	210	NA	0.590	<0.1	0	1000	0.68	5	5.05	18.7	2.96
	865	9/25/06	77.5	817	384	<0.5	1.2	<0.5	<0.5	<0.5	60	NA	0.530	<1.0	>1000	1000	0.62	-128	3.80	24.9	1.44
	951	12/20/06	284	7000	659	<0.5	1.8	<0.5	<10	28.3	6.9	NA	0.100	0.0	500	<10	NM	-16	8.20	17.5	10.45
	1062	4/10/07	309	74.7	754.8	<0.5	1.6/1.7	<0.5	NA	32.8/35.8	0.6	NA	0.300	0.0	500	NA	0.36	-68	8.80	16.7	12.50
	1252	10/17/07	1.70	2400	164	<0.5	0.6	<0.5	NA	<0.5	1.5	NA	0.230	NA	4100	NA	0.80	-158	7.60	21.3	3.53
17PSI-04	-43	3/31/04	18.0	<1.0	795.1	**	1.7	<0.5	<0.5	99.2	33	NA	0.470				2.12	121	5.40	16.0	3.54
	951	12/20/06	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-31	6.50	19.0	4.24
17PSI-05	-43	3/31/04	19.3	<1.0	931.1	**	1.9	<0.5	<0.5	80.9	44	NA	0.460				4.00	115	6.50	17.4	3.69
	951	12/20/06	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-38	5.40	17.6	3.51
17PSI-07	-43	3/31/04	18.5	<1.0	542.4	**	1.4	<0.5	<0.5	102.5	24	0.018	0.370	NA	NA	NA	3.93	74	6.10	17.9	2.49
	20	6/2/04	60.0	4560	1124	<5	2.3	<0.5	<0.5	1.8	180	<0.010	0.710	1.5	20.00	350	0.60	-102	5.51	20.2	5.05
	111	9/1/04	112	1240	597	<5.0	<0.5	<0.5	<1.0	0.5	300	0.045	0.820	0.0	<10	1000	0.13	-5	4.55	23.2	1.32
	188	11/17/04	79.2	1610	543	<10	1.6	<0.5	9.6	<0.5	240	0.026	0.740	0.1	70	NA	0.09	44	4.88	19.2	3.40
	271	2/8/05	59.9	1190	863	<5.0	2.3	<0.5	<1.0	<0.5	320	0.088	0.790	0.0	<10	1000	0.48	125	4.05	17.3	3.74
	377	5/25/05	103	1310	763	<5.0	2.4	< 0.5	10.9	< 0.5	310	0.110	0.810	0.2	<10	875	0.26	53	5.02	17.8	1.87
	468	8/24/05	83.4	892	970	<5.0	2.1	< 0.5	< 1.0	< 0.5	260	0.078	0.710	NA	0	850	0.39	12	4.60	22.3	3.62
	684	3/28/06	84.0	1110	679	<10	2.0	<0.5	<10	<0.5	420	0.076	0.530	<1.0	0.00	1000	0.61	12	4.98	17.4	3.66
	865	9/25/06	56.2	936	565	<0.5	1.3	<0.5	1.4	<0.5	320	0.056	0.620	<1.0	>1000	850	1.81	-147	3.34	24.2	1.65
	951	12/20/06	77.4	1250	1242.0/1217.4	<0.5	2.3/2.3	<0.5	<10	<0.5/0.7	220	0.028	0.750	120.0	<50	700	0.62	-69	4.70	17.8	3.88
	1062	4/10/07	90.2	104	726	<0.5	2.6	<0.5	NA	<0.5	250	0.054	0.700	120.0	<50	NA	0.98	-52	5.57	16.6	4.66
	1252	10/17/07	23.8	1010	466	<0.5	1.2	<0.5	NA	<0.5	120	0.027	0.720	NA	320.0	NA	1.00	-29	5.10	21.4	1.74

Well ID (Distance from Barrier	Days Since Injection 5/13/2004	Sample Date	Total Inorganic Carbon (mg/L)	Total Organic Carbon (mg/L)	Chloride (mg/L)	Nitrite (mg/L)	Bromide (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Sulfate (mg/L)	Dissolved Iron (mg/L)	Arsenic (mg/L)	Manganese (mg/L)	Sulfide (ppm)	Alkalinity (ppm)	Carbon Dioxide (ppm)	Dissolved Oxygen (mg/L)	ORP (mV)	pH	Temperature (°C)	Conductivity (mS/cm)
17PSI-10	-43	3/31/04	22.2	<1.0	677.1/681.2	**	1.5/1.3	<0.5	<0.5	58.7	29	<0.010	0.400	NA	NA	NA	4.05	79	6.50	17.1	2.66
	20	6/2/04	61.9	482	1033.3/1013.4	<5/<5	1.6/1.9	<0.5	<0.5	53.5/52.6	150	<0.010	0.920	2.0	<10	325	0.47	-60	5.46	20.1	6.60
	111	9/1/04	87.2	1110	959.6/954.5	<5.0/<5.0	<0.5	<0.5	<1.0	0.7	130	<0.010	0.700	2.5	<10	16	0.26	-20	6.45	25.0	0.29
	188	11/17/04	98.9	864	693	<10	1.8	<0.5	1.5	<0.5	190	0.049	0.940	0.0	100	700	0.14	33	5.23	18.7	3.47
	271	2/8/05	66.7	784	803	<5.0	2	<0.5	<1.0	<0.5	220	0.079	0.830	0.2	80	600	0.41	51	4.80	16.7	3.33
	377	5/25/05	84.4	685	828	<5.0	2.6	< 0.5	1.5	< 0.5	220	0.098	0.800	0.2	<10	<10	0.32	92	4.95	18.2	3.35
	468	8/24/05	37.7	633	839	<5.0	2.3	< 0.5	< 1.0	< 0.5	190	0.061	1.200	0.6	0	600	0.45	4	4.88	22.3	3.28
duplicate	468	8/24/05	65.2	629		NA	NA	NA	NA			NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	684	3/28/06	70	612	1,086	<10	3.2	<0.5	<10	<0.5	240	0.074	0.640	0.1	0	600	0.56	2	5.20	16.3	3.03
	866	9/26/06	18.8	524	485	<0.5	1.4	<0.5	12.6	<0.5	210	0.075	0.720	0.0	500	750	0.52	-69	4.04	24.7	3.28
duplicate	866	9/26/06	35.7	513	NA	NA	NA	NA	NA			NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	951	12/20/06	53.2	642	694.6	<0.5	1.8	<0.5	<10	0.7	170	0.068	0.590	0.0	60	100	0.74	-33	5.30	21.1	3.50
	1062	4/10/07	77.5	52.6	1014	<0.5	2.4	<0.5	NA	<0.5	200	0.076	0.750	0.0	<50	NM	0.51	-31	5.22	16.8	3.59
duplicate	1062	4/10/07	62.1	55.6	NA	NA	NA	NA	NA			NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	1252	10/17/07	1.90	646	752/746	<0.5	1.4/1.8	<0.5	NA	<0.5/0.6	40	0.045	0.510	NA	340	NA	0.80	-76	5.80	21.4	1.95
17PSI-12	-43	3/31/04	16.3/16.5	<1.0/<1.0	664.7	**	1.4	<0.5	<0.5	72.9/78.6	38	NA	0.49				3.91	124	6.90	16.9	2.94
	951	12/20/06	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-29	6.50	18.3	3.33
17PSI-13	-43	3/31/04	13.9	<1.0	677.1	**	1.4	<0.5	<0.5	102.6	53	NA	0.610	NA	NA	NA	4.66	99	6.90	16.8	3.99
	20	6/2/04	37.7	368	1123.5	<5	2.2	<0.5	<0.5	82.6	120	NA	0.920	1.0	<10	375	0.74	-107	5.69	20.2	5.70
	111	9/1/04	27.5	400	1219.8	<5.0	2.1	<0.5	<1.0	<0.5	200	NA	0.840	1.5	<10	1000	0.19	-47	4.87	23.3	1.34
	187	11/16/04	92.2	863	557.2/565.9	<10/<10	1.6/1.6	<0.5/<0.5	<0.5/<0.5	<0.5/<0.5	210	NA	0.920	0.0	150	300	0.10	50	5.04	19.7	3.07
	271	2/8/05	64.2	695	801	<5.0	2.1	<0.5	<1.0	<0.5	190	NA	0.880	0.2	<10	700	0.39	73	4.69	16.4	3.85
	376	5/24/05	79.8	629	745/737	<5.0/<5.0	2.2/2.2	<0.5/<0.5	6.4/7.0	<0.5/<0.5	160	NA	0.800	0.6	<10	750	0.29	60	4.91	22.5	2.06
	468	8/24/05	69.8	541	1,048	<5.0	2	< 0.5	< 1.0	< 0.5	160	NA	0.990	0.8	0	600	0.35	14	4.94	23.3	3.27
	684	3/28/06	57.2	672	1,282	<10	3.7	<0.5	<10	<0.5	260	NA	0.880	0.2	0	600	NA	-48	5.20	19.1	4.17
	866	9/26/06	41.1	403	613	<0.5	1.3	<0.5	1.6	<0.5	180	NA	0.830	0.0	125	425	0.56	-71	3.59	24.2	1.81
	951	12/20/06	60.6	475	1171.6	<0.5	2.8	<0.5	<10	1.1	260	NA	0.850	0.0	55	10	0.81	-131	5.80	21.4	4.02
	1062	4/10/07	72.9	42.4	1341	<0.5	3.3	<0.5	NA	<0.5	280	NA	0.840	0.0	55	NA	0.46	-35	5.41	16.9	4.88
	1252	10/17/07	1.10	583	1067	<0.5	4.1	<0.5	NA	<0.5	90	NA	0.570	NA	190	NA	0.60	-35	5.10	21.3	2.05
17PSI-15	-43	3/31/04	15.0	<1.0	667.2	**	1.4	<0.5	<0.5	86.2	48	NA	0.540				3.59	154	6.90	16.0	3.86
	951	12/20/06	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-24	5.40	18.2	4.14

Well ID (Distance from Barrier	Days Since Injection 5/13/2004	Sample Date	Total Inorganic Carbon (mg/L)	Total Organic Carbon (mg/L)	Chloride (mg/L)	Nitrite (mg/L)	Bromide (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Sulfate (mg/L)	Dissolved Iron (mg/L)	Arsenic (mg/L)	Manganese (mg/L)	Sulfide (ppm)	Alkalinity (ppm)	Carbon Dioxide (ppm)	Dissolved Oxygen (mg/L)	ORP (mV)	pH	Temperature (°C)	Conductivity (mS/cm)
MONITORING WELLS																					
17PS-01	-42	4/1/04	19.5	1.02	1281	**	2.8	<0.5	<0.5	65.5	78	NA	0.630	NA	NA	NA	0.67	176	6.70	15.9	5.19
	20	6/2/04	50.7	62.7	1133.6/1102.8	<5/<5	2.1/2.2	<0.5	<0.5	44.1/44.6	120	NA	0.720	0.4	<10	300	1.14	-113	5.94	20.5	9.28
	111	9/1/04	60.8	39.7	1093.2	<5.0	2.1	<0.5	<1.0	15.3	110	NA	0.540	2	30	400	0.15	-94	5.45	24.4	1.77
	187	11/16/04	77.3	4.92	1147	<10	2.9	<0.5	<0.5	23.4	130	NA	0.780	0	150	350	0.17	16	6.27	20.8	3.98
	271	2/8/05	36.2	13.0	973	<5.0	2.7	<0.5	<1.0	27.9	150	NA	0.680	0	100	250	0.23	-6	5.86	17.1	4.34
	377	5/25/05	108.0	55.6	692	<5.0	2.1	< 0.5	< 1.0	20.3	130	NA	0.690	0.1	200	500	0.34	39	6.28	18.1	1.91
duplicate	377	5/25/05	71.8	11.7	NA	NA	NA	NA	NA			NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	468	8/24/05	90.4	5.99	1,483	<5.0	3.5	< 0.5	< 1.0	21.6	190	NA	0.570	NA	80	130	0.33	-29	5.48	23.0	4.14
	685	3/29/06	73.0	5.08	798	<10	2.4	<0.5	<10	30.9	210	NA	0.490	<0.1	50	600	0.49	-30	5.73	19.5	3.80
	866	9/26/06	81.5	16.3	630.2/622.5	<0.5	1.4/1.9	<0.5	2.3/<0.5	<0.5	110	NA	0.690	0	300	520	0.81	-108	5.12	23.6	1.67
	951	12/20/06	171.0	5180	1171.3	<0.5	3	<0.5	<10	1.4	7.2	NA	0.190	0	<50	10	NA	-72	8.40	19.3	6.38
	1062	4/10/07	366.0	89.6	1272	<0.5	3.3	<0.5	NA	<0.5	1.0	NA	0.050	0	<50	NA	0.72	-238	7.83	17.1	7.28
	1252	10/17/07	2.3	653	1171.1	<0.5	1.7	1.3	NA	0.5	2.1	NA	0.230	NA	1500	NA	0.20	-149	6.80	21.5	2.73
17PS-02	-42	4/1/04	20.6	1.03	848.4/852.8	**	1.6/1.5	<0.5	<0.5	58	50	<0.010	0.560	NA	NA	NA	1.50	158	6.60	15.6	3.97
	20	6/2/04	49.2	62.9	1111.3	<5/<5	2.1	<0.5	<0.5	5.4	81	0.038	0.740	0.2	<10	150	3.36	-96	5.98	20.1	8.14
duplicate	20	6/2/04	45.3	52.2	880.1	<5.0	1.9	<0.5	<0.5	2.7		NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	111	9/1/04	38.1	13.3	955.3	<5.0	1.6	<0.5	<1.0	15.0	170	<0.010	0.570	2.0	12	250	0.14	-76	5.86	24.8	1.45
duplicate	111	9/1/04	59.7	13.2	NA	NA	NA	NA	NA			NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	187	11/16/04	75.7	17.2	771.7	<10	2	<0.5	<0.5	2.8	150	<.010	0.590	0.6	55	350	0.16	-5	6.12	20.7	OR
duplicate	187	11/16/04	68.4	19.1	833.1	<10	2	<0.5	<0.5	3.8	NA	NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	271	2/8/05	60.8	5.14	891/887	<5.0/<5.0	1.8/2.1	<0.5/<0.5	<1.0/<1.0	10.0	120	<0.010	0.520	0.2	130	250	0.20	18	5.38	17.2	3.47
	377	5/25/05	75.6	5.59	656	<5.0	2.0	< 0.5	< 1.0	6.7	92	0.019	0.660	0.2	150	400	0.47	26	6.26	18.2	1.66
	468	8/24/05	75.6	3.87	1057	<5.0	2.5	< 0.5	< 1.0	20.8	150	0.019	0.540	NA	0	425	0.32	-27	5.29	23.0	3.77
	685	3/29/06	120.0	3.66	696	<10	2	<0.5	<10	14	130	0.016	0.550	<0.1	110	600	0.50	-58	5.98	20.4	4.10
duplicate	685	3/29/06	94.8	3.23	NA	NA	NA	NA	NA			NA	NA	NA	NA	NA	NA	NM	NM	NM	NM
	866	9/26/06	66.6	2.93	742	<0.5	2.1	<0.5	<0.5	2.8	170	0.049	0.620	0.0	250	1000	0.48	-82	4.70	24.0	1.80
	951	12/20/06	133.0	2510	916.6	<0.5	2.4	<0.5	<10	9.6	1.10	0.0090 J	0.180	0.0	<50	0	NA	-72	8.10	20.4	6.13
	1062	4/10/07	63.4	45.6	1142.6/1103.9	<0.5	2.4/2.5	<0.5	NA	<0.5/0.57	12.0	0.015	0.260	0.0	<50	NA	0.75	-34	6.16	16.7	6.69
	1252	10/17/07	1.1	525.0	515	<0.5	1.6	1.1	NA	<0.5	0.41	0.012	0.075	NA	1800	NA	0.40	-229	8.50	21.6	2.33
17PS-03	-42	4/1/04	<1.0	<1.0	1038.5	**	2.2	<0.5	<0.5	77.5	69	NA	0.680	NA	NA	NA	0.40	178	6.90	15.6	4.65
	20	6/2/04	62.6	84.5	987.3	<5	2.1	<0.5	<0.5	10.0	110	NA	0.810	0.0	40	325	1.22	-111	5.93	20.4	7.66
	111	9/1/04	60.8	51.4	561.4	<5.0	<0.5	<0.5	<1.0	<0.5	130	NA	0.460	0.4	40	350.0	0.14	-79	5.92	23.6	0.14
	187	11/16/04	98.0	51.2	990.3/1027.9	<10/<10	2.4/2.3	<0.5/<0.5	<0.5/<0.5	0.5/<0.5	200	NA	0.800	0.0	175	300.0	0.18	-15	6.41	20.7	3.71
	271	2/8/05	106.0	23.0	651	<5.0	1.4	<0.5	<1.0	<0.5	180	NA	0.570	0.1	180	400	0.25	-14	5.74	17.3	3.72
	377	5/25/05	138.0	111.0	504	<5.0	1.5	< 0.5	< 1.0	< 0.5	180	NA	0.700	0	350	1000	0.31	3	6.32	18.1	1.57
	468	8/24/05	166.0	18.9	1,044	<5.0	2.5	< 0.5	< 1.0	2.10	190	NA	0.470	NA	75	625	0.37	-20	5.58	23.9	3.98
	685	3/29/06	130.0	17.1	741	<10	2.4	<0.5	<10	1.6	370	NA	0.430	<0.1	120	700.0	0.44	-75	6.00	21.5	3.80
	866	9/26/06	77.0	6.26	657	<0.5	1.4	<0.5	<0.5	1.9	96	NA	0.580	0.0	250	500	0.57	-68	5.52	24.7	3.39
	951	12/20/06	109.0	4440	863.5/859.0	<0.5	2.4/2.2	<0.5	<10	9.6/9.5	1.1	NA	0.170	0.0	<50	0	NA	-18	9.00	18.5	9.25
	1062	4/10/07	264.0	46.1	1166.5	<0.5	2.8	<0.5	NA	5.0	0.38	NA	0.055	0.0	<50	NA	0.68	-146	8.91	16.8	10.77
	1252	10/17/07	2.0	396	515	<0.5	1.7	1.3	NA	<0.5	0.58	NA	0.120	NA	1500	NA	0.40	-121	7.20	21.8	2.09

** Not quantifiable due to interference from high chloride.

NA denotes not analyzed.

J denotes estimated value between the Reporting Limit and the MDL

TABLE IV-3
Results of Geoprobe Groundwater Sampling Event Six Months after Injection of EOS®
November 9 and 10, 2004
Naval Weapons Station
Charleston, South Carolina

Sample ID	TCE (µg/L)	*cis* -1,2-DCE (µg/L)	*trans* -1,2-DCE (µg/L)	Vinyl Chloride (µg/L)	Ethene (µg/L)	Chlorine #	Chloroform (µg/L)	Methane (µg/L)	Ethane (µg/L)
17-PSTW-4	35,000	490	<50	<50	1.09	2.98	<50	32.3	0.2
17-PSTW-5	49,000	700	<50	<50	1.77	2.98	<50	49.5	0.1
17-PSTW-6	49,000	590	<50	<50	1.66	2.98	<50	38.6	0.1
17-PSTW-7	30,000	300	<50	<50	0.55	2.98	<50	47.1	0.1
17-PSTW-8	39,000	260	<50	<50	0.82	2.99	<50	89.3	0.1
17-PSTW-9	31,000	170	<50	<50	0.69	2.99	230	113.9	0.1
17-PSTW-10	11,000	190	16	<5.0	0.59	2.97	48	53.2	0.0
17-PSTW-11	6,800	71	<5.0	<5.0	0.41	2.98	77	69.2	0.0
17-PSTW-12	710	<5.0	<5.0	<5.0	0.05	2.98	<5.0	56.6	0.0
17-PSTW-13	3,900	100	25	<5.0	0.14	2.96	<5.0	18.0	0.0
17-PSTW-14	380	36	11	<0.5	0.03	2.85	<0.5	13.1	0.0
17-PSTW-15	1.5	<0.5	<0.5	<0.5	0.02	2.28	<0.5	10.2	0.0
Rinse Blank	<0.5	<0.5	<0.5	<0.5	NS		<0.5	NS	NS

Note: Values of one-half the reporting limit were used in the calculation of the Chlorine #.

Sample ID	TOC (mg/L)	Chloride (mg/L)	Nitrite (mg/L)	Bromide (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Sulfate (mg/L)	pH	Conductivity (µS)	ORP (mV)	Temperature (°C)	DO (mg/L)
17-PSTW-4	<1.0	708.0	<2.5	1.6	<0.5	<0.5	78.8	5.51	1916	99.3	19.1	1.06
17-PSTW-5	<1.0	490.6/488.2	<2.5/<2.5	1.2/1.2	<0.5/<0.5	<0.5/<0.5	78.2/76.6	5.70	1138	71.2	20.8	0.45
17-PSTW-6	<1.0	225.6	<2.5	0.7	<0.5	<0.5	81.1	5.84	911	66.8	18.8	0.36
17-PSTW-7	<1.0	518.8	<2.5	1.7	<0.5	<0.5	39.4	5.46	1662	51.2	19.7	0.34
17-PSTW-8	<1.0	479.3	<2.5	1.7	<0.5	<0.5	35.0	5.30	1538	65.5	19.7	0.38
17-PSTW-9	<1.0	51.2	<0.5	0.5	<0.5	<0.5	33.9	5.04	396	168.1	18.9	0.41
17-PSTW-10	<1.0	861.9/853.5	<5/<5	2.3/2.1	<0.5/<0.5	<0.5/<0.5	96.6/91.2	5.55	1932	57.8	19.7	0.46
17-PSTW-11	<1.0	1878.0	<10	4.0	<0.5	<0.5	132.5	5.56	5050	56.4	20.4	0.68
17-PSTW-12	<1.0	514.4	<5	1.6	<0.5	<0.5	96.8	5.98	1512	37.8	19.4	0.99
17-PSTW-13	<1.0	1356.5	<10	3.7	<0.5	<0.5	125.9	5.37	5350	52.4	19.2	0.21
17-PSTW-14	<1.0	1418.9	<10	4.0	<0.5	<0.5	177.1	5.76	5040	33.4	21.4	0.41
17-PSTW-15	<1.0	2797.3/2797.2	<5/<5	7.9/7.7	<0.5/<0.5	<0.5/<0.5	316/310.6	5.79	7800	52.5	20.4	0.37
Rinse Blank	<1.0	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	NA	NA	NA	NA	NA

Table IV-4
Summary of Soil Gas Measurements
Charleston Naval Weapons Station, SWMU 17
Charleston, SC

Well ID	Sample Date	Headspace O_2 %	Headspace H_2S ppm	Headspace LEL %	Headspace CO ppm
Upgradient Monitoring Wells					
17MW-5S	6/1/2004	20.9	0	0	2
	8/31/2004	18.6	0	4	12
	11/15/2004	20.3	0	0	1
	2/7/2005	20.9	0	0	6
	5/24/2005	20.9	0	0	3
	8/24/2005	20.9	0	0	0
	3/27/2006	18.8	0	0	1
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17MW-6S	6/1/2004	20.9	0	0	0
	8/31/2004	20.0	0	2	15
	11/15/2004	18.8	0	0	1
	2/7/2005	20.9	0	2	9
	5/24/2005	20.9	0	1	8
	8/24/2005	20.9	0	0	0
	3/27/2006	20.9	0	0	0
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17MW-7S	6/1/2004	20.9	0	0	0
	8/31/2004	19.4	0	0	47
	11/15/2004	19.2	0	0	0.0
	2/7/2005	20.9	0	2	16
	5/24/2005	20.7	0	0	13
	8/24/2005	20.9	0	0	0
	3/27/2006	20.9	0	0	0
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
Injection Wells					
17PSI-01	6/1/2004	20.2	0	0	86
	Abandoned after injection				
17PSI-02	6/1/2004	18.1	0	3	687
	8/31/2004	20.9	0	0	44
	11/15/2004	13.8	0	2	1
	2/7/2005	20.0	0	100	19
	5/24/2005	19.6	1	100	16
	8/24/2005	NM	NM	NM	NM
	3/27/2006	4.0	157	100	23
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17PSI-03	6/1/2004	19.2	0	0	382
	Abandoned after injection				
17PSI-04	6/1/2004	17.5	0	0	501
	8/31/2004	NM	NM	NM	NM
	11/15/2004	17.2	0.0	3.0	0
	2/7/2005	20.1	70	100	62
	5/24/2005	20.3	59	96	80
	8/24/2005	NM	NM	NM	NM
	3/27/2006	5.4	117	100	9
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM

Well ID	Sample Date	Headspace O_2 %	Headspace H_2S ppm	Headspace LEL %	Headspace CO ppm
17PSI-05	6/1/2004	17.8	0	0	383
	8/31/2004	NM	NM	NM	NM
	11/15/2004	15.4	0.0	3.0	56
	2/7/2005	20.8	0	8	25
	5/24/2005	20.9	2	12	31
	8/24/2005	NM	NM	NM	NM
	3/27/2006	5.2	0	100	24
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17PSI-06	6/1/2004	20.4	0	0	36
	Abandoned after injection				
17PSI-07	6/1/2004	19.1	0	0	205
	8/31/2004	20.8	0	0	0
	11/15/2004	18.1	0	0	167
	2/7/2005	20.9	3	19	22
	5/24/2005	20.9	7	14	24
	8/24/2005	NM	NM	NM	NM
	3/27/2006	11.8	1	100	16
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17PSI-08	6/1/2004	20.9	0	0	17
	Abandoned after injection				
17PSI-09	6/1/2004	18.8	0	0	158
	Abandoned after injection				
17PSI-10	6/1/2004	20.1	0	0	97
	8/31/2004	20.9	0	0	0
	11/15/2004	17.3	0	3	26
	2/7/2005	20.0	23	100	17
	5/24/2005	19.8	26	100	19
	8/24/2005	NM	NM	NM	NM
	3/27/2006	0.8	158	100	18
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17PSI-11	6/1/2004	19.7	0	0	123
	Abandoned after injection				
17PSI-12	6/1/2004	19.8	0	0	128
	8/31/2004	NM	NM	NM	NM
	11/15/2004	4.8	49.0	78.0	186
	2/7/2005	20.6	106	100	49
	5/24/2005	20.2	89	100	54
	8/24/2005	NM	NM	NM	NM
	3/27/2006	0.8	147	100	13
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17PSI-13	6/1/2004	19.7	0	0	174
	8/31/2004	20.9	0	0	0
	11/15/2004	20.6	0	0	0
	2/7/2005	20.2	26	20	24
	5/24/2005	20.5	41	16	31
	8/24/2005	NM	NM	NM	NM
	3/27/2006	7.4	157	100	25
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17PSI-14	6/1/2004	20.3	0	0	61

Well ID	Sample Date	Headspace O_2 %	Headspace H_2S ppm	Headspace LEL %	Headspace CO ppm
	Abandoned after injection				
17PSI-15	6/1/2004	20.2	0	0	66
	8/31/2004	NM	NM	NM	NM
	11/15/2004	7.3	0.0	33	31
	2/7/2005	20.1	4	27	19
	5/24/2005	19.9	0.0	33.0	17
	8/24/2005	NM	NM	NM	NM
	3/27/2006	5.4	157	100	27
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17PSI-16	6/1/2004				
	Abandoned after injection				
Monitoring Wells					
17PS-01	6/1/2004	20.5	0	0	1
	8/31/2004	19.9	0	0	7
	11/15/2004	16.4	0	26	20
	2/7/2005	20.9	0	3	10
	5/24/2005	20.9	0	4	10
	8/24/2005	20.9	0	0	0
	3/27/2006	20.5	0	0	1
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17PS-02	6/1/2004	20.9	0	0	2
	8/31/2004	18.1	0	0	18
	11/15/2004	20.1	0	0	5
	2/7/2005	20.9	0	1	9
	5/24/2005	20.8	2	5	12
	8/24/2005	20.9	0	0	0
	3/27/2006	20.9	0	0	1
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
17PS-03	6/1/2004	20.9	0	0	5
	8/31/2004	16.1	0	3	54
	11/15/2004	17.4	>100	6	6
	2/7/2005	20.4	8	100	15
	5/24/2005	20.1	11	100	26
	8/24/2005	20.9	3	>100	1
	3/27/2006	20.9	0	0	1
	4/9/2007	NM	NM	NM	NM
	10/17/2007	NM	NM	NM	NM
Soil Gas Monitoring Points					
17PSG-1	5/11/2004	12.3	0	5	2
	6/1/2004	20.1	0	0	1
	8/31/2004	14.5	0	0	8
	11/15/2004	17.1	0	0	0
	2/7/2005	20.9	0	0	2
	5/24/2005	20.9	0	0	1
	8/24/2005	NM	NM	NM	NM
	3/27/2006	19.6	0	0	0
	4/9/2007	17.1	0	20	1
	10/17/2007	16.3	0	3	0

Well ID	Sample Date	Headspace O_2 %	Headspace H_2S ppm	Headspace LEL %	Headspace CO ppm
17PSG-2	5/11/2004	18.8	0	4	1
	6/1/2004	20.9	0	0	0
	8/31/2004	18.3	0	0	12
	11/15/2004	19.0	0	0	0.0
	2/7/2005	20.9	0	0	3
	5/24/2005	20.9	0	0	3
	8/24/2005	20.9	0	0	0
	3/27/2006	14.2	0	0	1
	4/9/2007	20.9	0	0	0
	10/17/2007	20.4	0	0	0

NM denotes not measured.

Readings were field measured with a VRAE monitor.

Table IV-5
Results of Pre- and Post-Injection Soil Chlorinated Volatile Organic Compound Analyses
Naval Weapons Station
Charleston, SC

Sample Location	Sample Date	Sample Depth (ft bgs)	1,1-DCE (µg/kg)	1,1,2,2-Tetrachloroethane (µg/kg)	1,1,2-Trichloroethane (µg/kg)	Chloroform (µg/kg)	TCE (µg/kg)	*cis* -1,2-DCE (µg/kg)	*trans*- 1,2-DCE (µg/kg)	VC	Total CAHs* (µg/kg)	Sample Location	Sample Date	Sample Depth (ft bgs)	Acetone (µg/kg)	MEK (µg/kg)	Carbon Disulfide(µg/kg)	1,1,2-Trichloroethane (µg/kg)	Chloroform (µg/kg)	TCE (µg/kg)	*cis* -1,2-DCE (µg/kg)	*trans*- 1,2-DCE (µg/kg)	VC	Total CAHs* (µg/kg)
17PSI-01	3/1/04	0.5-4	<220	<220	<220	<220	390	<220	<220	<440	390	17PSSB-17	10/18/2007	10-12	36.0	<1.9	<0.31	<0.30	<0.35	<0.29	19	<0.36	400E*	419
	3/1/04	5-8	<260	<260	<260	<260	8,100	110 J	<260	<520	8,210		10/18/2007	12-14	60.0	<2.0	<0.46	<0.45	<0.54	23	93	<0.55	230	232
	3/1/04	9-12	<240	<240	<240	<240	4,000	<240	<240	<480	4,000		10/18/2007	14-16	24.0	<1.4	<0.33	<0.32	<0.38	13	56	<0.39	350	419
17PSI-04	3/1/04	5.5-6	<300	<300	<300	<300	14,000	210 J	<300	<600	14,210	17PSSB-21	10/18/2007	8-10	<1.7	<1.2	<0.28	<0.27	2.6 J	490	210	3.7 J	270E*	976
	3/1/04	12-14	<380	<380	<380	<380	8,200	<380	<380	<760	8,200		10/18/2007	12-14	<3.0	<2.1	<0.48	<0.47	9.1	650	490	15	240	1404
	3/1/04	14-16	<330	<330	<330	<330	16,000	200 J	<330	<660	16,200		10/18/2007	14-16	23	<1.4	<0.32	<0.31	<0.37	3.6 J	300E*	4.5 J	840	1148
17PSI-13	3/1/04	4-6.5	<270	<270	<270	<270	11,000	<270	<270	<540	11,000	17PSSB-19	10/18/2007	8-10	91	36		<0.44	<0.52	12	16	<0.53	<0.9	28
	3/1/04	6.5-7.75	<240	<240	<240	<240	9,200	<240	<240	<480	9,200		10/18/2007	10-12	<1.8	<1.3		<0.29	<0.34	<0.28	<0.20	<0.35	140	140
	3/1/04	15-16	<270	<270	<270	<270	4,800	<270	<270	<540	4,800		10/18/2007	12-14	<1.7	<1.2	2.0 J	<0.28	2.8 J	210	270E*	2.6 J	260	745
													10/18/2007	14-16	35	<1.4	<0.33	<0.32	<0.38	<0.31	93	2.9 J	390	486
17PSI-16	3/1/04	6-8	<270	<270	<270	<270	5,400	<270	<270	<540	5,400		10/18/2007	16-18	37	21	<0.30	<0.29	<0.35	90	66	<0.36	240	396
	3/1/04	9-11	<260	<260	<260	<260	3,100	<260	<260	<520	3,100													
	3/1/04	16-18	<5	<5	<5	<5	<5	2.3 J	<5	<10	2.3	17PSSB-18	10/18/2007	9-11	<2.0	<1.4	<0.33	5.9	24.0	3100	290	3.0 J	7.1J	3430
													10/18/2007	14-16	<3.0	<2.1	<0.49	<0.47	<0.56	210	380	5.1J	10J	605
17PSI-02	3/25/04	8-10	<260	<260	<260	<260	9,900	<260	<260	<520	9,900													
												17PSSB-20	10/18/2007	10-12	<3.0	<2.1	<0.49	<0.47	<0.57	<0.46	23	<0.58	57	80
17PSI-03	3/25/04	10-12	<240	<240	<240	<240	10,000	<240	<240	<480	10,000		10/18/2007	12-14	<2.0	<1.4	<0.32	<0.31	<0.37	43	76	<0.38	120	239
													10/18/2007	14-16	<1.9	<1.4	<0.32	<0.31	<0.37	<.30	<0.22	<0.37	100	100
17PSI-06	3/25/04	8-9	<2,500	<2,500	<2,500	<2,500	9,000	<2,500	<2,500	<5,000	9,000													
	3/25/04	9-10	<250	<250	<250	<250	9,100	<250	<250	<500	9,100													
	3/25/04	10-11	<250	<250	<250	<250	5,300	<250	<250	<500	5,300													
	3/25/04	11-12	<260	<260	<260	<260	9,800	<260	<260	<520	9,800													
	3/25/04	12-13	<260	<260	<260	<260	9,000	<260	<260	<520	9,000													
	3/25/04	13-14	<250	<250	<250	<250	7,200	<250	<250	<500	7,200													
	3/25/04	14-15	<250	<250	<250	<250	5,800	<250	<250	<500	5,800													
	3/25/04	15-16	<250	<250	<250	<250	5,900	<250	<250	<500	5,900													
	3/25/04	16-17	<250	<250	<250	<250	8,700	<250	<250	<500	8,700													
	3/25/04	17-18	<280	<280	<280	<280	5,900	<280	<280	<560	5,900													
17PSI-08	3/24/04	10-12	<5	3.4 J	3.7 J	55	5,000	26	<5	<10	5,088													
17PSI-09	3/25/04	16-18	<1,300	<1,300	<1,300	<1,300	3,200	<1,300	<1,300	<2,600	3,200													
17PSI-14	3/24/04	12-14	<5	8.6	5.6	40	7,200	19	<5	<10	7,273													
17PSI-15	3/24/04	10-11	<5	6.3	5.3	34	6,500	13	<5	<10	6,559													
17PSI-16	3/24/04	6-8	<5.0	5.7	8.5	120	11,000	72	<5	<10	11,206													
	3/24/04	8-12	5.3	4.9 J	9.8	100	13,000	160	<5.0	<10	13,280													
		Average					7,523	170	BDL		7,564			Average						303	149		228	678
		Std Dev.					3,656	231			3,704			Std Dev.						770	153		210	835

* Total CAHs include TCE;*cis* -1,2-DCE; 1,1-DCE; 1,1,2,2-PCA; 1,1,2-TCA; chloroform; and dichlorofluoromethane.
ND = Not Detected; NA = Not Analyzed
Averages calculated using 1/2 the minimum detection limit where concentrations were reported as below detection.
Concentrations shown as "<" are less than the Minimum Detection Limit.

APPENDIX V

WATER LEVEL MEASUREMENTS

Table V-1. Historical Groundwater Elevation Measurements

Table V-1
Historical Groundwater Elevation Measurements
Charleston Naval Weapons Station, SWMU 17
Charleston, SC

Well ID	Northing	Easting	Ground Surface Elevation (feet MSL)	Top of Casing Elevation (feet MSL)	DTW 44 Days Pre-Inj. 3/30/2004	GW Elev. 44 Days Pre-Inj. 3/30/2004	DTW 19 Days Post-Inj. 6/1/2004	GW Elev. 19 Days Post-Inj. 6/1/2004	DTW 187 Days Post-Inj. 11/15/2004	GW Elev. 187 Days Post-Inj. 11/15/2004	DTW 272 Days Post-Inj. 2/8/2005	GW Elev. 272 Days Post-Inj. 2/8/2005	DTW 467 Days Post-Inj. 8/23/2005	GW Elev. 467 Days Post-Inj. 8/23/2005	DTW 683 Days Post-Inj. 3/27/2006	GW Elev. 683 Days Post-Inj. 3/27/2006	DTW 865 Days Post-Inj. 9/25/2006	GW Elev. 865 Days Post-Inj. 9/25/2006	DTW 1061 Days Post-Inj. 4/9/2007	GW Elev. 1061 Days Post-Inj. 4/9/2007	DTW 1252 Days Post-Inj. 10/17/2007	GW Elev. 1252 Days Post-Inj. 10/17/2007
17MW-5S	397272.7887	2321215.29	4.95	7.77	5.73	2.04	7.49	0.28	6.46	1.31	4.31	3.46	NM		5.16	2.61	5.38	2.39	6.47	1.30	7.20	0.57
17MW-6S	397253.9852	2321209.39	5.23	7.89	5.87	2.02	7.61	0.27	6.55	1.34	4.37	3.52	NM		5.28	2.61	5.46	2.43	6.60	1.29	7.29	0.60
17MW-7S	397234.3491	2321203.959	5.18	7.93	5.94	1.99	7.65	0.27	6.59	1.34	4.60	3.33	NM		5.34	2.59	5.49	2.44	6.65	1.28	7.30	0.63
PSI-01	397252.4063	2321239.796	6.18	8.19	4.74	3.45	6.50	1.69	NM		NM		NM		NM		NM		NM		NM	
PSI-02	397247.779	2321238.521	4.69	6.83	4.76	2.07	6.55	0.28	3.42	1.27	1.26	3.43	1.70	2.99	2.19	2.50	3.03	1.66	8.39	-3.70	6.06	-1.37
PSI-03	397242.9505	2321237.232	4.79	6.86	4.80	2.06	6.57	0.29	3.51	1.28	NM		NM		NM		NM		NM		NM	
PSI-04	397237.4408	2321236.303	4.82	6.77	4.70	2.07	6.47	0.30	3.48	1.34	1.69	3.13	1.95	2.87	2.37	2.45	2.79	2.03	NM		4.81	0.01
PSI-05	397251.7482	2321244.718	6.11	8.12	4.65	3.47	6.76	1.36	NM		1.35	4.76	1.76	4.35	2.20	3.91	2.54	3.57	NM		4.41	1.70
PSI-06	397247.4348	2321244.172	4.84	7.15	5.04	2.11	6.87	0.28	NM		NM		NM		NM		NM		NM		NM	
PSI-07	397241.6953	2321242.324	4.98	6.74	4.69	2.05	7.38	-0.64	3.67	1.31	1.52	3.46	2.00	2.98	2.47	2.51	2.71	2.27	3.78	1.20	4.88	0.10
PSI-08	397236.8438	2321241.237	4.95	6.89	4.85	2.04	6.60	0.29	NM		NM		NM		NM		NM		NM		NM	
PSI-09	397249.9361	2321249.322	6.04	8.07	4.62	3.45	6.39	1.68	NM		NM		NM		NM		NM		NM		NM	
PSI-10	397244.5505	2321248.223	4.80	6.66	4.57	2.09	6.36	0.30	3.48	1.32	1.29	3.51	1.89	2.91	3.57	1.23	3.4	1.40	5.59	-0.79	4.31	0.49
PSI-11	397240.1693	2321247.006	4.89	6.87	4.78	2.09	6.54	0.33	NM		NM		NM		NM		NM		NM		NM	
PSI-12	397236.2913	2321245.878	4.73	6.87	4.79	2.08	6.55	0.32	3.53	1.20	1.29	3.44	1.71	3.02	3.52	1.21	6.41	-1.68	NM		4.27	0.46
PSI-13	397248.6439	2321253.862	4.68	6.70	4.61	2.09	6.39	0.31	3.37	1.31	1.14	3.54	1.69	2.99	2.24	2.44	2.75	1.93	3.42	1.26	3.96	0.72
PSI-14	397243.2775	2321253.556	4.90	7.18	5.10	2.08	7.04	0.14	NM		NM		NM		NM		NM		NM		NM	
PSI-15	397238.4016	2321251.888	4.90	6.94	4.84	2.10	6.65	0.29	3.56	1.34	1.40	3.50	1.87	3.03	2.42	2.48	2.62	2.28	NM		4.84	0.06
PSI-16	397234.4705	2321249.89	4.72	6.79	4.70	2.09	6.58	0.21	NM		NM		NM		NM		NM		NM		NM	
17PS-01	397239.0561	2321244.25	6.29	9.36	5.92	3.44	7.61	1.75	6.65	2.71	4.37	4.99	4.97	4.39	5.41	3.95	5.61	3.75	5.31	4.05	7.22	2.14
17PS-02	397241.5962	2321249.443	6.35	9.31	5.85	3.46	7.59	1.72	6.60	2.71	4.58	4.73	4.93	4.38	5.32	3.99	5.55	3.76	5.19	4.12	7.09	2.22
17PS-03	397248.0191	2321247.222	6.19	9.22	5.80	3.42	7.50	1.72	6.51	2.71	5.15	4.07	4.86	4.36	5.23	3.99	5.46	3.76	8.07	1.15	7.07	2.15

feet MSL = feet above mean sea level
DTW = Depth to water (ft.)
GW Elev. = Groundwater elevation (ft MSL)
Groundwater elevations for all 6 monitor wells were calculated from depth to water measured from the top of casing elevation.
Groundwater elevations measurements for all 16 injection wells on March 30 and June 1, 2004 were calculated from depth to water measured from top of casing (stick-up) elevations.
Groundwater elevations for 8 remaining injection wells collected from November 15, 2004 to the end of the study were calculated from ground surface elevations. The stick-up portion had been cut off in June 2004 and these were completed with flush mount finishes and not re-surveyed.

Remaining wells were re-surveyed on Nov 10, 2004 see preceeding workbook

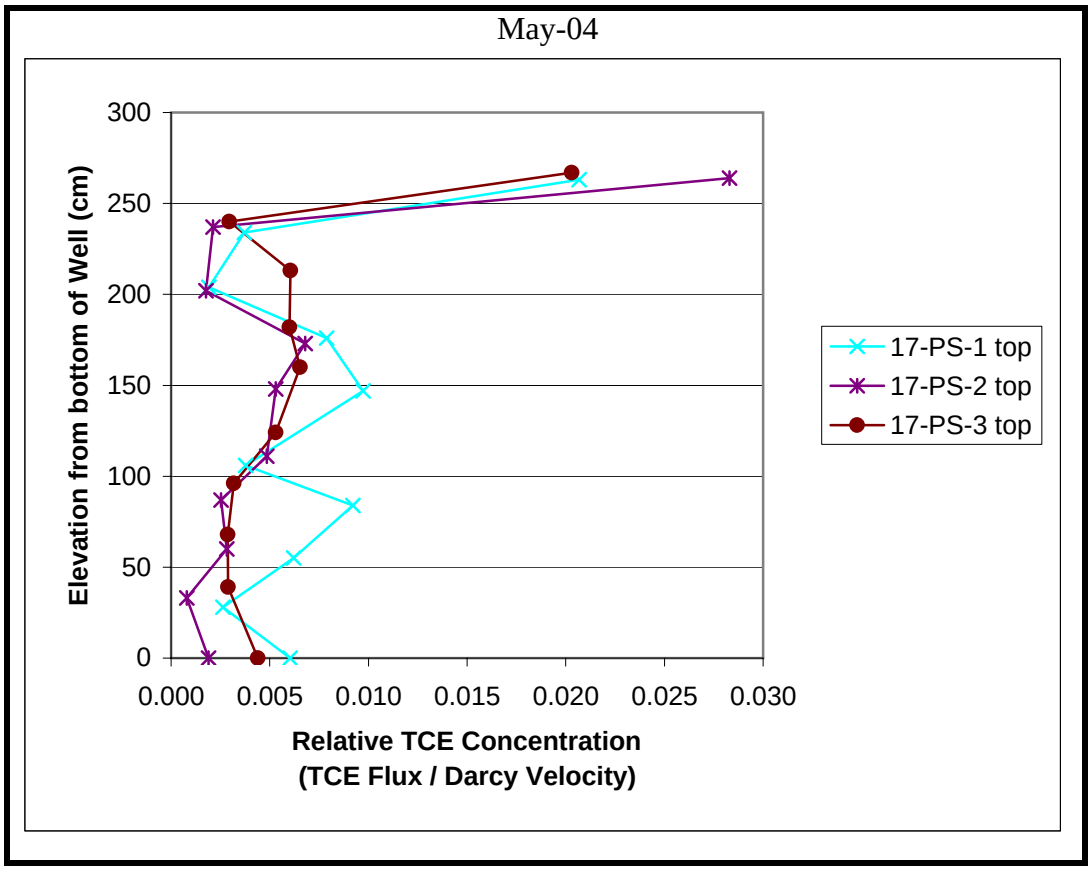
APPENDIX VI

MASS FLUX MEASUREMENTS

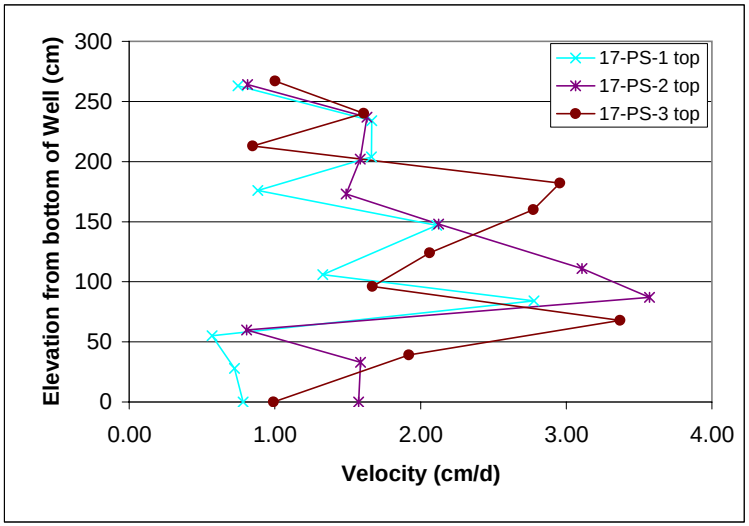
Table VI-1. Charleston NWS Flux Meter Samples (May 2004)

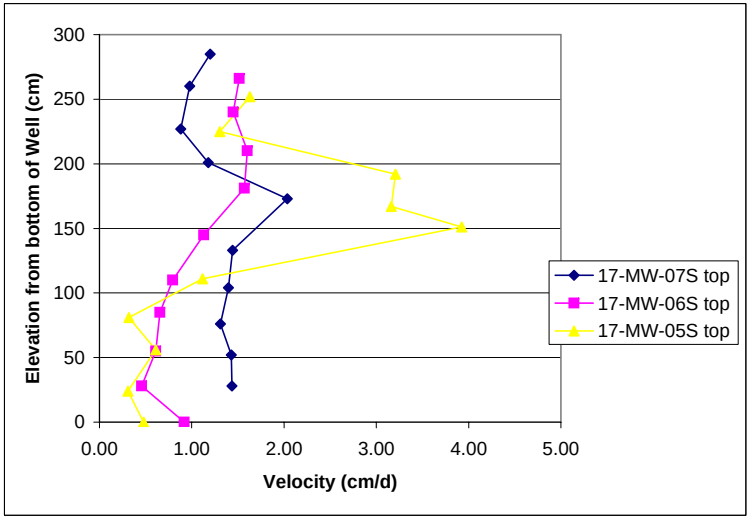
Sample Interval Elevation from bottom of well				Darcy Velocity	DCE flux	DCE flux	TCE flux	TCE flux	Relative Conc.
Name	**cm**	**ft**	**cm**	**cm/day**	**mg/cm^2/day**	**mg/m^2/day**	**mg/cm^2/day**	**mg/m^2/day**	
17-MW-07S top	260	8.53	285	1.20	0.0008	8.09	0.106	1056.19	0.088
	227	7.45	260	0.98	0.0003	3.48	0.031	313.00	0.032
	201	6.59	227	0.88	0.0000	0.00	0.022	224.37	0.026
	173	5.68	201	1.18	0.0000	0.00	0.035	350.70	0.030
	143	4.69	173	2.03	0.0015	14.99	0.215	2152.05	0.106
	104	3.41	133	1.44	0.0004	4.00	0.052	521.44	0.036
	76	2.49	104	1.40	0.0003	2.62	0.035	348.26	0.025
	52	1.71	76	1.31	0.0002	2.38	0.032	317.21	0.024
	28	0.92	52	1.43	0.0000	0.00	0.029	291.16	0.020
17-MW-07S bottom	0	0.00	28	1.44	0.0000	0.00	0.039	388.92	0.027
			Average	**1.33**	**0.0004**	**3.56**	**0.060**	**596.33**	
17-MW-06S top	266	8.73	284	1.52	0.0003	3.30	0.031	305.97	0.020
	240	7.87	266	1.45	0.0003	2.55	0.016	155.56	0.011
	210	6.89	240	1.60	0.0008	7.51	0.014	136.32	0.009
	181	5.94	210	1.57	0.0001	1.36	0.011	108.19	0.007
	145	4.76	181	1.13	0.0002	2.08	0.015	151.27	0.013
	110	3.61	135	0.79	0.0007	6.57	0.032	315.92	0.040
	85	2.79	110	0.66	0.0003	3.35	0.008	80.40	0.012
	55	1.80	85	0.61	0.0009	8.61	0.012	119.58	0.020
	28	0.92	55	0.46	0.0006	5.53	0.006	57.14	0.012
17-MW-06S bottom	0	0.00	28	0.92	0.0027	26.87	0.011	107.19	0.012
			Average	**1.07**	**0.0007**	**6.77**	**0.015**	**153.75**	
17-MW-05S top	252	8.27	277	1.63	0.0000	0.00	0.005	54.02	0.003
	225	7.38	252	1.30	0.0001	0.89	0.007	73.40	0.006
	192	6.30	225	3.21	0.0001	0.89	0.025	254.29	0.008
	167	5.48	192	3.16	0.0001	1.36	0.021	210.28	0.007
	151	4.95	167	3.93	0.0004	3.87	0.022	217.50	0.006
	111	3.64	141	1.11	0.0000	0.00	0.009	93.36	0.008
	81	2.66	111	0.32	0.0000	0.00	0.008	79.27	0.025
	56	1.84	81	0.61	0.0000	0.04	0.009	94.17	0.015
	24	0.79	56	0.31	0.0000	0.00	0.006	61.33	0.020
17-MW-05S bottom	0	0.00	24	0.48	0.0001	0.54	0.008	79.36	0.017
			Average	**1.61**	**0.0001**	**0.76**	**0.012**	**121.70**	
		Background Average		**1.33**	**0.0004**	**3.70**	**0.029**	**290.60**	**0.023**
17-PS-1 top	263	8.63	289	0.75	0.0000	0.00	0.015	154.23	0.021
	234	7.68	263	1.66	0.0000	0.33	0.006	61.73	0.004
	204	6.69	234	1.66	0.0001	0.64	0.003	31.78	0.002
	176	5.77	204	0.88	0.0004	4.06	0.007	69.57	0.008
	147	4.82	176	2.11	0.0000	0.42	0.021	205.45	0.010
	106	3.48	137	1.33	0.0001	0.68	0.005	50.15	0.004
	84	2.76	106	2.78	0.0027	27.26	0.026	255.82	0.009
	55	1.80	84	0.57	0.0001	1.42	0.004	35.31	0.006
	28	0.92	55	0.72	0.0000	0.00	0.002	18.95	0.003
17-PS-1 bottom	0	0.00	28	0.78	0.0000	0.00	0.005	47.17	0.006
			Average	**1.32**	**0.0003**	**3.48**	**0.009**	**93.02**	
17-PS-2 top	264	8.66	289	0.81	0.0006	5.57	0.023	230.16	0.028
	237	7.78	264	1.63	0.0000	0.00	0.003	34.66	0.002
	202	6.63	237	1.59	0.0000	0.00	0.003	27.95	0.002
	173	5.68	202	1.49	0.0004	3.66	0.010	101.30	0.007
	148	4.86	173	2.12	0.0004	3.86	0.011	112.73	0.005
	111	3.64	138	3.11	0.0004	4.03	0.015	150.98	0.005
	87	2.85	111	3.57	0.0003	2.73	0.009	90.08	0.003
	60	1.97	87	0.81	0.0000	0.00	0.002	22.74	0.003
	33	1.08	60	1.59	0.0000	0.00	0.001	12.71	0.001
17-PS-2 bottom	0	0.00	33	1.58	0.0000	0.00	0.003	29.88	0.002
			Average	**1.83**	**0.0002**	**1.98**	**0.008**	**81.32**	
17-PS-3 top	267	8.76	283	1.00	0.0003	3.09	0.020	203.37	0.020
	240	7.87	267	1.61	0.0000	0.00	0.005	47.39	0.003
	213	6.99	240	0.85	0.0000	0.00	0.005	51.27	0.006
	182	5.97	213	2.96	0.0004	3.52	0.018	177.42	0.006
	160	5.25	182	2.77	0.0004	3.78	0.018	181.15	0.007
	124	4.07	150	2.06	0.0000	0.00	0.011	109.57	0.005
	96	3.15	124	1.67	0.0000	0.00	0.005	53.07	0.003
	68	2.23	96	3.37	0.0007	6.53	0.010	96.86	0.003
	39	1.28	68	1.92	0.0000	0.00	0.006	55.52	0.003
17-PS-3 bottom	0	0.00	39	0.99	0.0000	0.00	0.004	43.50	0.004
			Average	**1.92**	**0.0002**	**1.69**	**0.010**	**101.91**	
		Treatment Plot Average		**1.692**	**0.0002**	**2.387**	**0.009**	**92.082**	**0.006**

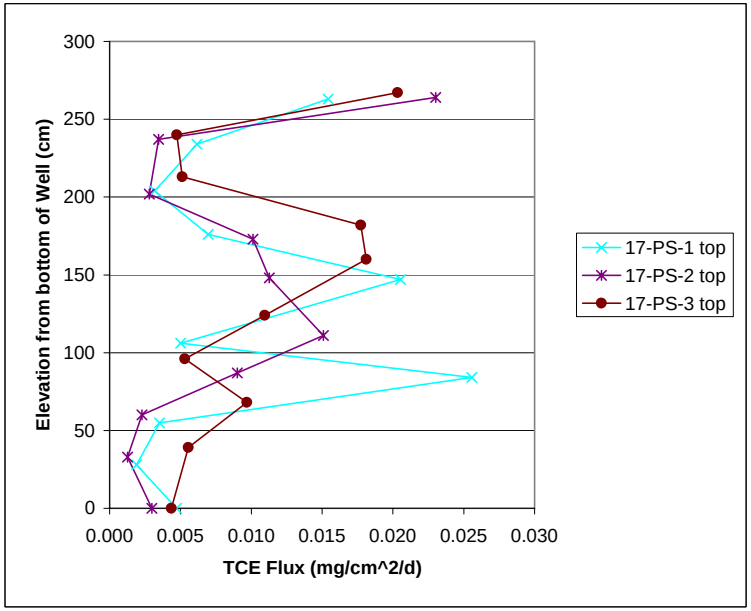
Figure VI-1.


May-04
Elevation from bottom of Well (cm)
300
250
200
150
100
50
0
0.000
0.005
0.010
0.015
0.020
0.025
0.030
Relative TCE Concentration
(TCE Flux / Darcy Velocity)
17-PS-1 top
17-PS-2 top
17-PS-3 top

Figures VI-2. Darcy Velocity and Mass Flux Calculations (May 2004)







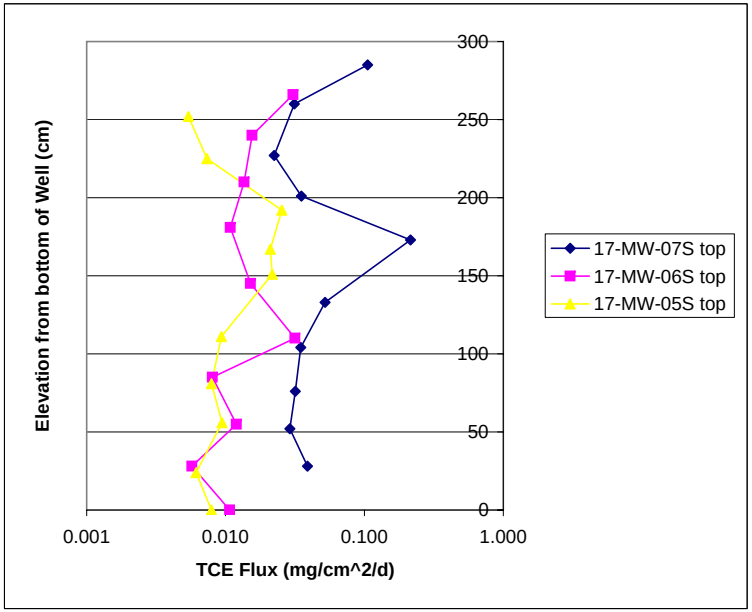


Table VI-2. Charleston NWS Passive Flux Meter Results (November 2007)					
Well ID	**Distance from bottom of well screen (ft)**	**Approx. Depth below top of well casing (ft)**	**Darcy Velocity (cm/day)**	**DCE flux ($mg/m^2/day$)**	**TCE flux ($mg/m^2/day$)**
PS-1	8.92	9.08	6.3	0	6.8
PS-1	8.08	9.92	5.3	0	4.6
PS-1	7.12	10.88	4.9	0	0
PS-1	6.13	11.87	5.5	0	0
PS-1	5.18	12.82	5.4	0	0
PS-1	4.02	13.98	5.5	0	0
PS-1	3.35	14.65	6.1	0	0
PS-1	2.56	15.44	6.1	0	0
PS-1	1.64	16.36	3.5	0	0
PS-1	0.51	17.49	3.3	0	3.5
PS-2	9.02	8.98	0.3	0	2.14
PS-2	8.12	9.88	0.3	0	0
PS-2	7.27	10.73	0.3	0	0
PS-2	6.37	11.63	0.3	0	0
PS-2	5.48	12.52	2.0	0	0
PS-2	4.33	13.67	4.2	0	0.75
PS-2	3.35	14.65	3.7	0	0.70
PS-2	2.48	15.52	6.6	0	1.71
PS-2	1.58	16.42	3.4	0	0.57
PS-2	0.72	17.28	3.6	0	0.61
PS-3	9.00	9.00	0.3	0	1.56
PS-3	8.11	9.89	0.3	0	0.66
PS-3	7.31	10.69	0.3	0	0.52
PS-3	6.47	11.53	1.2	0	0.29
PS-3	5.51	12.49	1.1	0	1.81
PS-3	4.38	13.62	3.8	0	1.50
PS-3	3.48	14.52	5.3	0	0.61
PS-3	2.47	15.53	5.9	0	1.50
PS-3	1.40	16.60	5.0	0	0.46
PS-3	0.53	17.47	4.8	0	1.68
		Average	**3.5**	**0**	**1.07**
MW5S	8.84	9.2	1.5	38.3	48.8
MW5S	7.83	10.2	1.4	75.5	145.4
MW5S	7.01	11.0	1.3	36.7	90.3
MW5S	6.15	11.8	1.6	30.2	183.6
MW5S	5.37	12.6	4.1	36.8	628.1
MW5S	4.25	13.7	1.8	88.4	223.9
MW5S	3.28	14.7	1.8	66.1	127.4
MW5S	2.41	15.6	1.8	62.5	138.2
MW5S	1.54	16.5	1.6	58.9	151.7
MW5S	0.67	17.3	1.4	33.3	90.2
MW6S	9.09	8.91	0.3	95.2	21.8
MW6S	8.20	9.80	0.3	28.1	17.5
MW6S	7.24	10.76	0.8	72.7	37.6
MW6S	6.31	11.69	1.1	156.7	54.3
MW6S	5.40	12.60	1.0	53.2	117.1
MW6S	4.27	13.73	1.7	39.5	39.7
MW6S	3.30	14.70	1.8	253.8	188.4
MW6S	2.40	15.60	0.3	86.2	74.0
MW6S	1.53	16.47	0.9	52.6	91.5
MW6S	0.63	17.37	0.9	21.7	65.3
MW7S	8.93	9.07	1.0	221.6	157.7
MW7S	7.86	10.14	0.3	57.1	36.2
MW7S	6.97	11.03	0.3	74.8	28.1
MW7S	6.17	11.83	0.6	72.0	73.5
MW7S	5.35	12.65	1.9	59.1	129.8
MW7S	4.50	13.50	0.6	151.1	54.7
MW7S	3.69	14.31	0.5	116.5	69.4
MW7S	2.63	15.37	1.7	129.2	166.2
MW7S	1.59	16.41	1.4	76.1	97.6
MW7S	0.71	17.29	1.3	48.1	144.6
		Average	**1.2**	**79.7**	**116.4**

Figures VI-3. Darcy Velocity Measurements (November 2007)

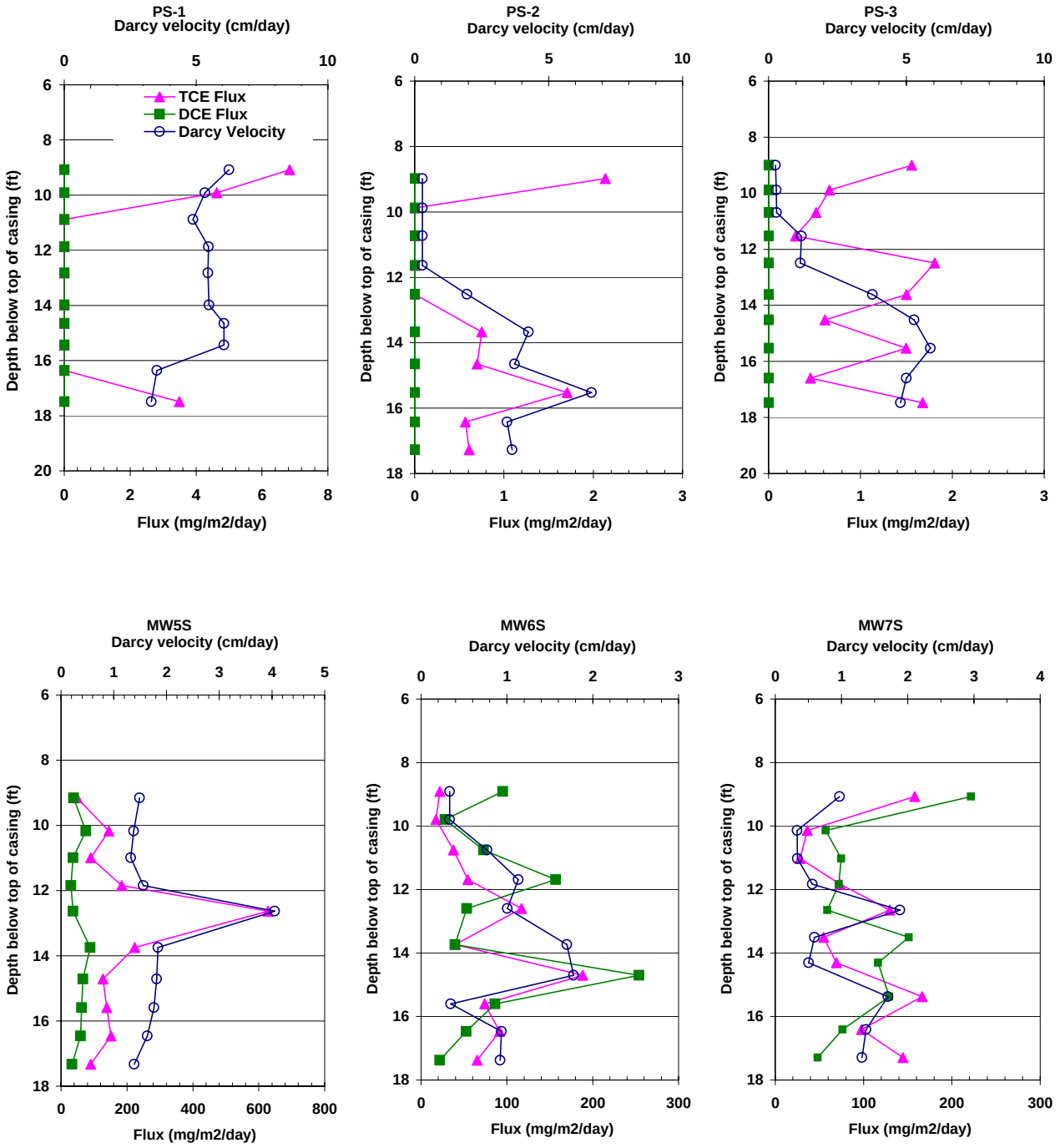
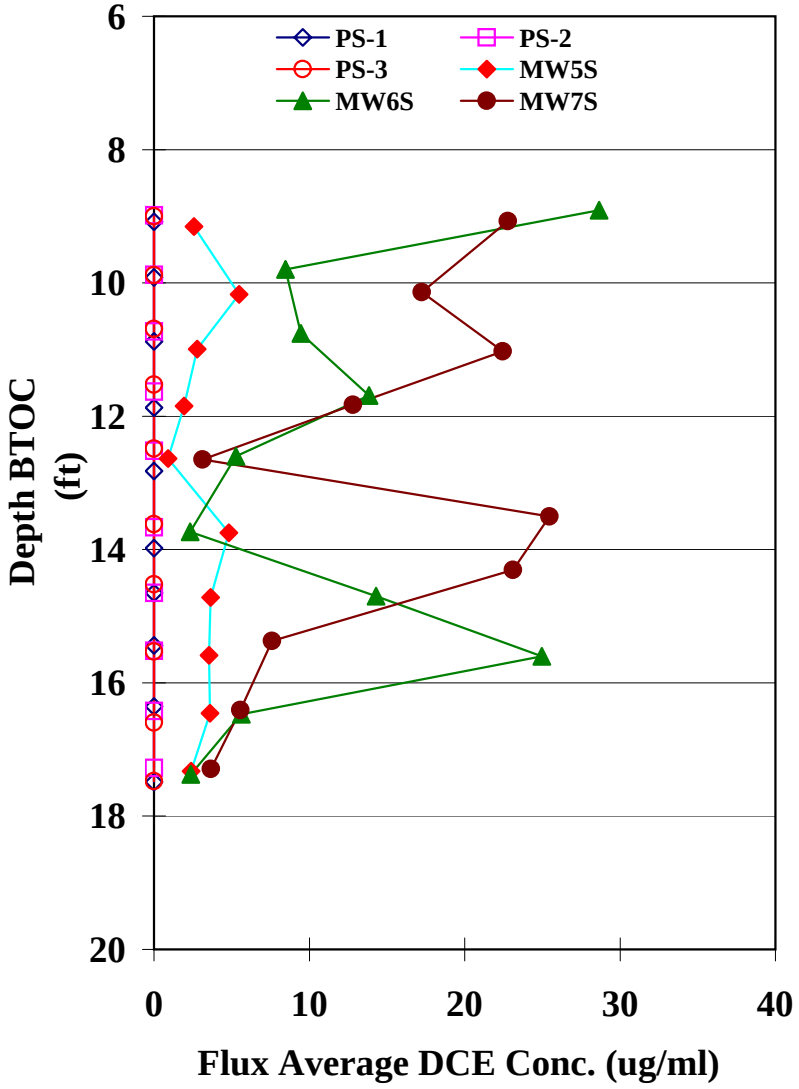
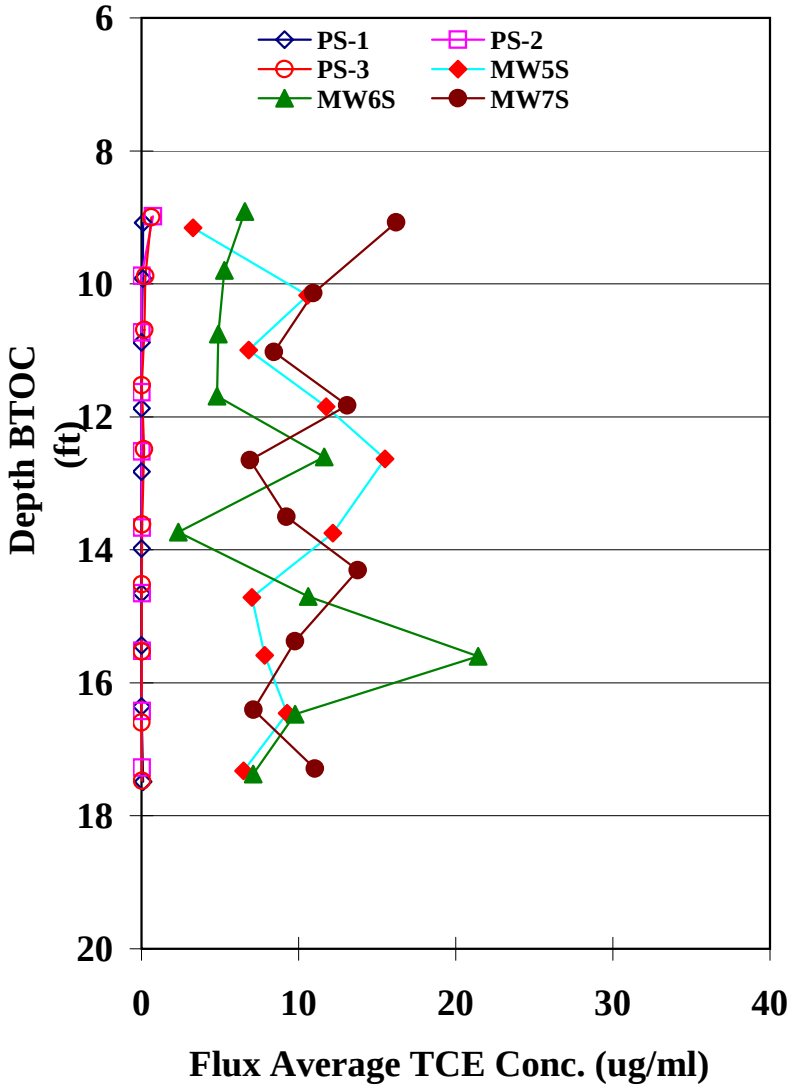


Figure VI-4. Mass Flux Calculations (November 2007)





APPENDIX VII

MICROBIAL ANALYSIS ANALYTICAL REPORTS

- **Table VII-1. Pre- and Post – Injection Soil DHC and PLFA Census Analyses**
- **Microbial Insights BDC Report, March 29, 2004**
- **Microbial Insights BDC Report, April 5, 2004**
- **SIREM DHC Report, April 19, 2004**
- **Microbial Insights PLFA Report, April 26, 2005**
- **Microbial Insights Census Report, October 23, 2007**

Table VII-1
Pre- and Post-Injection Soil DHC and PLFA Census Analyses
Naval Weapons Station
Charleston, SC

Sample Location	Sample Date	Sample Depth (ft bgs)	DHC (gene copies/ sample)
17PSI-01	3/1/04	0.5-4	NA
	3/1/04	5-8	NA
	3/1/04	9-12	NA
17PSI-04		5.5-6	NA
		12-14	NA
		14-16	NA
17PSI-13	3/1/04	4-6.5	NA
	3/1/04	6.5-7.75	NA
	3/1/04	15-16	NA
17PSI-16	3/1/04	6-8	NA
	3/1/04	9-11	NA
	3/1/04	16-18	NA
17PSI-02	3/25/04	8-10	NA
17PSI-03	3/25/04	10-12	NA
17PSI-05	3/25/04	8-10	NA
17PSI-06	3/25/04	8-9	NA
	3/25/04	9-10	NA
	3/25/04	10-11	NA
	3/25/04	11-12	NA
	3/25/04	12-13	NA
	3/25/04	13-14	NA
	3/25/04	14-15	NA
	3/25/04	15-16	NA
	3/25/04	16-17	NA
	3/25/04	17-18	NA
17PSI-07	3/24/04	10-16	< 5E+02
17PSI-08	3/24/04	10-12	NA
17PSI-09	3/25/04	16-18	NA
17PSI-14	3/24/04	12-14	NA
17PSI-15	3/24/04	10-11	NA
17PSI-16	3/24/04	6-8	NA
	3/24/04	8-12	NA

Sample Location	Sample Date	Sample Depth (ft bgs)	PLFA (cells/ml)
17PSSB-1	2/10/2005	10-12	3.09E+08
		16-18	NA
17PSSB-2	2/11/2005	16-18	NA
17PSSB-3	2/11/2005	16-18	NA
17PSSB-4	2/11/2005	10-12	5.05E+06
		16-18	1.62E+06
17PSSB-5	2/11/2005	10-12	2.21E+07
		16-18	NA
17PSSB-6	2/11/2005	10-12	NA
		16-18	2.87E+06

Sample Location	Sample Date	Sample Depth (ft bgs)	DHC (cells/g)
17PSSB-18	10/18/2007	9-11	<9.19E+02
17PSSB-19	10/18/2007	10-12	1.02E+03
	10/18/2007	14-16	3.87E+06
17PSSB-20	10/18/2007	10-12	4.75E+04

NA = Not Analyzed
ND = Not Detected

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Microbial Analysis Report

Client:	Christie Zowtocki Solutions IES 3722 Benson Drive Raleigh, NC 27609	Phone: Fax:	919-873-1060 919-873-1074

MI Identifier: 42BC Date Rec.: 03/26/04 Report Date: 03/29/04

Analysis Requested: BDC

Project: ESTCP NWS

Comments:

All samples within this data package were analyzed under U.S. EPA Good Laboratory Practice Standards: Toxic Substances Control Act (40 CFR part 790). All samples were processed according to standard operating procedures. Test results submitted in this data package meet the quality assurance requirements established by Microbial Insights, Inc.

Reported by: Reviewed by:

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Bio-Dechlor CENSUS

Overview of Approach

Nucleic acid technology allows for specific, sensitive detection of microorganisms from a variety of environments. Information can be obtained about the kinds of organisms present (phylogenetic assessment) and also about the specific capabilities of the organisms present (functional assessment). Thus, this technology has become an invaluable tool for detecting specific organisms and/or their functional genes. A limitation of one widely used nucleic acid technology, PCR, was that it was not quantitative. As technology advanced, this limitation has been overcome, and quantitative (real-time) PCR is now possible thorough the combined use of specialized PCR reagents (e.g., TaqMan) and refined instrumentation. Q-PCR is particularly useful for the bioremediation field because the population size (i.e., the number of particular organisms) can be determined, and so population changes can be tracked over time or in response to a treatment.

For this sample set, DNA was extracted from each sample using MoBio DNA extraction kits and analyzed for the following.

Target group/organism	Acronym	Description
Dehalococcoides spp.	DHC	Determines the concentration of a known dechlorinating bacteria

The results are presented in Table 1.

CENSUS Results:

Table 1. Quantitative Real time PCR (Q-PCR) was used to determine the number of *Dehalococcoides spp*. gene copies in DNA extracted from each sample.

		Dechlorinating Bacteria
		Dehalococcoides spp.[C,F]
Sample Name	Date Sampled	Abundance 16S rRNA genomes/gram
17PSI-7	03/19/04	ND
QA/QC Controls		
Positive Control		6.09E+06
Negative Control		Not Detected

[C] Assuming *Dehalococcoides ethenogenes* contains 1 rRNA operon per genome, the value given also may represent the number of cells per mL or g of sample for bacteria in this phylogenetic group.

[F] The practical quantitation limit (PQL) is ~$5*10^2$ 16S rRNA gene copies per sample.

ND = Not Detected

J = Estimated gene copies below PQL but above LQL

I = Inhibited

[1] Bio-Dechlor Census technology was developed by Dr. Loeffler and colleagues at Georgia Institute of Technology and was licensed for use through Regenesis.

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Microbial Analysis Report

Client: Christie Zowtocki
Solutions IES
3722 Benson Drive
Raleigh, NC 27609

Phone: 919-873-1060

Fax: 919-873-1074

MI Identifier: 2BD **Date Rec.:** 04/02/04 **Report Date:** 04/05/04

Analysis Requested: BDC

Project: ESTCP NWS

Comments:

All samples within this data package were analyzed under U.S. EPA Good Laboratory Practice Standards: Toxic Substances Control Act (40 CFR part 790). All samples were processed according to standard operating procedures. Test results submitted in this data package meet the quality assurance requirements established by Microbial Insights, Inc.

Reported by:

Reviewed by:

microbialinsights

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Bio-Dechlor CENSUS

Overview of Approach

Nucleic acid technology allows for specific, sensitive detection of microorganisms from a variety of environments. Information can be obtained about the kinds of organisms present (phylogenetic assessment) and also about the specific capabilities of the organisms present (functional assessment). Thus, this technology has become an invaluable tool for detecting specific organisms and/or their functional genes. A limitation of one widely used nucleic acid technology, PCR, was that it was not quantitative. As technology advanced, this limitation has been overcome, and quantitative (real-time) PCR is now possible thorough the combined use of specialized PCR reagents (e.g., TaqMan) and refined instrumentation. Q-PCR is particularly useful for the bioremediation field because the population size (i.e., the number of particular organisms) can be determined, and so population changes can be tracked over time or in response to a treatment.

For this sample set, DNA was extracted from each sample using MoBio DNA extraction kits and analyzed for the following.

Target group/organism	Acronym	Description
Dehalococcoides spp.	DHC	Determines the concentration of a known dechlorinating bacteria

The results are presented in Table 1.

CENSUS Results:

Table 1. Quantitative Real time PCR (Q-PCR) was used to determine the number of *Dehalococcoides spp.* gene copies in DNA extracted from each sample.

		Dechlorinating Bacteria
		Dehalococcoides spp.[C,F]
Sample Name	Date Sampled	Abundance 16S rRNA genomes/mL
17PSI-7	03/31/04	2.92 E+00
QA/QC Controls		
Positive Control		2.14 E+06
Negative Control		Not Detected

[C] Assuming *Dehalococcoides ethenogenes* contains 1 rRNA operon per genome, the value given also may represent the number of cells per mL or g of sample for bacteria in this phylogenetic group.

[F] The practical quantitation limit (PQL) is ~$5*10^2$ 16S rRNA gene copies per sample.

ND = Not Detected

J = Estimated gene copies below PQL but above LQL

I = Inhibited

[1] Bio-Dechlor Census technology was developed by Dr. Loeffler and colleagues at Georgia Institute of Technology and was licensed for use through Regenesis.

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DNA Analysis Report

Client: Tony Lieberman
Solutions IES
1101 Nowell Road
Raleigh, NC 27607

Phone: (919) 873-1060

Fax: (919) 873-1074

MI Identifier: 051EJ **Date Rec:** 10/18/2007 **Report Date:** 10/23/2007

Client Project #: 1130.02A3.ESTC Task 11 **Client Project Name:** NWS Charleston, SC

Purchase Order #: 1130.02A3.ESTC Task 11

Analysis Requested: CENSUS

Comments:

All samples within this data package were analyzed under U.S. EPA Good Laboratory Practice Standards: Toxic Substances Control Act (40 CFR part 790). All samples were processed according to standard operating procedures. Test results submitted in this data package meet the quality assurance requirements established by Microbial Insights, Inc.

Reported By: Anita Biernacki

Reviewed By: Lora M Eglo

MICROBIAL INSIGHTS, INC.

2340 Stock Creek Blvd. Rockford, TN 37853-3044
Tel: (865) 573-8188; Fax: (865) 573-8133

Q Potential (DNA)

Client: **Solutions IES**
Project: NWS Charleston, SC

MI Project Number: **051EJ**
Date Received: 10/18/2007

Sample Information

Client Sample ID:		**17-MW-6S**	**17-PSI-7**	**17-PSI-10**	**17-PS-2**	**17-PSSB-18 (9-11)**
Sample Date:		10/17/2007	10/17/2007	10/17/2007	10/17/2007	10/18/2007
Units:		cells/mL	cells/mL	cells/mL	cells/mL	cells/g
Dechlorinating Bacteria						
Dehalococcoides spp (1)	DHC	**8.21E+01**	**1.78E+05**	**1.28E+06**	**1.46E+05**	<9.19E+02
Dehalobacter spp.	DHB	**2.32E+04**	<2.22E+00	<2.5E+00	<2E+00	--
Functional Genes						
TCE R-Dase (1)	TCE	**1.51E+01**	**1.92E+04**	**1.18E+05**	**1.18E+04**	--
BAV1 VC R-Dase (1)	BVC	<5E-01	<1.11E+00	<1.25E+00	<1E+00	--
VC R-Dase	VCR	<5E-01	<1.11E+00	<1.25E+00	<1E+00	--

Legend:
NA = Not Analyzed NS = Not Sampled J = Estimated gene copies below PQL but above LQL I = Inhibited
< = Result not detected

Notes:
1 Bio-Dechlor Census technology was developed by Dr. Loeffler and colleagues at Georgia Institute of Technology and was licensed for use through Regenesis.

MICROBIAL INSIGHTS, INC.
2340 Stock Creek Blvd. Rockford, TN 37853-3044
Tel: (865) 573-8188; Fax: (865) 573-8133

Q Potential (DNA)

Client: **Solutions IES**
Project: NWS Charleston, SC

MI Project Number: **051EJ**
Date Received: 10/18/2007

Sample Information

Client Sample ID:		**17-PSSB-19 (10-12)**	**17-PSSB-20(10-12)**	**17-PSSB-19 (14-16)**
Sample Date:		10/18/2007	10/18/2007	10/18/2007
Units:		cells/g	cells/g	cells/g
Dechlorinating Bacteria				
Dehalococcoides spp (1)	DHC	**1.02E+03**	**4.75E+04**	**3.87E+06**

Legend:
NA = Not Analyzed NS = Not Sampled J = Estimated gene copies below PQL but above LQL I = Inhibited
< = Result not detected

Notes:
1 Bio-Dechlor Census technology was developed by Dr. Loeffler and colleagues at Georgia Institute of Technology and was licensed for use through Regenesis.

REPORT TO:

Reports will be provided to the contact(s) listed below. Parties other than the contact(s) listed below will require prior approval.

Name: Tony Lieberman
Company: Solutions-IES
Address: 1101 Nowell Rd
Raleigh NC 27607

email: tlieberman@solutions-ies.com
Phone: (919) 873-1060
Fax: ( )

Project Manager: Tony Lieberman
Project Name: NWS Charleston, SC
Project No.: 1130.02A3. ESTC TASK 11

INVOICE TO:

For Invoices **paid by a third party** it is imperative that contact information & corresponding reference No. be provided.

Name: MARY Howard
Company: Solutions-IES
Address:

email:
Phone: ( )
Fax: ( )

Purchase Order No. 1130.02A3. ESTC TASK 11
Subcontract No.

microbial insights

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Rockford, TN 37853-3044
phone (865) 573-8188
fax: (865) 573-8133
email: info@microbe.com
www.microbe.com

Please Check One:
X More samples to follow (Soil)
~~No~~ Additional Samples

Saturday Delivery
Please see sampling protocol for instructions

Report Type: X Standard (default) ☐ Comprehensive (15% surcharge) ☐ Historical (30% surcharge)

Please contact us prior to submitting samples regarding questions about the analyses you are requesting at (865) 573-8188 (8:00 am to 4:00 pm M-F). After these hours please call (865) 300-8053.

MI ID (Laboratory Use Only)	Sample Name	Date Sampled	Time Sampled	Matrix	PLFA	VFA	MEE	DGGE	DGGE		qDHC (Dehalococcoides)	DHC Functional genes	qDHB (Dehalobacter)	qDSM (Desulfuromonas)	qDSB (Desulfitobacterium)	qEBAC (Total)	qSRB	qSRB	qMGN (methanogens)	qMOB (methanotrophs)	qDNF (Denitrifying)	qAOB (ammonia oxidizing)	qPM1 (MTBE aerobic)	qTOD (total PAHs aerobic)	qCAT (Intermediate PAHs aerobic)	qBSS (Toluene/Xylene Anaerobic)	qNAH (Naphthalene aerobic)	add qPCR	add qPCR	add qPCR	RNA (Expression Option)*	Other	Other	Other	Other
051EJ 1	17-MW-6S 3	10-17	1320	W		X					X	X	X																						
2	17-PSI-7 5	↓	1425	↓		X					X	X	X																						
3	17-PSI-10 5	↓	1500	↓		X					X	X	X																						
~~4~~	~~13-PSI-13~~																																		
4	17-PS-2 3	↓	1600	↓		X					X	X	X																						

Relinquished by: [signature] Date: 10-17-07 Received by: Date:

In order for analysis to be completed correctly, it is vital that chain of custody is filled out correctly & that all relative information is provided. Failure to provide sufficient and/or correct information regarding reporting, invoicing & analyses requested information may result in delays for which MI will not be liable. *** additional cost and sample preservation are associated with RNA samples.**

REPORT TO:

Reports will be provided to the contact(s) listed below. Parties other than the contact(s) listed below will require prior approval.

Name: Tony Lieberman
Company: Solutions - IES
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email: tlieberman@solutions-ies.com
Phone: (919) 873-1060
Fax: ( )

Project Manager: Tony Lieberman
Project Name: NWS, Charleston, SC
Project No.: 1130.02A3.ESTC Task 11

INVOICE TO:

For invoices **paid by a third party** it is imperative that contact information & corresponding reference No. be provided.

Name: Mary Howard
Company: Solutions - IES
Address:
email:
Phone: ( )
Fax: ( )

Purchase Order No. 1130.02A3.ESTC Task 11
Subcontract No.

+ only run DHC

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email: info@microbe.com
www.microbe.com

Please Check One:

☐ More samples to follow
☒ No Additional Samples

Saturday Delivery
Please see sampling protocol for instructions

Report Type: ☒ Standard (default) ☐ Comprehensive (15% surcharge) ☐ Historical (30% surcharge)

Please contact us prior to submitting samples regarding questions about the analyses you are requesting at (865) 573-8188 (8:00 am to 4:00 pm M-F). After these hours please call (865) 300-8053.

Sample Information												Q-Targets: Prior to selecting targets mark either Q-Potential for DNA or Q-Expression for RNA																							
MI ID (Laboratory Use Only)	Sample Name	Date Sampled	Time Sampled	Matrix		VFA	MEE	DGGE+SD	DGGE+SD	Q-Potential (DNA)	Q-Expression (RNA)*	qDHC (Dehalococcoides)	qTCE R-Dase	qBAV1 VC R-Dase	qDHB (Dehalobacter)	qDSM (Desulfuromonas)	qDSB (Desulfitobacterium)	qEBAC (Total)	qDSR (SRBs only)	qSRB/SRB	qMGN (methanogens)	qMOB (methanotrophs)	qDNF (Denitrifying)	qAOB (ammonia oxidizing)	qPM1 (MTBE aerobic)	qTOD (Initial PAHs aerobic)	qNCAT (Intermediate PAHs aerobic)	qBSS (Toluene/Xylene Anaerobic)	qNAH (Naphthalene aerobic)	qPCR	qPCR	qPCR	Other	Other	Other
051EJ	~~17-PSSB-18~~ ( )			S								X																							
5	17-PSSB-18(9-11)	10-18	1005	↓								X																							
6	17-PSSB-17(10-12)	↓	1055	↓								X																							
7	17-PSSB-20(10-12)	↓	1140	↓								X																							
8	17-PSSB-19(14-16)	↓	1115	↓								X																							

Relinquished by: [signature] Date: 10/18/07 Received by: [signature] Date: 10/19/07

In order for analysis to be completed correctly, it is vital that chain of custody is filled out correctly & that all relative information is provided. Failure to provide sufficient and/or correct information regarding reporting, invoicing & analyses requested information may result in delays for which MI will not be liable. *** additional cost and sample preservation are associated with RNA samples.**

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Microbial Analysis Report

Client: Christie Zawtocki
Solutions IES
3722 Benson Drive
Raleigh, NC 27609

Phone: (919) 873-1060
Fax: (919) 873-1074
Email: czawtocki@solutions-ies.com

MI Identifier: 004CD Date Rec.: 04/01/05 Report Date: 04/26/05

Analysis Requested: PLFA

Project: ESTCP NWS Project #1130

Comments:

All samples within this data package were analyzed under U.S. EPA Good Laboratory Practice Standards: Toxic Substances Control Act (40 CFR part 790). All samples were processed according to standard operating procedures. Test results submitted in this data package meet the quality assurance requirements established by Microbial Insights, Inc.

Reported by: **Reviewed by:**

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Phone (865) 573-8188
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Email: info@microbe.com

Microbial Analysis Report

Results and Discussion

The microbial communities of five soil samples from the ESTCP NWS Project were characterized according to their phospholipid fatty acid composition (PLFA Analysis). Results from this analysis revealed the following key observations:

- Estimated viable biomass, based on total PLFA concentrations were lowest (~106 cells/gram dry weight) in samples 17-PSSB-4 10'-12', 17-PSSB-4 16'-18', and 17-PSSB-6 16'-18'. Biomass in 17-PSSB-5 10'-12' was ~10^7 cells/gram and ~10^8 cells/gram in sample 17-PSSB-1 10'-12'. In location 17-PSSB-4, which was sampled at two depths, biomass was highest at the most shallow depth. (Figure 1, Table 2)

- PLFA profiles showed that the microbial community structures varied considerably among the samples. The community in sample 17-PSSB-1 10'-12' was relatively simple, consisting primarily of Gram negative Proteobacteria, as shown by the proportion of monoenoic PLFA, which comprised over half of the total PLFA. This sample also contained ~19% of the total PLFA as biomarkers indicative of eukaryotes (polyenoic PLFA). Gram negative Proteobacteria were also the primary community member in sample 17-PSSB-6 16'-18' (~50% of the total PLFA).

- The four samples with more diverse microbial communities contained notable proportions of "anaerobic" biomarkers, including those for Firmicutes (terminally branched saturate PLFA), metal reducing bacteria (branched monoenoics) and sulfate reducing bacteria (mid-chain branched saturates). In samples from both depths of 17-PSSB-4, anaerobes accounted for ~15% of the total PLFA, while in 17-PSSB-6 16'-18' these biomarkers were ~10% of the PLFA. The highest proportion of anaerobes was seen in sample 17-PSSB-5 10'-12', in which over half of the PLFA was attributed to the presence of anaerobic members of the community. Among the particular types of anaerobes, Firmicutes (which include Clostridia-like fermenting bacteria) were the most abundant in all four samples. This data suggests that conditions in location 17-PSSB-5 10'-12' are considerably more anaerobic than conditions at the other sampling locations. Likewise, conditions at 17-PSSB-1 10'-12' are likely quite aerobic. The community structures of the samples from location 17-PSSB-4 were quite similar except that Gram negative Proteobacteria were slightly more abundant in the sample from the lower depth, while eukaryotes were 3-fold more abundant in the sample from the shallowest depth. (Figure 2, Table 2)

- The physiological status of the Gram negative Proteobacteria population was assessed through the ratios of key biomarkers indicative of slowed growth and also of decreased membrane permeability. Among these samples, three showed indications of slowed growth rate: sample 17-PSSB-1 10'-12' (moderate level); 17-PSSB-4 10'-12' (high level); and 17-PSSB-4 16'-18' (low level). It should be noted that this measure of slowed growth is comparative, and does not directly correspond to either stationary or log phases of growth. It is useful however for comparisons among sampling locations and over time. For example, in this data set, the Gram negative population is likely most slow growing in location 17-PSSB-4 10'-12'. Only sample 17-PSSB-1 10'-12' had a notable level decreased permeability of the cell membrane, and this was a relatively moderate level. (Figure 3, Table 2).

Overview of Approach

Examining the phospholipid fatty acids (PLFA) in environmental samples is an effective tool for monitoring microbial responses to their environment. They are essential components of the membranes of all cells (except for the Archea, a minor component of most environments), so their sum includes all important members of most microbial communities. PLFA analysis provides three types of information: biomass; community structure; and physiological status.

Biomass: PLFA analysis is the most reliable and accurate method available for the determination of viable microbial biomass. Phospholipids break down rapidly upon cell death (21, 23), so the PLFA biomass does not contain 'fossil' lipids of dead cells. The sum of the PLFA, expressed as picomoles (1 picomole = 1×10^{-12} mole), is proportional to the number of cells. The proportion used in this report, 20,000 cells/pmole, is taken from cells grown in laboratory media, and varies somewhat with type of organism and environmental conditions. Starving bacterial cells have the lowest cells/pmol, and healthy eukaryotic cells have the highest.

Community Structure: The PLFA in an environmental sample is the sum of the microbial community's PLFA, and reflects the proportions of different organisms in the sample. PLFA profiles are routinely used to classify bacteria and fungi (19) and are one of the characteristics used to describe new bacterial species (25). Broad phylogenic groups of microbes have different fatty acid profiles, making it possible to distinguish among them (4, 5, 22, 24). Table 1 describes the six major structural groups employed in this report.

Table 1. Description of PLFA structural groups.

PLFA Structural Group	General classification
Monoenoic (Monos)	Abundant in Proteobacteria (Gram negative bacteria), typically fast growing, utilize many carbon sources, and adapt quickly to a variety of environments.
Terminally Branched Saturated (TerBrSats)	Characteristic of Firmicutes (Low G+C Gram-positive bacteria), and also found in Bacteriodes, and some Gram-negative bacteria (especially anaerobes).
Branched Monoenoic (BrMonos)	Found in the cell membranes of micro-aerophiles and anaerobes, such as sulfate- or iron-reducing bacteria
Mid-Chain Branched Saturated (MidBrSats)	Common in Actinobacteria (High G+C Gram-positive bacteria), and some metal-reducing bacteria.
Normal Saturated (Nsats)	Found in all organisms.
Polyenoic	Found in eukaryotes such as fungi, protozoa, algae, higher plants, and animals.

Physiological status: The membrane of a microbe adapts to the changing conditions of its environment, and these changes are reflected in the PLFA. Toxic compounds or environmental conditions may disrupt the membrane and some bacteria respond by making *trans* fatty acids instead of the usual *cis* fatty acids (7) in order to strengthen the cell membrane.. Many Proteobacteria and other microbes respond to lack of available substrate or to highly toxic conditions by making cyclopropyl (7) or mid-chain branched fatty acids (20). The physiological status biomarkers for Decreased permeability (trans/cis ratio) and for slowed growth (cy/cis ratio) are based on dividing the amount of the fatty acid induced by environmental conditions by the amount of its biosynthetic precursor.

PLFA were analyzed by extraction of the total lipid (21) and then separation of the polar lipids by column chromatography (6). The polar lipid fatty acids were derivatized to fatty acid methyl esters, which were quantified using gas chromatography (15). Fatty acid structures were verified by chromatography/mass spectrometry and equivalent chain length analysis.

Figures and Tables

Phospholipid Fatty Acid Analysis

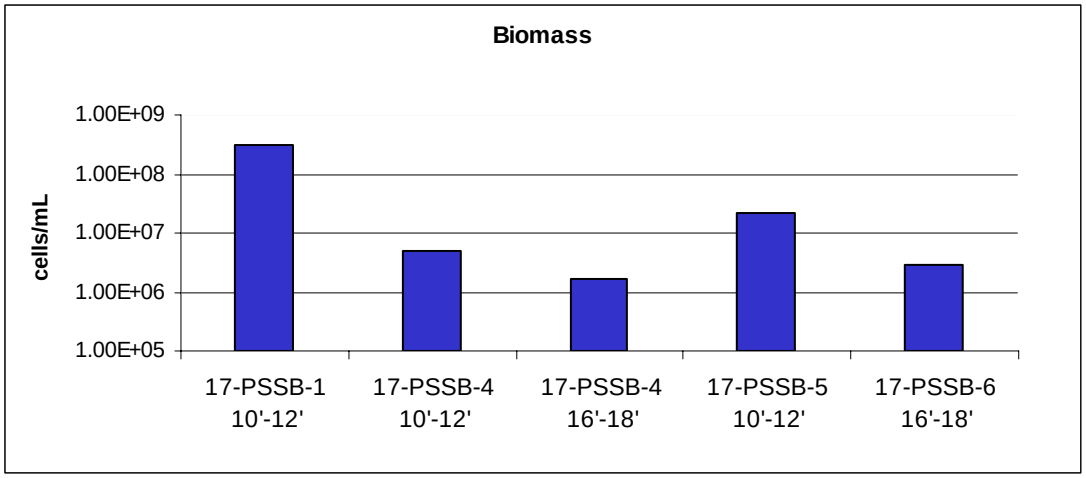

Figure 1. Biomass content is presented as a cell equivalent based on the total amount of phospholipid fatty acids (PLFA) extracted from a given sample. Total biomass is calculated based upon PLFA attributed to bacterial and eukaryotic biomass (associated with higher organisms).

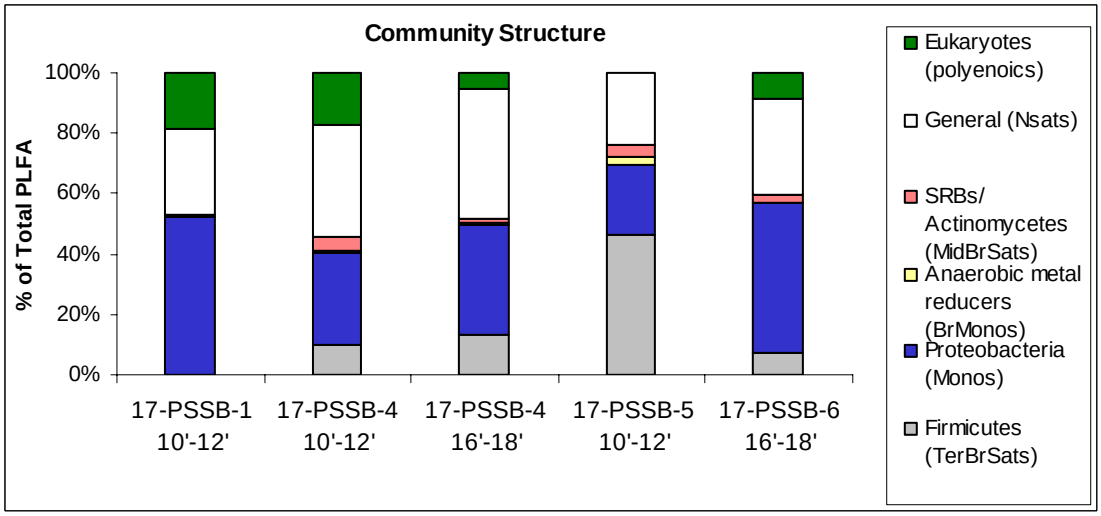

Figure 2. Relative percentages of total PLFA structural groups in the samples analyzed. Structural groups are assigned according to PLFA chemical structure, which is related to fatty acid biosynthesis. See Table 1 for detailed descriptions of structural groups.

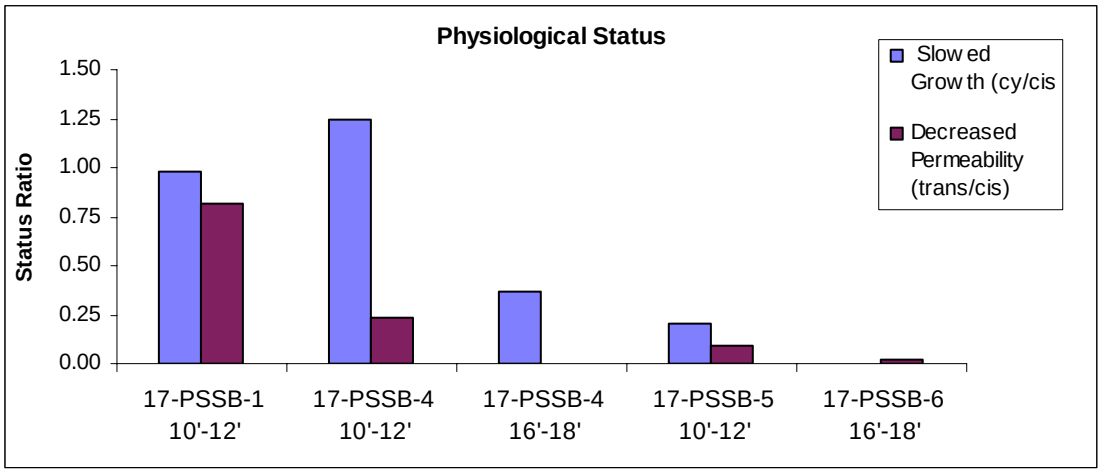

Figure 3. Microbial physiological stress markers. Slowed growth of the Gram-negative bacterial community is assessed by the ratios of cyclopropyl fatty acids to their metabolic precursors. Adaptation of the Gram-negative community to toxic stress through decreased membrane permeability is determined by the ratio of ω7t/ω7c fatty acids because Gram-negative bacteria generate *trans* fatty acids to minimize the permeability. Ratios (16:1ω7t/16:1ω7c and 18:1ω7t/18:1ω7c) greater than 0.25 have been shown to indicate an adaptation resulting in decreased membrane permeability.

Table 2. Values below are: viable microbial biomass (based on total PLFA content) is expressed as cells per mL or g of sample; fatty acid structural groups as percent of total PLFA; and physiological status biomarkers as mole ratio.

Sample		Biomass	Community Structure (% of total PLFA)						Physiological Status	
Sample Name	Sample Date	cells/mL	Firmicutes Anaerobic Gram Neg./ (TerBrSats)	Proteobacteria (Monos)	Anaerobic metal reducers (BrMonos)	SRBs/ Actinomycetes (MidBrSats)	General (Nsats)	Eukaryotes (polyenoics)	Starved cy/*cis*	Membrane Stress, *trans/cis*
17-PSSB-1 10'-12'	2/10/05	3.09E+08	0.3	51.8	0.2	0.4	28.8	18.5	0.98	0.82
17-PSSB-4 10'-12'	2/11/05	5.05E+06	10.2	30.2	0.9	4.0	37.1	17.5	1.25	0.24
17-PSSB-4 16'-18'	2/11/05	1.62E+06	13.0	37.0	0.6	1.0	43.4	5.1	0.37	0.00
17-PSSB-5 10'-12'	2/11/05	2.21E+07	46.6	23.3	2.7	4.0	23.3	0.3	0.20	0.09
17-PSSB-6 16'-18'	2/11/05	2.87E+06	7.5	49.6	0.0	2.8	31.6	8.5	0.00	0.02

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Test Results for Gene-Trac *Dehalococcoides* Assay

Customer Name: Solutions IES	**Test Reference Number:** DT-0169 **Shipment Reference Number:** S-0198, S-0201
Contact: Christie Zowtocki	**Report Issued:** 19-Apr-04
Site Location: ESTCP NWS	**Site Sampling:** 25-Mar-04, 01-Apr-04 **Sample(s) Received:** 31-Mar-04, 05-Apr-04 **DNA Extraction:** 31-Mar-04, 13-Apr-04
Telephone: (919) 873-1060	**Gel Image Numbers:** DHC-UP-0095, DHC-UP-0097, QIA-0034, AG-0198
Fax: (919) 873-1074	**Positive Control (+ve control):** Assay with Cloned *Dehalococcoides* 16S rRNA gene
E-mail: czawtocki@solutions-ies.com	**Negative Control (-ve control):** Assay with DNA extraction blank

Test Results:

Customer Sample ID	SiREM ID	Non-*Dehalococcoides* Bacterial DNA	*Dehalococcoides* Test, Intensity (% of Positive Control)	Intensity Score	Test Result: *Dehalococcoides* DNA
17PSi-7 (10-16)	DHC-0904	Not Detected	0%	-	Not Detected
17PSi-7	DHC-0927	Detected	0%	-	Not Detected
Not applicable	+ve control	Not applicable	100%	+++	Detected (3 of 3 primer sets)
Not applicable	-ve control	Not applicable	0%	-	Not Detected

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 three 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 tetrachloroethene or trichloroethene 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 may 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 (4-33%), -/+ = inconclusive (1-3%), - = no detectable band (0%)

Analyst: _____ **Reviewed by:** _____ **Date:** _____

Ximena Druar,
Laboratory Technologist

Philip Dennis, M.A.Sc.,
Technology Manager

Gene-Trac *Dehalococcoides* Case Narrative, Test DT-0169

Sample Condition:

SiREM received one -250 g soil sample from Solutions IES on 31-Mar-2004 and one-1L ground water sample on 05-Apr-04. The samples arrived in coolers with measured temperatures of 14.6 °C and 16.1°C respectively. Each sample was stored at 4°C upon arrival in the laboratory. The ground water sample was vacuum filtered for the preparation of the genomic DNA. Genomic DNA isolation was performed directly on the soil sample.

Sample Description:

Customer Sample ID	SiREM ID	*"Debris Description"	**Volume of Sample
17PSi-7 (10-16)	DHC-0904	Light brown sandy soil	0.5 g soil
17PSi-7	DHC-0927	Orange brown debris	1000 mL groundwater

Notes:

*"Debris" refers to solid material (including biomass) remaining after vacuum filtration of groundwater through a 0.45 µM filter.

** Varying amounts of groundwater may be used up to a maximum depending on the amount of debris recovered or the capacity of the filter prior to clogging, maximum is 1L.

Test Notes:

- Genomic DNA extraction was performed on the samples on 31-Mar-04 and 05-Apr-04.
- A PCR reaction using a universal bacterial primer was performed on both samples on 31-Mar-04, 07-Apr-04.
- The initial universal PCR for the soil sample was negative. DNA for this sample was further purified, and a second universal PCR was repeated. The second Universal PCR remained negative, indicating PCR amplifiable DNA was extracted only from the water sample.
- DHC specific PCR was performed on 12-Apr-04. All controls were normal, results included herein.

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Interpretation of Gene-Trac *Dehalococcoides* Test Results

Explanation of Test Certificate Results:

Upon completion of the Gene-Trac assay, the presence of *Dehalococcoides* DNA is assessed as either "Detected" or "Not Detected" based on interpretation of an electronic image of a DNA gel. Detects (gel bands) are then quantified using densitometry software and assigned a "band intensity percentage" using the relative intensity of the strongest bands obtained to the intensity of the positive control reaction. This value is in-turn used to assign a " Test intensity score" as follows:

- 0% of positive control "-" = Not Detected
- >0-1% of positive control "+/-" = Inconclusive
- >1-33% of positive control "+" = Detected
- >33-67% of positive control "++" = Detected
- >67-100% of positive control = "+++" Detected
- >100% of positive control = "++++" Detected
- Following a positive designation, the number of primer sets that effectively amplified sequences are listed. A test may be positive with 1 of 3, 2 of 3 or 3 of 3 primer sets.

Interpretation of Positive Results

Positive Gene-Trac test results ("*Dehalococcoides* DNA detected") indicate that genetic material from organisms belonging to the *Dehalococcoides* group was detected in site materials. A positive test result indicates favorable potential for complete dechlorination of chloroethene compounds.

Quantification: The strength of positive results is a parameter that can be useful in certain cases, but it must be noted, that Gene-Trac is only a semi-quantitative method and results are meant to be interpreted for presence or absence of *Dehalococcoides*. Customers may wish to use the semi-quantitative information provided by the test at their discretion. In general, the presence of a very high intensity score, for example, "++++" can be interpreted to represent a sample that has a higher concentration of *Dehalococcoides* organisms than a sample with a low intensity score of "+". Interpretation of less extreme differences between "+" and "++", for example, carries more uncertainty. If sampling is consistent between events, an increase in the intensity score might be used to assess an increase in the population density of *Dehalococcoides* over time.

The greater the number of primer sets that test positive for a particular sample (of the three used) provides increasing confidence that the characteristics of the organism detected is typical of *Dehalococcoides* organisms. Therefore, a positive test result which is "+++ (3 of 3 primer sets)" would be considered more indicative of a "typical" *Dehalococcoides* organism than would a result of "+++ (1 of 3 primers sets)". In certain cases where the concentration of *Dehalococcoides* DNA is very low (usually +), only the most efficient primer set produces Polymerize Chain Reaction (PCR) product. This scenario is not usually indicative of variants of *Dehalococcoides* organisms but rather the detection threshold of the less efficient primer sets.

Rule of thumb: high intensity scores with multiple primer sets e.g. ++++ (3 of 3 primers sets) provide the most conclusive results, while low intensity scores e.g. "+ (1 of 3 primer sets)", provide somewhat less conclusive evidence for the potential of indigenous organisms able to facilitate complete dechlorination to ethene.

Interpretation of Negative Result

Negative Gene-Trac results indicate that *Dehalococcoides* DNA was not detected in a sample. This indicates the site has a poor potential for complete dechlorination of chloroethene components. In certain cases, a negative test result may not indicate the absence of *Dehalococcoides* DNA at a site. For example:

1) The concentration of *Dehalococcoides* DNA may be below the detection limit of the assay. The detection limit for the assay is approximately 200-300 gene copies per liter, therefore, a very low level of *Dehalococcoides* DNA may not be detectable.

2) Due to sampling bias, a particular sample might not contain *Dehalococcoides* DNA, even at sites that contain this organism at other locations. Therefore, the absence of detectable *Dehalococcoides* DNA over several site samples is suggestive (but not conclusive) that *Dehalococcoides* organisms are absent from the entire site. Confidence in negative results is increased where a larger numbers of samples are assessed and where "non- *Dehalococcoides* Bacterial DNA" is detected in these samples. This indicates that DNA was successfully extracted from the samples but that *Dehalococcoides* DNA was not detectable. It might occur, that no DNA is extractable from a sample, simply because a particular sample contains no biomass and not because *Dehalococcoides* is actually absent from the site.

Rule of thumb: negative *Dehalococcoides* test results obtained where numerous samples are taken and where "non-*Dehalococcoides*" Bacterial DNA is detected, are more conclusive than negative results where few samples are tested and where Bacterial DNA is not detected.

APPENDIX VIII

DESIGN TOOL SUMMARY SHEETS FOR VARIOUS SCENARIOS

Area Treatment Using a Series of Barriers - Selected Design

This sheet shows a summary of the selected design that can be saved or printed before looking at alternative designs.

1 *Site Information*

a	Name	Scenario 1: Base Case (50 X 50 X 25)	
b	Description (e.g., project number)	0	
c	Location	0	
d	Maximum Oil Retention	0.009	lbs oil/lbs soil

2 *Treatment Design Criteria*

a	Reinjection Interval	4	years
b	Timeframe in which all groundwater in targeted area should theoretically flush through active treatment zones.	7	years

3 *Well Layout*

a	Well Spacing	10	ft	3.05	m
b	Number of Wells per Row	5	wells/row		
c	Row Spacing	10	ft	3.05	m
d	Number of Rows	5	rows		
e	Total Number of Wells	25	wells		

4 *Logistics for Each Injection Event*

a	Total Mass of Oil Injected	7,140	lbs	3,239	kg
b	Total Injection Volume	13,465	gallons	50,970	L
c	Total Injection Volume per well	539	gal/well	2,039	L/well
d	Estimated Injection Rate	0.3	gpm/well		
e	Number of wells injected simultaneously	10	wells		

5 *Costs for Initial Installation and Injection*

a	Fixed Costs (planning and installation)	$65,000
b	Well Installation Costs	$35,500
c	Injection Costs	$14,900
d	Substrate Costs	$29,155
e	Total Installation and Injection Costs	$144,555

6 *Costs for Future Injection Events*

a	Fixed Costs (engineering and installation)	$10,000
b	Well Rehabilitation and/or Installation Costs	$8,875
c	Labor Cost for Injection	$14,900
d	Substrate Costs	$29,155
e	Total Installation and Injection Costs	$62,930

7 *Total Life Cycle Costs*

a	Annual Interest Rate	4%
b	Monitoring and Reporting	$90,031
c	Total Injection Costs (fixed, well installation, labor for injection, and substrate)	$198,348
d	Project Life NPV	$288,379

8 *Design Parameters*

a	Volume Scaling Factor	0.5		
b	Mass Scaling Factor	0.5		
c	Estimated Contact Efficiency for Injection	40%	to	54%

Area Treatment Using a Series of Barriers - Selected Design

This sheet shows a summary of the selected design that can be saved or printed before looking at alternative designs.

1 *Site Information*

a	Name	Scenario 2: Base Case Vol. + Low Oil Ret.=.005 g/	
b	Description (e.g., project number)	0	
c	Location	0	
d	Maximum Oil Retention	0.005	lbs oil/lbs soil

2 *Treatment Design Criteria*

a	Reinjection Interval	4	years
b	Timeframe in which all groundwater in targeted area should theoretically flush through active treatment zones.	7	years

3 *Well Layout*

a	Well Spacing	10	ft	3.05	m
b	Number of Wells per Row	5	wells/row		
c	Row Spacing	10	ft	3.05	m
d	Number of Rows	5	rows		
e	Total Number of Wells	25	wells		

4 *Logistics for Each Injection Event*

a	Total Mass of Oil Injected	4,200	lbs	1,905	kg
b	Total Injection Volume	13,465	gallons	50,970	L
c	Total Injection Volume per well	539	gal/well	2,039	L/well
d	Estimated Injection Rate	0.3	gpm/well		
e	Number of wells injected simultaneously	10	wells		

5 *Costs for Initial Installation and Injection*

a	Fixed Costs (planning and installation)	$65,000
b	Well Installation Costs	$35,500
c	Injection Costs	$14,900
d	Substrate Costs	$17,150
e	Total Installation and Injection Costs	$132,550

6 *Costs for Future Injection Events*

a	Fixed Costs (engineering and installation)	$10,000
b	Well Rehabilitation and/or Installation Costs	$8,875
c	Labor Cost for Injection	$14,900
d	Substrate Costs	$17,150
e	Total Installation and Injection Costs	$50,925

7 *Total Life Cycle Costs*

a	Annual Interest Rate	4%
b	Monitoring and Reporting	$90,031
c	Total Injection Costs (fixed, well installation, labor for injection, and substrate)	$176,081
d	Project Life NPV	$266,112

8 *Design Parameters*

a	Volume Scaling Factor	0.5		
b	Mass Scaling Factor	0.5		
c	Estimated Contact Efficiency for Injection	40%	to	54%

Area Treatment Using a Series of Barriers - Selected Design

This sheet shows a summary of the selected design that can be saved or printed before looking at alternative designs.

1 *Site Information*

a	Name	Scenario 3: Small Source Area (25 x 25 x 25)	
b	Description (e.g., project number)	0	
c	Location	0	
d	Maximum Oil Retention	0.009	lbs oil/lbs soil

2 *Treatment Design Criteria*

a	Reinjection Interval	4	years
b	Timeframe in which all groundwater in targeted area should theoretically flush through active treatment zones.	7	years

3 *Well Layout*

a	Well Spacing	8	ft	2.29	m
b	Number of Wells per Row	4	wells/row		
c	Row Spacing	7.5	ft	2.29	m
d	Number of Rows	4	rows		
e	Total Number of Wells	16	wells		

4 *Logistics for Each Injection Event*

a	Total Mass of Oil Injected	1,785	lbs	810	kg
b	Total Injection Volume	3,366	gallons	12,743	L
c	Total Injection Volume per well	210	gal/well	796	L/well
d	Estimated Injection Rate	0.3	gpm/well		
e	Number of wells injected simultaneously	8	wells		

5 *Costs for Initial Installation and Injection*

a	Fixed Costs (planning and installation)	$65,000
b	Well Installation Costs	$22,720
c	Injection Costs	$5,960
d	Substrate Costs	$7,289
e	Total Installation and Injection Costs	$100,969

6 *Costs for Future Injection Events*

a	Fixed Costs (engineering and installation)	$10,000
b	Well Rehabilitation and/or Installation Costs	$5,680
c	Labor Cost for Injection	$5,960
d	Substrate Costs	$7,289
e	Total Installation and Injection Costs	$28,929

7 *Total Life Cycle Costs*

a	Annual Interest Rate	4%
b	Monitoring and Reporting	$60,021
c	Total Injection Costs (fixed, well installation, labor for injection, and substrate)	$125,697
d	Project Life NPV	$185,718

8 *Design Parameters*

a	Volume Scaling Factor	0.5		
b	Mass Scaling Factor	0.5		
c	Estimated Contact Efficiency for Injection	40%	to	54%

Area Treatment Using a Series of Barriers - Selected Design

This sheet shows a summary of the selected design that can be saved or printed before looking at alternative designs.

1 *Site Information*

a	Name	Scenario 4: Mid-Size Area; Large Vol (100x100x25	
b	Description (e.g., project number)	0	
c	Location	0	
d	Maximum Oil Retention	0.009	lbs oil/lbs soil

2 *Treatment Design Criteria*

a	Reinjection Interval	4	years
b	Timeframe in which all groundwater in targeted area should theoretically flush through active treatment zones.	7	years

3 *Well Layout*

a	Well Spacing	10	ft	3.05	m
b	Number of Wells per Row	10	wells/row		
c	Row Spacing	10	ft	3.05	m
d	Number of Rows	10	rows		
e	Total Number of Wells	100	wells		

4 *Logistics for Each Injection Event*

a	Total Mass of Oil Injected	28,560	lbs	12,955	kg
b	Total Injection Volume	53,860	gallons	203,881	L
c	Total Injection Volume per well	539	gal/well	2,039	L/well
d	Estimated Injection Rate	0.3	gpm/well		
e	Number of wells injected simultaneously	10	wells		

5 *Costs for Initial Installation and Injection*

a	Fixed Costs (planning and installation)	$68,750
b	Well Installation Costs	$142,000
c	Injection Costs	$59,600
d	Substrate Costs	$116,620
e	Total Installation and Injection Costs	$386,970

6 *Costs for Future Injection Events*

a	Fixed Costs (engineering and installation)	$13,750
b	Well Rehabilitation and/or Installation Costs	$35,500
c	Labor Cost for Injection	$59,600
d	Substrate Costs	$116,620
e	Total Installation and Injection Costs	$225,470

7 *Total Life Cycle Costs*

a	Annual Interest Rate	4%
b	Monitoring and Reporting	$240,082
c	Total Injection Costs (fixed, well installation, labor for injection, and substrate)	$579,703
d	Project Life NPV	$819,785

8 *Design Parameters*

a	Volume Scaling Factor	0.5		
b	Mass Scaling Factor	0.5		
c	Estimated Contact Efficiency for Injection	40%	to	54%

Area Treatment Using a Series of Barriers - Selected Design

This sheet shows a summary of the selected design that can be saved or printed before looking at alternative designs.

1 *Site Information*

a	Name	Scenario 5: Base Volume w/ Groundwater @ 105	
b	Description (e.g., project number)	0	
c	Location	0	
d	Maximum Oil Retention	0.009	lbs oil/lbs soil

2 *Treatment Design Criteria*

a	Reinjection Interval	4	years
b	Timeframe in which all groundwater in targeted area should theoretically flush through active treatment zones.	7	years

3 *Well Layout*

a	Well Spacing	10	ft	3.05	m
b	Number of Wells per Row	5	wells/row		
c	Row Spacing	10	ft	3.05	m
d	Number of Rows	5	rows		
e	Total Number of Wells	25	wells		

4 *Logistics for Each Injection Event*

a	Total Mass of Oil Injected	7,140	lbs	3,239	kg
b	Total Injection Volume	13,465	gallons	50,970	L
c	Total Injection Volume per well	539	gal/well	2,039	L/well
d	Estimated Injection Rate	1.0	gpm/well		
e	Number of wells injected simultaneously	10	wells		

5 *Costs for Initial Installation and Injection*

a	Fixed Costs (planning and installation)	$73,500
b	Well Installation Costs	$106,625
c	Injection Costs	$5,790
d	Substrate Costs	$29,155
e	Total Installation and Injection Costs	$215,070

6 *Costs for Future Injection Events*

a	Fixed Costs (engineering and installation)	$18,500
b	Well Rehabilitation and/or Installation Costs	$26,656
c	Labor Cost for Injection	$5,790
d	Substrate Costs	$29,155
e	Total Installation and Injection Costs	$80,101

7 *Total Life Cycle Costs*

a	Annual Interest Rate	4%
b	Monitoring and Reporting	$90,031
c	Total Injection Costs (fixed, well installation, labor for injection, and substrate)	$283,541
d	Project Life NPV	$373,572

8 *Design Parameters*

a	Volume Scaling Factor	0.5		
b	Mass Scaling Factor	0.5		
c	Estimated Contact Efficiency for Injection	40%	to	54%

Area Treatment Using a Series of Barriers - Selected Design

This sheet shows a summary of the selected design that can be saved or printed before looking at alternative designs.

1 *Site Information*

a	Name	Scenario 6: Base Area; 10 ft Thickness; deep gw	
b	Description (e.g., project number)	0	
c	Location	0	
d	Maximum Oil Retention	0.009	lbs oil/lbs soil

2 *Treatment Design Criteria*

a	Reinjection Interval	4	years
b	Timeframe in which all groundwater in targeted area should theoretically flush through active treatment zones.	7	years

3 *Well Layout*

a	Well Spacing	10	ft	3.05	m
b	Number of Wells per Row	5	wells/row		
c	Row Spacing	10	ft	3.05	m
d	Number of Rows	5	rows		
e	Total Number of Wells	25	wells		

4 *Logistics for Each Injection Event*

a	Total Mass of Oil Injected	2,856	lbs	1,295	kg
b	Total Injection Volume	5,386	gallons	20,388	L
c	Total Injection Volume per well	215	gal/well	816	L/well
d	Estimated Injection Rate	1.0	gpm/well		
e	Number of wells injected simultaneously	10	wells		

5 *Costs for Initial Installation and Injection*

a	Fixed Costs (planning and installation)	$73,500
b	Well Installation Costs	$56,625
c	Injection Costs	$8,190
d	Substrate Costs	$11,662
e	Total Installation and Injection Costs	$149,977

6 *Costs for Future Injection Events*

a	Fixed Costs (engineering and installation)	$18,500
b	Well Rehabilitation and/or Installation Costs	$14,156
c	Labor Cost for Injection	$8,190
d	Substrate Costs	$11,662
e	Total Installation and Injection Costs	$52,508

7 *Total Life Cycle Costs*

a	Annual Interest Rate	4%
b	Monitoring and Reporting	$90,031
c	Total Injection Costs (fixed, well installation, labor for injection, and substrate)	$194,861
d	Project Life NPV	$284,892

8 *Design Parameters*

a	Volume Scaling Factor	0.5		
b	Mass Scaling Factor	0.5		
c	Estimated Contact Efficiency for Injection	40%	to	54%

Area Treatment Using a Series of Barriers - Selected Design

This sheet shows a summary of the selected design that can be saved or printed before looking at alternative designs.

1 *Site Information*

a	Name	Scenario 7: Base Area; 50 ft Sat'd Thickness	
b	Description (e.g., project number)	0	
c	Location	0	
d	Maximum Oil Retention	0.009	lbs oil/lbs soil

2 *Treatment Design Criteria*

a	Reinjection Interval	4	years
b	Timeframe in which all groundwater in targeted area should theoretically flush through active treatment zones.	7	years

3 *Well Layout*

a	Well Spacing	10	ft	3.05	m
b	Number of Wells per Row	5	wells/row		
c	Row Spacing	10	ft	3.05	m
d	Number of Rows	5	rows		
e	Total Number of Wells	25	wells		

4 *Logistics for Each Injection Event*

a	Total Mass of Oil Injected	14,280	lbs	6,477	kg
b	Total Injection Volume	26,930	gallons	101,940	L
c	Total Injection Volume per well	1,077	gal/well	4,078	L/well
d	Estimated Injection Rate	1.0	gpm/well		
e	Number of wells injected simultaneously	10	wells		

5 *Costs for Initial Installation and Injection*

a	Fixed Costs (planning and installation)	$73,500
b	Well Installation Costs	$62,875
c	Injection Costs	$9,650
d	Substrate Costs	$58,310
e	Total Installation and Injection Costs	$204,335

6 *Costs for Future Injection Events*

a	Fixed Costs (engineering and installation)	$18,500
b	Well Rehabilitation and/or Installation Costs	$15,719
c	Labor Cost for Injection	$9,650
d	Substrate Costs	$58,310
e	Total Installation and Injection Costs	$102,179

7 *Total Life Cycle Costs*

a	Annual Interest Rate	4%
b	Monitoring and Reporting	$90,031
c	Total Injection Costs (fixed, well installation, labor for injection, and substrate)	$291,678
d	Project Life NPV	$381,709

8 *Design Parameters*

a	Volume Scaling Factor	0.5		
b	Mass Scaling Factor	0.5		
c	Estimated Contact Efficiency for Injection	40%	to	54%

Area Treatment Using a Series of Barriers - Selected Design

This sheet shows a summary of the selected design that can be saved or printed before looking at alternative designs.

1 *Site Information*

a	Name	Scenario 8 Lg Area; Lg Vol. (100 x 200 x 25)	
b	Description (e.g., project number)	0	
c	Location	Charleston, SC	
d	Maximum Oil Retention	0.009	lbs oil/lbs soil

2 *Treatment Design Criteria*

a	Reinjection Interval	4	years
b	Timeframe in which all groundwater in targeted area should theoretically flush through active treatment zones.	7	years

3 *Well Layout*

a	Well Spacing	10	ft	3.05	m
b	Number of Wells per Row	20	wells/row		
c	Row Spacing	10	ft	3.05	m
d	Number of Rows	10	rows		
e	Total Number of Wells	200	wells		

4 *Logistics for Each Injection Event*

a	Total Mass of Oil Injected	57,120	lbs	25,909	kg
b	Total Injection Volume	107,719	gallons	407,762	L
c	Total Injection Volume per well	539	gal/well	2,039	L/well
d	Estimated Injection Rate	0.3	gpm/well		
e	Number of wells injected simultaneously	10	wells		

5 *Costs for Initial Installation and Injection*

a	Fixed Costs (planning and installation)	$71,750
b	Well Installation Costs	$162,000
c	Injection Costs	$119,200
d	Substrate Costs	$233,240
e	Total Installation and Injection Costs	$586,190

6 *Costs for Future Injection Events*

a	Fixed Costs (engineering and installation)	$16,750
b	Well Rehabilitation and/or Installation Costs	$40,500
c	Labor Cost for Injection	$119,200
d	Substrate Costs	$233,240
e	Total Installation and Injection Costs	$409,690

7 *Total Life Cycle Costs*

a	Annual Interest Rate	5%
b	Monitoring and Reporting	$235,708
c	Total Injection Costs (fixed, well installation, labor for injection, and substrate)	$929,740
d	Project Life NPV	$1,165,448

8 *Design Parameters*

a	Volume Scaling Factor	0.5		
b	Mass Scaling Factor	0.5		
c	Estimated Contact Efficiency for Injection	40%	to	54%

Area Treatment Using a Series of Barriers - Selected Design

This sheet shows a summary of the selected design that can be saved or printed before looking at alternative designs.

1 *Site Information*

a	Name	SWMU 17 Fullscale Estimate with Buffered EOS	
b	Description (e.g., project number)	1130	
c	Location	Charleston, SC	
d	Maximum Oil Retention	0.009	lbs oil/lbs soil

2 *Treatment Design Criteria*

a	Reinjection Interval	4	years
b	Timeframe in which all groundwater in targeted area should theoretically flush through active treatment zones.	7	years

3 *Well Layout*

a	Well Spacing	10	ft	3.05	m
b	Number of Wells per Row	20	wells/row		
c	Row Spacing	10	ft	3.05	m
d	Number of Rows	10	rows		
e	Total Number of Wells	200	wells		

4 *Logistics for Each Injection Event*

a	Total Mass of Oil Injected	22,848	lbs	10,364	kg
b	Total Injection Volume	43,088	gallons	163,105	L
c	Total Injection Volume per well	215	gal/well	816	L/well
d	Estimated Injection Rate	0.3	gpm/well		
e	Number of wells injected simultaneously	10	wells		

5 *Costs for Initial Installation and Injection*

a	Fixed Costs (planning and installation)	$71,750
b	Well Installation Costs	$162,000
c	Injection Costs	$59,600
d	Substrate Costs	$197,064
e	Total Installation and Injection Costs	$490,414

6 *Costs for Future Injection Events*

a	Fixed Costs (engineering and installation)	$16,750
b	Well Rehabilitation and/or Installation Costs	$40,500
c	Labor Cost for Injection	$59,600
d	Substrate Costs	$197,064
e	Total Installation and Injection Costs	$313,914

7 *Total Life Cycle Costs*

a	Annual Interest Rate	4%
b	Monitoring and Reporting	$240,082
c	Total Injection Costs (fixed, well installation, labor for injection, and substrate)	$758,749
d	Project Life NPV	$998,831

8 *Design Parameters*

a	Volume Scaling Factor	0.5		
b	Mass Scaling Factor	0.5		
c	Estimated Contact Efficiency for Injection	40%	to	54%