



Shaw Environmental, Inc.

2790 Mosside Boulevard  
Monroeville, PA 15146  
412.372.7701  
Fax: 412.372.7135

October 16, 2007

Ms. Marilyn Czimer Long, P.G.  
Texas Commission on Environmental Quality  
MC-136  
State Lead Section  
12100 Park 35 Circle  
Austin, TX 78753

Subject: **Final Treatability Study Report for  
Jones Road Groundwater Plume Federal Superfund Site  
Houston, Harris County, Texas  
Shaw Project Number 128885**

Dear Ms. Long:

Enclosed are three copies of the above referenced report. Shaw Environmental, Inc. (Shaw) incorporated TCEQ and EPA comments into this final version of the report. A hard copy of this report was also sent to Mr. Gary Baumgarten of EPA Region 6. An electronic version of this report, minus the CD with the raw analytical data reports, was e-mailed to the distribution on this letter.

If you have any questions or comments, please feel free to call me at (412) 858-3309.

Very truly yours,

A handwritten signature in blue ink that reads "Richard B. Wice".

Richard B. Wice, P.G., CHMM  
Senior Project Hydrogeologist

RBW/bam

cc: Gary Baumgarten, EPA Region 6  
Subash Pal, TCEQ  
Russell Perry, Shaw  
Project File 128885

**FINAL  
TREATABILITY STUDY REPORT  
for  
JONES ROAD GROUNDWATER PLUME FEDERAL SUPERFUND SITE  
HOUSTON, HARRIS COUNTY, TEXAS**

**Shaw's Project No. 128885**

**Prepared for:**

**State Lead Section  
Remediation Division  
Texas Commission on Environmental Quality**

**Prepared by:**



**Shaw Environmental, Inc.  
3010 Briarpark Drive, Suite 400  
Houston, Texas 77042**

**October 2007**

## ***Table of Contents***

---

LIST OF FIGURES .....	II
LIST OF TABLES .....	II
LIST OF APPENDICES .....	II
EXECUTIVE SUMMARY .....	1
1.0 INTRODUCTION .....	1-1
1.1 Site Description .....	1-1
1.2 Study Objectives .....	1-2
1.3 Treatability Study Sample Collection .....	1-2
2.0 TREATMENT TECHNOLOGY DESCRIPTION.....	2-1
2.1 Permanganate Oxidation.....	2-1
2.2 Activated Persulfate Oxidation .....	2-2
2.3 Technology Description of Bioaugmentation, Biostimulation, and Abiotic Treatment Using ZVI.....	2-3
3.0 ISCO TREATMENT STUDY .....	3-1
3.1 Sample Preparation and Chemicals .....	3-1
3.2 Soil Oxidant Demand Testing.....	3-1
3.3 Oxidation Effectiveness Tests .....	3-2
3.4 Sample Characterization Results .....	3-4
3.5 Soil Oxidant Demand Results.....	3-4
3.6 Batch Slurry Test Results .....	3-5
3.7 Conclusions and Recommendations .....	3-8
4.0 BIOSTIMULATION, BIOAUGMENTATION, AND ZVI TREATMENT STUDY.....	4-1
4.1 Materials and Methods .....	4-1
4.2 Results and Discussion .....	4-3
4.3 Conclusions.....	4-8
5.0 CONCLUSION AND RECOMMENDATION.....	5-1
6.0 REFERENCES .....	6-1

## List of Figures

---

Figure 1-1	Site Plan – Jones Road Site
Figure 3-1	PCE Concentration Change Over Time In FeEDTA Activated Persulfate Oxidation
Figure 4-1	PCE Levels in Biostimulation and Bioaugmentation Microcosms

## List of Tables

---

Table 3-1	Permanganate Oxidation Batch Test Experimental Details
Table 3-2	FeEDTA Activated Persulfate Oxidation Batch Test Experimental Details
Table 3-1	Jones Road Site Material Composite Characterization
Table 3-2	Summary of Persulfate Consumption Rates in SOD Tests
Table 3-3	Concentrations of Selected Metals in Initial and Final Time Point Samples
Table 4-1	PCE Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms
Table 4-2	TCE Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms
Table 4-3	DCE Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms
Table 4-4	VC Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms
Table 4-5	Ethene Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms
Table 4-6	Ethane Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms
Table 4-7	pH (Standard Units) in the Bioaugmentation and Biostimulation Microcosms
Table 4-8	ORP (Millivolts) in the Bioaugmentation and Biostimulation Microcosms
Table 4-9	Contaminant Levels ( $\mu\text{M}$ ) in Jones Road ZVI Microcosms
Table 4-10	Final Ethane and Ethene Values ( $\mu\text{M}$ ) for ZVI Microcosms

## List of Appendices

---

Appendix A	Soil Acid Buffering Capacity Measurement Data
Appendix B	Soil Oxidant Demand Test Data
Appendix C	Treatment Effectiveness Test VOC Analysis Data
Appendix D	Treatment Effectiveness Test Metal Analysis Data

## ***EXECUTIVE SUMMARY***

---

Soil and groundwater samples from the Jones Road Groundwater Plume Federal Superfund Site (Jones Road), Houston, Texas were used to perform remedial technology treatability studies. Samples were collected from the site during the summer of 2006 and the laboratory treatability study tests were conducted during the Fall of 2006. Tetrachloroethene (PCE) and its daughter products are present in site soils and groundwater in shallow (water table) and deeper aquifer zones. Insitu chemical oxidation (ISCO) treatability studies were performed using potassium permanganate and activated persulfate oxidation at the Shaw Technology Development Laboratory (TDL) in Knoxville, Tennessee. Biostimulation, bioaugmentation, and Zero Valent Iron (ZVI) treatability studies were performed at the Shaw Technology Laboratory in Lawrenceville, New Jersey.

Treatability tests for potassium permanganate and bioaugmentation with lactate were most effective in treating PCE and its daughter products. To a lesser extent, activated persulfate oxidation also reduced PCE and its daughter products. Implementation of insitu technologies at the Jones Road site will be complicated due to the clays, the presence of discontinuous clayey sand, and sand lenses beneath the site. Initial pilot testing should be performed using potassium permanganate to treat source zone contamination in the shallow 28-50 foot depth saturated zone. Deeper contamination, greater than 50 feet, may be part of a follow-up pilot test using bioaugmentation and lactate to develop treatment zones as contaminant migration barriers. Prior to the final design of a pilot study, a detailed conceptual site model (CSM) showing the subsurface, and a hydraulic analysis of the site (in and around the former Bell Dry Cleaners), is needed. The CSM will help determine where to install pilot test injection/extraction wells and monitoring points, as well as provide inputs for dosage control and flow rates.

## 1.0 INTRODUCTION

---

Shaw Environmental, Inc. (Shaw) is pleased to present to the Texas Commission on Environmental Quality (TCEQ) this Treatability Study Report for soils and groundwater contamination at the Jones Road Groundwater Plume Federal Superfund site (Jones Road), located in Houston, Texas. The work items performed as part of this treatability study were presented to the TCEQ in the Treatability Study Work Plan (Shaw, October 12, 2006). The following technologies were included in the Work Plan for consideration at the Jones Road site:

- Activated Persulfate Insitu Chemical Oxidation (ISCO)
- Potassium Permanganate ISCO
- Biostimulation
- Bioaugmentation
- Abiotic Treatment Using Zero Valent Iron (ZVI)

The ISCO technology treatability studies were performed at Shaw's technology development laboratory (TDL) located in Knoxville, Tennessee. The biostimulation, bioaugmentation, and ZVI treatability studies were performed at Shaw's Technology Laboratory in Lawrenceville, New Jersey. Standard Operating Procedures (SOPs) and standard industry practices, procedures, and professional judgment were used by the Shaw labs during these studies. Samples for the treatability studies were collected during the summer of 2006 as part of the Geoprobe<sup>®</sup> and deep well rotosonic drilling field activities. Raw laboratory analytical data reports are included as a CD in this report.

This report is organized as follows: the remainder of Section 1.0 provides a brief site description, the test objectives, and the field activities associated with the treatability study sample collection. Section 2.0 provides a description of the treatability study technologies. ISCO technology treatability study procedures and test results are presented in Section 3.0. Biostimulation., bioaugmentation and ZVI treatability study procedures and test results are presented in Section 4.0. Section 5.0 presents a discussion on the implementation of the appropriate technology at the site as part of a pilot test, including a discussion of site factors that may affect full-scale implementation.

### 1.1 Site Description

The Jones Road site is located approximately one-half mile north of the intersection of Jones Road and FM 1960, outside the city limits of northwest Houston, Harris County, Texas. The Vadose Zone shallow and deeper groundwater in this area has been impacted by chlorinated

solvents volatile organic compounds (VOCs), mainly tetrachloroethene (PCE), trichloroethene (TCE), dichloroethene (DCE) and vinyl chloride (VC), believed to be from operations conducted at the former Bell Dry Cleaners site located in the Cypress Center Shopping Center at 11600 Jones Road.

A comprehensive description of the Jones Road site background and site conditions may be found in the Remedial Investigation Report (Shaw, 2006). Details of the Geoprobe<sup>®</sup> field investigation may be found in the July 2006 Geoprobe<sup>®</sup> Investigation Report (Shaw, 2007).

## *1.2 Study Objectives*

The Jones Road site treatability study objective is to evaluate potential insitu remedial technologies that will effectively remediate the chlorinated solvents in the saturated zone soils and groundwater at the site. Treatability studies determine if the technology is effective and provide information on the application concentrations and time required for the target VOCs to be treated.

Specific objectives of the ISCO treatability studies include:

- Evaluate treatment effectiveness of permanganate and FeEDTA-activated persulfate for destruction of VOCs in soil/groundwater slurries;
- Provide an estimate of the oxidant dosing requirements by measuring the soil oxidant demand (SOD);
- Measure the acid buffering capacity of the soil to determine the effect of persulfate oxidation on soil pH;
- Evaluate the effect of pH and ORP change on metals.

Specific objectives of the bioaugmentation, biostimulation, and ZVI treatability studies include:

- Determine which technology would provide the most rapid and complete biodegradation of PCE under site-specific conditions;
- Determine the dosage of bacteria, electron donor, or ZVI required for treatment.

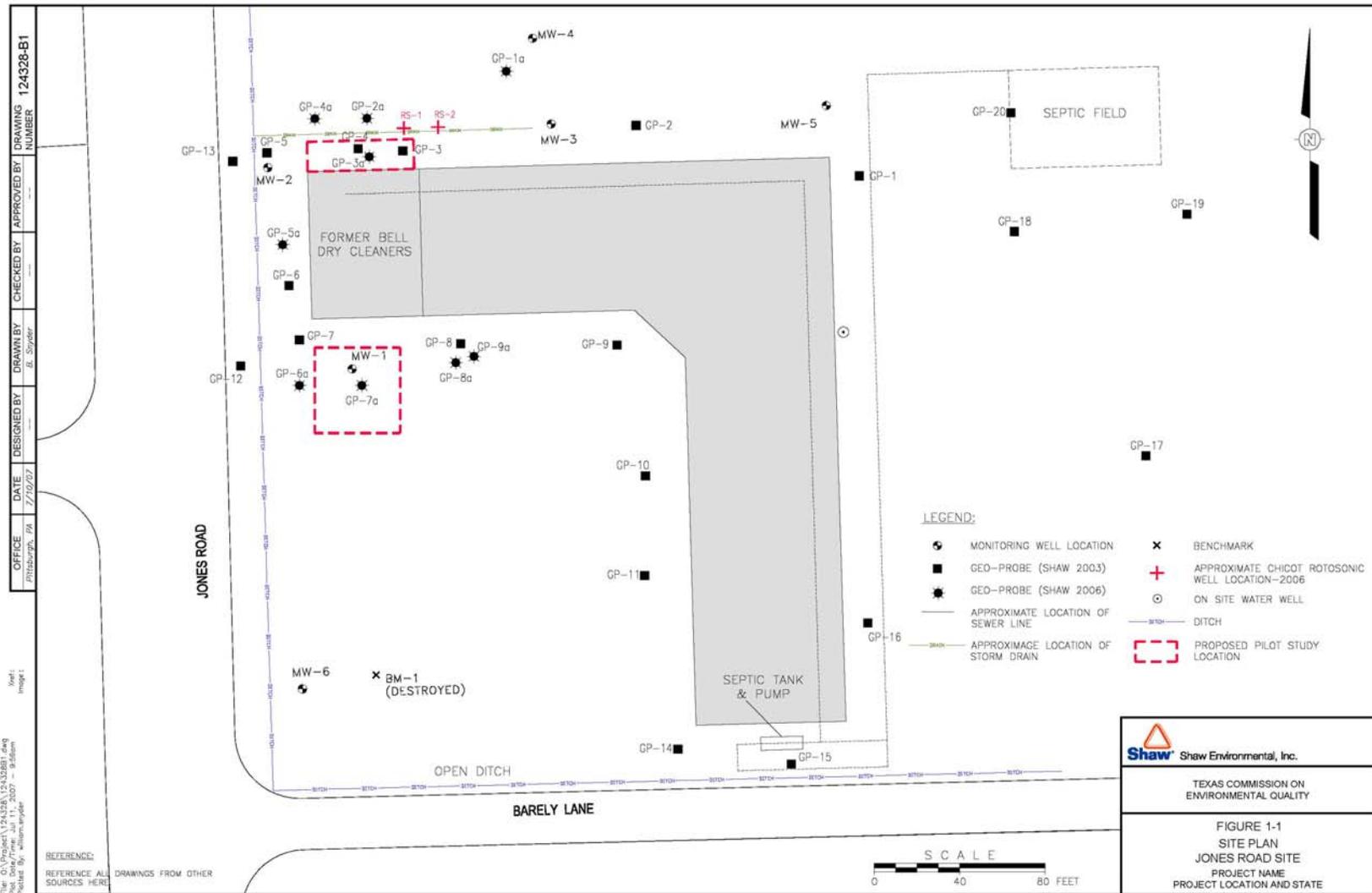
## *1.3 Treatability Study Sample Collection*

Soil and groundwater samples for this treatability study were collected during the July 2006 Jones Road Geoprobe<sup>®</sup> Study and the July 2006 rotosonic well drilling field activities. The soil and groundwater samples for the Lawrenceville Technology Laboratory studies were collected from Geoprobe<sup>®</sup> boring GP-3A (see **Figure 1-1**). Soil and groundwater samples were collected in accordance with the Jones Road Site Treatability Study Work Plan and other project-specific planning documents (Health and Safety, QA).

Soil samples from GP-3A for the bioremediation treatability studies were collected from four depth intervals (20-21 feet below ground surface [bgs], 27-29 feet bgs, 37-38 feet bgs, and 49-50 feet bgs) representing silts, clays, and clay sand at this location. Samples were field prepared in sealed paraffin wax coated tubes to preserve insitu conditions. Groundwater for the treatability studies was collected in five 1-liter bottles from the temporary well installed at GP-3A. The well screen in temporary well GP-3A was from 30 to 50 feet bgs.

Composite soil samples for the Knoxville TDL Treatability Studies were collected from rotonsonic drilling location RS-1 (see **Figure 1-1**). RS-1 is located approximately 24 feet northeast of GP-3A. Both locations are on the north side of the building, an area with very high PCE concentrations in groundwater.

During the July 2006 Geoprobe<sup>®</sup> investigation, the groundwater PCE concentration for temporary well GP-3A was 190,000 micrograms per liter ( $\mu\text{g/L}$ ). Water samples were not obtained from rotonsonic location RS-1. Soils underlying the site in the shallow aquifer zone are generally low permeability clays, silty clays, and clayey sands. A geotechnical sample profile at location GP-9A from 6 to 32 feet bgs had low levels of organic carbon (good for ISCO applications), and permeabilities range from  $10^{-6}$  cm/s to  $10^{-8}$  cm/s. Soil boring data from the July 2006 Geoprobe<sup>®</sup> work also indicates subsurface soils are generally low permeability; sands or clayey sands, if present, are discontinuous layers or lenses. Section 5.0, dealing with recommendations for pilot tests, discusses technology implementation issues.



## 2.0 TREATMENT TECHNOLOGY DESCRIPTION

---

The following sections describe the treatment technologies that were evaluated as part of this study.

### 2.1 *Permanganate Oxidation*

Chemical oxidation using potassium or sodium permanganate is widely used in drinking water applications. ISCO using sodium or potassium permanganate is also used to remediate hazardous waste sites with soil and groundwater contaminated with chlorinated VOCs. ISCO technology has been applied to a wide range of site soils, from clays to sands. The greater the clay content, the more closely spaced injection points and multiple applications of oxidant may be needed. Ideally, any insitu technology application is best suited at sites with moderate permeabilities and lower fine (silt/clayey) content. PCE and TCE are well-suited for oxidation by permanganate. Permanganate reacts rapidly with nonconjugated (i.e., nonaromatic) double bonds in chlorinated ethenes, and oxidizes the chlorinated ethenes to carbon dioxide and chloride ions. The reaction between PCE and permanganate is shown below.

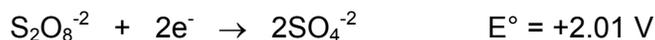


Insitu permanganate oxidation involves the injection (by gravity or under pressure) of sodium or potassium permanganate solution into the subsurface. Oxidant is delivered to the subsurface using injection probes, treatment walls, soil mixing, hydraulic fracturing, or vertical or horizontal wells.

The effectiveness of ISCO with permanganate depends on three factors: 1) the kinetics of the reaction between the permanganate and the contaminants; 2) the contact between the oxidant and the contaminants, and 3) competitive reaction of permanganate with other reduced/oxidizable species. If the contaminants targeted are reactive (e.g., chlorinated ethenes), and if sufficient oxidant is added (to overcome the demand from other reduced species, as well as naturally occurring organic matter), the limiting factor to the successful application is the transport of the oxidant to the contaminated area, but not the reaction itself. Clayey silts at Jones Road will somewhat complicate oxidant transport and distribution in the subsurface. The oxidation of contaminants by permanganate is essentially an instantaneous reaction. If the permanganate contacts the contaminant, a reaction will occur. Significant oxidation is observed in as little as a few hours after addition.

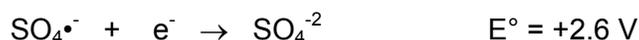
## 2.2 Activated Persulfate Oxidation

Persulfate ion ( $S_2O_8^{2-}$ ) is a strong oxidant capable of oxidizing most organic compounds to carbon dioxide and other mineral products. The standard reduction potential for the half reaction shown below is +2.01 volts (V).



It is on the same order as that for ozone and higher than that for permanganate and hydrogen peroxide, but less than that for the hydroxyl radical (Fenton's reagent intermediate). As shown in the half reaction above, the product of persulfate reduction is sulfate ion ( $SO_4^{2-}$ ), which is a relatively benign species. Sulfate ion has a secondary federal drinking water standard maximum contaminant level (MCL), which is a recommended, but unenforceable limit of 250 mg/L.

It is believed that persulfate reacts with organic compounds primarily by the sulfate radical ( $SO_4^{\bullet-}$ ), which can be generated in solution by several mechanisms. The sulfate radical shown, in the reaction below, is a powerful oxidizing species with a standard electrode reduction potential of +2.6 V, which is similar to that for the hydroxyl radical ( $OH^\bullet$ ) species (+2.8 V).

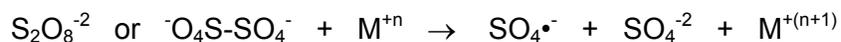


The hydroxyl radical is a powerful oxidizing species that is generated with catalyzed hydrogen peroxide (CHP) systems. The persulfate anion radical in contrast to the hydroxyl radical has a longer lifetime in solution and is more selective in its reactions (P. Neta, 1987). Generation of the sulfate radical may be accomplished by homolytic scission of the persulfate ion, which can be activated by heat or ultraviolet (UV) radiation (G. E. Hoag, 2000; P. Neta, 1987 and C. Liang, 2001):



Heat activation for persulfate activation can be accomplished at temperatures in the range of 20°C to 60°C, which can be accomplished insitu without extreme heat generation processes. Steam heating has been used as a practical means to provide persulfate activation for insitu treatment. However, at the Jones Road site, due to cost, steam heat would not be a viable alternative.

Sulfate radicals may also be generated by one-electron oxidation reactions, such as with metals (C. Liang, 2001; FMC, 2001 and G. E. Hoag, 2000):



Recently, new methods of persulfate reaction activation have been developed using: chelated metals, such as iron (II) ethylenediamine tetraacetic acid (FeEDTA), hydrogen peroxide addition,

or an alkaline pH (P. Block, 2004). These new methods most likely also involve the generation of the sulfate radical, and possibly the hydroxyl radical and related species for reaction with organic compounds.

Metal complex activation of persulfate has been effective in treating aromatics and chlorinated ethenes, but chlorinated ethanes and chlorinated methanes have proven to be somewhat resistant to persulfate with this form of activation (P. Block, 2004).

Alkaline activation of persulfate has been shown to be most effective for the treatment of chlorinated ethane and chlorinated methane compounds. Alkaline activation uses a base such as sodium hydroxide to adjust initial pH in the range of 11 to 12.5. The alkaline conditions are typically neutralized during treatment by the generation of hydrogen sulfate anion ( $\text{HSO}_4^-$ ), which is an acid. This occurs during natural decomposition of the persulfate reagent that is catalyzed by high pH and species present in the soil. The equation for the decomposition reaction is shown below.



Study results show that persulfate can be effective on recalcitrant organics. Specifically, persulfate has been shown to degrade BTEX, chlorinated ethenes, chlorinated ethanes, and chlorinated methane compounds (C. Liang, 2001 and P. Block, 2004).

The persulfate reagent is very soluble in water to concentrations of 30 to 40 percent and the solutions are relatively stable especially at lower concentrations (1 to 10 percent). These properties allow for optimum delivery and distribution to the subsurface matrix without the solubility limitations encountered with potassium permanganate. The reagent is similar to permanganate with respect to safety issues (e.g., handling and reactivity). All ISCO materials are handled in accordance with manufacturers' instructions, and only properly trained field personnel are used to handle, mix, and inject ISCO materials.

### ***2.3 Technology Description of Bioaugmentation, Biostimulation, and Abiotic Treatment Using ZVI***

Both bioaugmentation and biostimulation are insitu remedial biotechnologies that have been shown to be cost-effective treatments for the removal of chlorinated ethenes. ZVI treatment of chlorinated ethenes is an abiotic reaction that occurs at the surface of the metal particle. The purpose for performing laboratory testing of these technologies is to verify that the complete biodegradation of PCE will occur at a reasonable rate under site-specific conditions. As is the case with ISCO, the ability to deliver and distribute the bioremediation amendments may be complicated by site conditions (clayey soil).

PCE can be degraded under anaerobic conditions by specific bacteria through reductive dehalogenation, where PCE is sequentially reduced to TCE, cis-1,2- DCE, VC, then ethene. In each case, the reactions are mediated by bacteria that thrive under low oxidation-reduction potential, and are driven by the presence of an electron donor (carbon source or hydrogen). In order for complete biodegradation/dechlorination of PCE to occur, specific bacteria capable of this process must also be present. *Dehalococcoides* sp. (DHC), some of which are capable of degrading chlorinated ethenes to ethene, are the only microbial species known to completely dechlorinate PCE, so their abundance and distribution in a contaminated aquifer is critical for effective biodegradation of TCE.

### **Biostimulation**

In situ anaerobic biostimulation involves stimulating the degradation of indigenous microbial populations by introducing electron donor (substrate) and/or nutrients into the subsurface. These materials can be delivered to the subsurface using injection probes, treatment walls, soil mixing, pneumatic fracturing, or vertical or horizontal wells. The assumption with this approach is that the indigenous microbial population contains DHC, but the native DHC are unable to maintain high levels of degradation due to unfavorable oxidation-reduction potential, insufficient nutrient (e.g., nitrogen, phosphorous) levels, insufficient microbial levels, and/or lack of electron donor. As such, the success of a biostimulation approach is dependent upon the ability to distribute amendments in the subsurface, create favorable oxidation-reduction potential in situ, enhance the growth of DHC, and ultimately stimulate microbially-enhanced reductive dehalogenation of PCE and its daughter products.

Biostimulation requires that DHC are present within the contaminated aquifer. The presence of reduced gases, such as ethene or ethane, are often evidence that the complete reduction of PCE is occurring biologically, and that DHC are present and active. In addition, polymerase chain reaction (PCR) analysis is a recently developed molecular biological tool that is capable of determining the presence of DHC in aquifers.

### **Bioaugmentation**

Bioaugmentation is similar to biostimulation, except that it involves the delivery of microorganisms (in addition to substrate and nutrients) to the subsurface to stimulate biological degradation. These organisms can be cultured directly from site material, or can be obtained from an outside source. Evidence of biological degradation found at a site, such as the presence of daughter products of the degradation of the target contaminants and suitable geochemical conditions, may be indicative of an active microbial population. Alternately, PCR analysis can be used to determine whether a particular species of bacteria is present in site soil and groundwater, indicating whether complete dechlorination of native bacteria is likely. Site soil

collected from the area of the site where degradation appears to be occurring, or where these organisms appear to be present, can often be enriched in the laboratory to select the population responsible for degradation. The bacterial culture can then be grown in the laboratory to produce large batches of active microorganisms that are then added to the subsurface, along with appropriate substrate and nutrient.

Alternate sources of active microbial cultures of DHC have been obtained from sites where DHC are naturally occurring. There are several cultures available to Shaw, most notably our SDC-9™ culture, which has been shown to completely and rapidly degrade PCE to ethene using lactate as an electron donor.

### **Abiotic Treatment Using ZVI**

ZVI treatment of chlorinated ethenes is an abiotic reaction that occurs at the surface of the metal particle. The degradation reaction occurs via electron transfer between the dissolved contaminant and the iron, as corrosion of the iron facilitates the reductive dehalogenation reactions needed to sequentially dechlorinate the PCE to ethene and ethane. Several types of ZVI have been used, including iron filings (1 mm diameter), microscale ZVI (micron-sized particles), and bimetallic nanoscale ZVI (100 nm diameter, doped with palladium catalyst). Addition of metal catalysts to the surface of the ZVI particles typically increases the rate of the dehalogenation and hydrogenation surface reactions, thereby increasing the overall rate of contaminant removal. Field applications have included the use of permeable reactive barrier, dispersed injection into source areas, and *ex situ* reactors. Selection of the most appropriate ZVI type and field application is dependent upon several factors. These factors include site geochemical conditions, contaminant type and concentration, site hydrogeologic conditions, and cost.

### 3.0 ISCO TREATMENT STUDY

---

Treatability studies were conducted to evaluate permanganate and activated persulfate oxidation for the treatment of PCE and PCE degradation products in Jones Road soil and groundwater slurries. These studies were conducted during the Fall of 2006. The batch experiments investigated both oxidant dosing and treatment time requirements. Persulfate was activated using a ferrous iron ( $\text{Fe}^{+2}$ ) EDTA complex (FeEDTA).

The experimental approach described below entailed site soil preparation, characterization of test soils and groundwater, soil oxidant demand tests, acid/base titration of site soil, and reagent treatment effectiveness tests on soil and groundwater mixtures.

#### 3.1 Sample Preparation and Chemicals

Soil and groundwater samples were received at the TDL on July 25 and July 26, 2006. The samples were shipped on ice and stored at 4°C until used in treatment study testing. Samples were identified as follows:

<u>Type</u>	<u>Amount</u>	<u>TDL Lab #</u>
SOIL	5-GAL BUCKET	10506
GW	5 X 1-LITER	10507

The samples of soil received for batch slurry testing were mixed manually in the 5-gallon bucket to apparent homogeneity at 4°C in a manner to minimize VOC loss. The 5 liters of site groundwater collected were homogenized in a sterile chilled glass container. Samples were stored with zero headspace at 4°C prior to testing. The homogenized site groundwater and site soil were sampled for analysis of volatile organic compounds (VOCs) of concern using a modified EPA SW-846 Method 8015, which uses purge-and-trap gas chromatography with flame ionization detection methodology (GC/FID).

Potassium permanganate was obtained from Carus (Carox USP grade), and sodium persulfate was obtained from FMC (Klozur™ Environmental grade).

The soil sample was also analyzed for acid buffering capacity using laboratory standard operating procedures (SOP). These measurements were used to determine the soil's ability to adjust the pH in response to protons released from persulfate decomposition.

#### 3.2 Soil Oxidant Demand Testing

Soil Oxidant Demand (SOD) tests were performed to measure the amount of oxidant consumed in the course of treatment required to destroy the target VOCs. The amount and rate of oxidant

consumption is used to determine oxidant dosing and reaction condition requirements for treatment. The soil composite was used to measure the SOD with various oxidant systems. Tests were performed on soil/groundwater slurries containing 200 grams (g) of soil and 200 milliliters (mL) of groundwater in 500-mL polyethylene sample bottles. The soil sample was also analyzed for percent solids. Permanganate SOD was tested using an initial potassium permanganate concentration of 10 g/L. FeEDTA activated persulfate SOD was tested with a starting concentration of 20 g/L sodium persulfate and 150 mg/L  $\text{Fe}^{2+}$  as FeEDTA. The test bottles were capped, placed onto a temperature controlled oscillating shaker table at 15°C and mixed periodically for the duration of the test.

In each test the amount of oxidant consumed was determined by measuring the loss of oxidant as a function of time to define the consumption characteristics for each oxidant system. Because of the impact of pH on persulfate and the potential for pH decrease during treatment due to persulfate degradation, the pH was also monitored. Tests were monitored for a six week time period using sample points of 2, 7, 14, 21, 28, 35, 42 and 49 days.

### ***3.3 Oxidation Effectiveness Tests***

Slurry tests using permanganate and FeEDTA activated persulfate were performed on site soil and groundwater mixtures. The bench scale testing designed to evaluate the two oxidation methods is described in detail below.

The test samples were prepared by mixing 100 g site soil and 150 mL groundwater in 210 mL test bottles. A small volume of headspace was left in each bottle to allow for slurry mixing. Initial characterization of site soil and groundwater indicated the PCE concentration levels were 532  $\mu\text{g/L}$  PCE in groundwater and non detectable in soil (10  $\mu\text{g/kg}$  detection limit), which were probably too low to determine the treatment effect. Therefore, PCE was spiked by adding 1.5 mL of 144 mg/L aqueous PCE solution into each test bottle to produce an aqueous test concentration in the range of 1-2 mg/L. Then all test bottles were allowed to equilibrate overnight before adding any reagent. All bottles were hand mixed periodically at 24 to 72 hour intervals by gently turning each bottle end over end. Test bottles were temperature controlled at 15°C for the test duration.

#### **Permanganate Oxidation**

Permanganate was tested at three dosages (3, 5, and 10 g/L) and three treatment times (1, 4, and 14 days). A total of 11 bottles (three permanganate dosages at three sampling times and two control bottles at sampling times of 0 and 14 days) were prepared for permanganate oxidation. Each test bottle was amended with the appropriate amount of potassium permanganate to produce the desired initial concentration as detailed in **Table 3-1**. Control slurry tests (no amendment) were established identical to the oxidant slurry test to measure any VOC loss due to

procedures or bacterial degradation. The control bottles were sampled at T-0 hours and T-14 days (water and soil). **Table 3-1** below describes the slurry batch tests and sampling schedule.

**Table 3-1**  
**Permanganate Oxidation Batch Test Experimental Details**

Test	Potassium Permanganate Conc. (g/L)	Sample Points (Days)				Soil (g)	Water (ml)	Potassium Permanganate (g)	Manganese Sulfate <sup>1</sup> (g)
		T-0	T-1	T-4	T-14				
C1	0	X			X	100	150	0	0
M1	3		X	X	X	100	150	0.3	0.8
M2	5		X	X	X	100	150	0.75	1.5
M3	10		X	X	X	100	150	1.5	2.9

Note:

<sup>1</sup> Manganese sulfate ( $MnSO_4 \cdot H_2O$ ) was added to the samples at the end of the treatment to quench the remaining permanganate.

At three sampling points, T-1, T-4, and T-14 days, a bottle from each permanganate treatment concentration was sacrificed for analysis. A portion of the water phase was transferred to 50 mL plastic vials for analysis for remaining permanganate. The rest of the soil/groundwater slurry was quenched by the addition of manganese sulfate ( $MnSO_4 \cdot H_2O$ ). Both soil and groundwater phases were sampled at all three time points for VOC analysis. The soil phase was also analyzed for moisture content.

### **FeEDTA Activated Persulfate Oxidation**

Persulfate was tested at three dosages (2, 5, and 10 g/L) and three treatment times (4, 8, and 21 days). A total of 11 bottles (three persulfate dosages at 3 sampling times and two control bottles at sampling times of 0 and 21 days) were prepared for persulfate oxidation. Each test bottle was amended with appropriate amount of sodium persulfate and FeEDTA to produce the desired initial concentration as detailed in **Table 3-2**. The low persulfate dose resulted in a nominal aqueous concentration of 2 g/L sodium persulfate activated with 100 mg/L chelated iron (Fe as FeEDTA). The medium level dose was 2.5 times (2.5X) the low dose amount, which produced a nominal aqueous concentration of 5 g/L activated with 150 mg/L chelated iron. The high level dose was 2 times (2 X) the medium dose, producing a nominal aqueous concentration of 10 g/L activated with 200 mg/L FeEDTA.

At three sampling points, T-7, T14 and T-21 days, a bottle from each persulfate treatment concentration was sacrificed for analysis. The reaction was quenched by placing the test bottle

in the refrigerator at ~4°C. The low temperature also helps to minimize the volatilization loss of VOC of concern. A portion of the water phase was transferred to 50 mL plastic vials for analysis of the remaining persulfate and pH. Both soil and groundwater phases were sampled at all three time points for VOC analysis. Soil phase was also analyzed for moisture content. The control bottles were sampled at T-0 hours and T-21 days (water and soil). **Table 3-2** below describes the slurry batch tests and sampling schedule.

**Table 3-2**  
**FeEDTA Activated Persulfate Oxidation Batch Test Experimental Details**

Test	Sodium Persulfate Conc. (g/L)	FeEDTA Conc. (mg Fe/L)	Sample Points (Days)				Soil (g)	Water (ml)	Sodium Persulfate (g)	FeEDTA Solution, 20 g/L (mL)
			T-0	T-4	T-8	T-21				
C2	0	0	X			X	100	150	0	0
S1	2	100		X	X	X	100	150	0.3	0.75
S2	5	150		X	X	X	100	150	0.75	1.13
S3	10	200		X	X	X	100	150	1.5	1.5

### 3.4 Sample Characterization Results

Results from the VOC analyses of site soil and groundwater sample composites, as well as soil buffering capacity or alkalinity, are summarized in **Table 3-3** for PCE and PCE degradation products. Measurement data for the soil buffering capacity are included in **Appendix A**.

**Table 3-3**  
**Jones Road Site Material Composite Characterization**

Sample Type	Units	PCE	TCE	cis-1,2 DCE	trans-1,2 DCE	Vinyl chloride	Alkalinity to pH 4.50
Jones Road Soil Comp.	µg/Kg	5U	5U	5U	5U	5U	1700 mg CaCO <sub>3</sub> /kg
Jones Road GW Comp.	µg/L	532	91.3	82.2	12.5U	12.5U	NA

U = Analyte was not detected at the stated detection limit. Detection limits elevated due to laboratory dilution requirements.  
J = Analyte was detected at a level below the method quantification limit; stated values is an estimate

### 3.5 Soil Oxidant Demand Results

Results from the SOD tests are tabulated below in **Table 3-4**. The data collected included plots of oxidant consumption as a function of time, as presented in **Appendix B**. The value given is the total grams of oxidant consumed per kilogram of wet soil in 49 days treatment time.

**Table 3-4**  
**Summary of Persulfate Consumption Rates in SOD Tests**

Test	Description <sup>a</sup>	Oxidant Consumption g oxidant / kg wet soil
Persulfate SOD	20 g/L Persulfate +150 mg F <sup>2+</sup> /L as FeEDTA	0.9 <sup>b</sup>
Permanganate SOD	10g/L Permanganate	2.4 <sup>b</sup>

<sup>a</sup> Both tests in 200 g soil composite: 200 mL GW

<sup>b</sup> Based on measurement on day 49.

**Table 3-4** shows the total grams of oxidant consumed per kilogram of wet soil in 49 days treatment time. Both the FeEDTA activated persulfate SOD and the permanganate SOD at 0.9 and 2.4 g/kg, respectively, were in the very low range for oxidant consumption showing very little change in concentration with the majority of the oxidant remaining after 49 days treatment time. The plots show variability in test results as a function of time, and this was primarily due to the low consumption observed compared to the test dose value. Small errors in oxidant concentration measurement at test points produced relatively large swings in the resulting consumption value.

The pH behavior from the persulfate tests is typically characterized by a shift to low pH over time. This is caused by the acid product from persulfate decomposition and the low site soil buffering capacity. The persulfate tests ended in the pH range of 7.0, which is consistent with very little persulfate decomposition. Minimal pH effect, as shown here, indicates efficient use of persulfate in destroying VOCs and not in reacting with matrix interferences.

### ***3.6 Batch Slurry Test Results***

Samples were analyzed using a modified EPA SW-846 Method 8015 (purge-and-trap GC/FID methodology). A summary of VOC analytical data is included in **Appendix C**. Initial sample characterization indicated that the percent solids in the site soil composite was 84.2 percent, and that there was 532 µg/L PCE in the groundwater composite, and non-detectable VOC in the soil composite. To better test the treatment effectiveness, all samples were spiked with PCE solution, which resulted in final PCE concentrations of 1.2~1.5 mg/L.

#### **Permanganate Oxidation**

The permanganate treated sample had no detectable VOCs (detection limit 2.5 µg/L) after one (1) day treatment, indicating that permanganate oxidation is very effective in treating PCE and daughter products. Consistent with SOD results, permanganate consumption was fairly low with

more than 80 percent of the originally dosed permanganate remaining in the sample after 14 days of treatment. Permanganate concentrations at three dosage levels didn't change significantly from one (1) day treatment samples to 14 day treatment samples, indicating most of the oxidation reaction occurred in the first 24 hours. This is expected based on the relatively fast reaction kinetics between permanganate and the target VOCs.

The 14 day control sample had a PCE concentration of 1,575 µg/L comparing to the 0 day control concentrations of 1,244 µg/L and 1,252 µg/L. The increase in PCE concentration in control is probably due to the equilibrium between soil and aqueous phases. It also indicates that there was no significant loss during the test due to volatilization or biodegradation, etc.

The completed data set from metal analysis is presented in **Appendix D**. Highlighted values in **Table 3-5** show metals that exceeded EPA drinking water MCLs in some treated samples and, therefore, are of particular concern. Permanganate treated samples liberated metals that exceeded MCL concentrations for silver, barium, chromium, lead, selenium, and thallium. There are two sources for the elevated metal concentration: the trace metal content in permanganate and mobilization from the soil. Based on the product specification from the permanganate supplier (Carus), the possible contribution from metal content in permanganate was calculated and it accounts for no more than 15 percent of the metal concentrations measured in the permanganate treated samples. Therefore, the elevated metal concentrations are mostly from mobilization from the soil. However, based on experience, the metal concentrations will attenuate to baseline levels after the permanganate is consumed and the natural site redox condition is reestablished to static conditions. Pilot study and full-scale design applications are developed with thought to mobilized metals attenuation. These results provide guidance for metals monitoring during pilot-scale testing.

### **FeEDTA Activated Persulfate Oxidation**

After 21 days of treatment, there were significant concentrations of VOCs detected in the FeEDTA activated persulfate samples. Unexpectedly, the low persulfate dose (2 g/L persulfate activated with 100 mg/L chelated iron) achieved the highest treatment efficiency with 96.9 percent PCE reduction in 21 days, and the medium persulfate dose (5 g/L persulfate activated with 150 mg/L chelated iron) resulted in the lowest treatment efficiency with 63.25 percent PCE reduction in 21 days. Other VOCs, including VC, DCE, and TCE, also showed different extent of reduction. **Figure 3-1** plotted the PCE concentrations at different treatment durations and different persulfate doses.

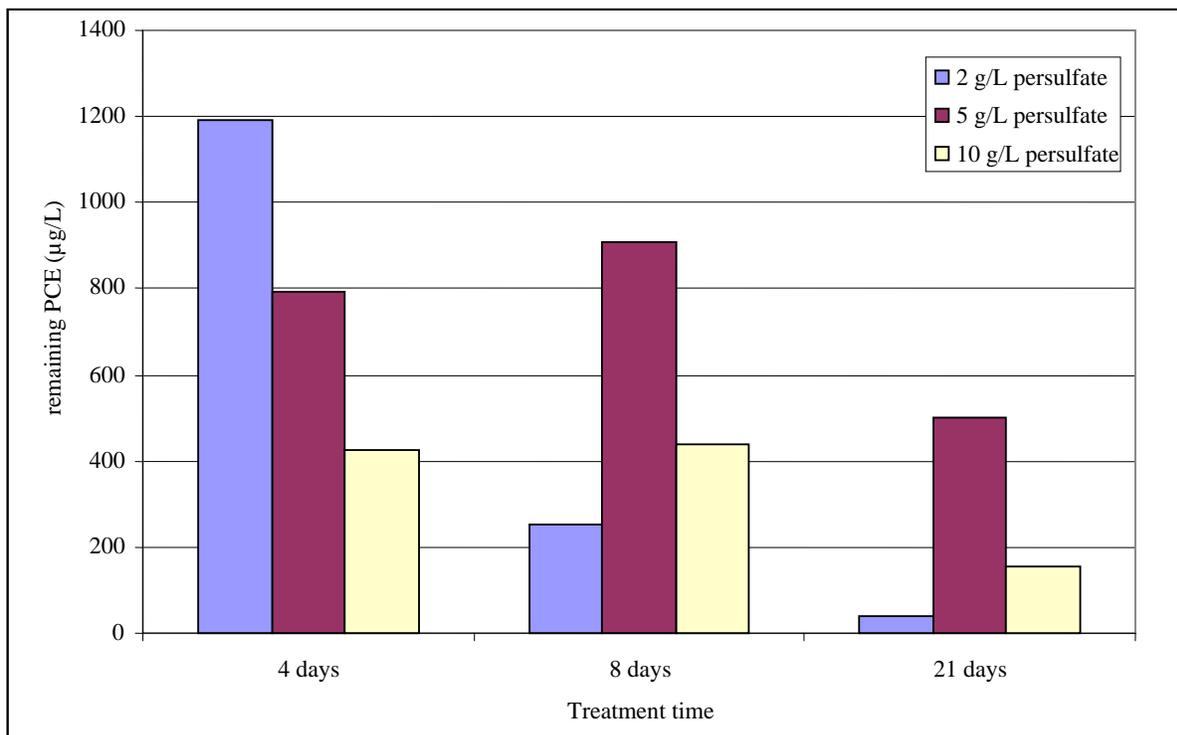
**Table 3-5**  
**Concentrations of Selected Metals in Initial and Final Time Point Samples**

Sample ID	Treatment	Ag (mg/L)	Ba (mg/L)	Cr (mg/L)	Pb (mg/L)	Se (mg/L)	Ti (mg/L)
<i>EPA Drinking Water MCL</i>	NA	0.1	2	0.1	0.015	0.05	0.002
C1-0	Baseline control	0.012U	0.171	0.026U	0.012U	0.012U	0.012U
C2-0	Baseline control	0.012U	0.162	0.026U	0.012U	0.012U	0.012U
C1-21	21 day control	0.012U	0.162	0.026U	0.012U	0.012U	0.012U
C2-14	14 day control	0.012U	0.213	0.026U	0.012U	0.012U	0.012U
M1-14	3 g/L permanganate for 14 days	0.076	1.61	<b>0.232</b>	<b>0.015</b>	<b>0.153J</b>	<b>0.243</b>
M2-14	5 g/L permanganate for 14 days	<b>0.114</b>	<b>2.19</b>	<b>0.288</b>	<b>0.033</b>	<b>0.299J</b>	<b>0.496</b>
M3-14	10 g/L permanganate for 14 days	<b>0.242</b>	<b>4.5</b>	<b>0.472</b>	<b>0.107</b>	<b>0.747J</b>	<b>1.3</b>
S1-21	2 g/L persulfate for 21 days	0.017	0.438	0.026U	<b>0.357</b>	0.012U	0.012U
S2-21	5 g/L persulfate for 21 days	0.034	0.164	0.026U	<b>0.35</b>	0.012U	0.012U
S3-21	10 g/L persulfate for 21 days	0.044	0.106	0.026U	<b>0.298</b>	0.012U	0.012U

U – Laboratory reporting limits;  
 J – Estimated value may be biased slightly low. Continuing standard outside 80-120 percent criteria at 79 percent;  
 Bold numbers indicate the values exceed EPA drinking water MCL.

**Figure 3-1**

**PCE Concentration Change Over Time In FeEDTA Activated Persulfate Oxidation**



The analysis results for the 21 day control sample at 96 µg/L PCE revealed a loss of more than 90 percent PCE concentration from the day 0 control concentration of 1,243 and 1,252 µg/L. This is probably due to the breakage of the bottle mouth of this sample, which resulted in loss of VOCs due to volatilization. However, the analysis results of the 14 day control used in permanganate treatment can be used here to verify that the loss due to volatilization or biodegradation is negligible given the normal test condition.

The batch test pH measurement results were consistent with persulfate concentration. The pH of control samples and low dose persulfate treated samples remained consistent from day 4 to day 21. The medium dose persulfate treated samples had a trend of decreasing pH slowly from 7.64 on day 4 to 7.21 on day 21. The high dose persulfate treated sample resulted in a pH decrease from 7.69 on day 4 to 6.94 on day 21, but was still in the neutral range.

The batch test persulfate consumption was consistent with the SOD test results. Less than 20 percent of the dosed persulfate was consumed over the 21 days of treatment.

As shown in **Table 3-5**, Fe-EDTA activated persulfate didn't elevate the metal concentrations in the water phase except for lead. The lead concentrations in persulfate treated samples ranged from 0.298 mg/L to 0.357 mg/L, much higher than the EPA drinking water action level (0.015 mg/L). Based on FMC product specification, the lead from persulfate contributes less than 1 percent to the actual measured concentrations. So the elevated lead concentration is likely due to leaching from the soil. Similar to the permanganate treatment, the lead concentration is expected to decrease to baseline level over time after the oxidant is consumed. Lead should be monitored during the pilot-study and any full-scale application.

### ***3.7 Conclusions and Recommendations***

Results of the Knoxville TDL Study indicate that permanganate oxidation is an effective method to treat the PCE and daughter products found at the Jones Road site, with 100 percent reduction in one day. A permanganate dose of 3 g KMnO<sub>4</sub> per kg of soil is recommended for field implementation. However, permanganate treatment caused leaching of metals, including silver, barium, chromium, lead, selenium, and thallium from the soil to water phase.

FeEDTA activated persulfate oxidation was effective to a certain extent in treating the PCE at the site, with up to 96.9 percent of reduction in 21 days. This treatment method was not able to reduce PCE concentration below USEPA drinking water MCLs (5 µg/L) within the time frame of this study (21 days) due to the slow reaction kinetics, but it's possible that it can reach the standard given sufficiently long reaction time. A dose of 2 g of persulfate per kg of soil is appropriate for this site. Persulfate oxidation did not significantly alter the metal concentrations in the water phase, except for lead which was increased to concentrations above the MCL.

Given that the SOD of the site soil is fairly low and the reaction between permanganate and VOCs is fast compared to persulfate, 3 g permanganate per kg soil is recommended to be applied at the Jones Road site. Metal concentrations, particularly silver, barium, chromium, lead, selenium, and thallium, should be monitored to document metal concentrations over time. Elevated concentrations of these metals should be expected in the short term, but they should attenuate to baseline levels over time, based on the experience of both Shaw and others.

## 4.0 *BIOSTIMULATION, BIOAUGMENTATION, AND ZVI TREATMENT STUDY*

---

Treatability studies were conducted to evaluate biostimulation, bioaugmentation, and ZVI for the treatment of PCE and PCE degradation products in Jones Road soil and groundwater slurries. These studies were conducted during the Fall of 2006. The experimental approach described below entailed site soil and groundwater preparation, application of various biostimulation amendments, application of Shaw's SDC-9<sup>TM</sup> culture to amended samples, and tests of ZVI using various amendments.

### 4.1 *Materials and Methods*

#### **Biostimulation/Bioaugmentation Microcosms**

Microcosms were prepared in glass serum bottles (approximate volume, 160 mL). All microcosm preparation and sampling was performed in a Coy anaerobic chamber. Thirty grams of homogenized site soil and 143-mL of site groundwater was added to each bottle. For the treatment tests that had lactate or emulsified oil substrate (EOS) added as an electron donor, the concentration of the admendment was 1,000 milligrams per liter (mg/L). This concentration was based on the extensive knowledge and experience of the personnel conducting the test. Lactate and EOS were not added to the killed and live control treatments. A total of 24 bottles was prepared. The bottles were sealed with Teflon<sup>®</sup>-lined butyl rubber stoppers and crimp caps.

Six sets of microcosm treatments were prepared in triplicate as follows:

Treatment 1: **KILLED CONTROL:** These treatments were amended with a formaldehyde solution (final concentration in groundwater approximately one (1) percent by volume) to inactivate microbial activity, and were used to evaluate abiotic loss of VOCs.

Treatment 2: **LIVE CONTROL:** This treatment did not receive any amendments except for deionized water (to simulate addition of amendments performed for the other treatments). This treatment served as a control to monitor VOC loss in the absence of any amendments.

Treatment 3: **BIOSTIMULATION 1 (LACTATE):** Bottles were amended with lactate to serve as the electron donor. Lactate was added such that a concentration of approximately 1,000 mg/L was attained. Nutrient solution and yeast extract was also added to ensure that the bacteria were not limited in nitrogen, phosphorus, or other trace nutrients. This treatment was used to evaluate the effects of anaerobic biostimulation on contaminant biodegradation.

Treatment 4: **BIOSTIMULATION 2 (EOS)**: Bottles were also amended with an emulsified EOS to serve as the electron donor. EOS was added such that a concentration of approximately 1,000 mg/L was attained. Nutrient solution and yeast extract were also added to ensure that the bacteria were not limited in nitrogen, phosphorus, or other trace nutrients. This treatment was used to evaluate the effects of anaerobic biostimulation on contaminant biodegradation.

Treatment 5: **BIOAUGMENTATION 1**: Shaw's SDC-9™ culture was used as the bacterial inoculum. SDC-9™ was added in a one-time event concentration of  $10^5$  cells per milliliter (ml). Nutrient solution and yeast extract were also added to ensure that the bacteria were not limited in nitrogen, phosphorus, or other trace nutrients. Bottles were amended with lactate to serve as the electron donor. Lactate was added such that a concentration of 1,000 mg/L was attained.

Treatment 6: **BIOAUGMENTATION 2**: Shaw's SDC-9™ culture was used as the bacterial inoculum. SDC-9™ was added in a one-time event concentration of  $10^5$  cells per milliliter (ml). Nutrient solution was also added to ensure that the bacteria were not limited in nitrogen, phosphorus, or other trace nutrients. Bottles were amended with an EOS to serve as the electron donor. EOS was added such that a concentration of 1,000 mg/L was attained.

A parallel set of bottles was prepared for each treatment (six [6] bottles total) and sampled at each time point to measure anions, pH and ORP throughout the study.

*Sampling and Analysis.* Bottles were incubated with gentle shaking at 15°C at all times except during the actual sampling procedure. Bottles were allowed to shake for 24 hours after initial setup to allow complete mixing of amendments into the soil and groundwater matrix, after which the aqueous phase was sampled and analyzed for VOCs via EPA Method 8260. This sampling was designated as time zero ( $t_0$ ).

Sampling events were performed at 1, 5, 7, 9, and 13 weeks of incubation. At each sampling event, microcosm bottles were removed from the shaker and placed in the anaerobic chamber. Sufficient time was allowed for the solids to settle (usually 30 to 60 minutes), so that the supernatant groundwater could be sampled. At each sampling event, approximately 2-3 ml of groundwater was removed from the serum bottle and analyzed for VOCs and reduced gases. In addition, at least one bottle from the live control, biostimulation, and bioaugmentation treatments was analyzed for volatile fatty acids, anions, pH, and ORP at each sampling event (equal sample volume was collected from all bottles and treatments to maintain equal groundwater volumes in all the treatments). Glass beads were added to the bottles after sampling to maintain zero headspace.

## **ZVI Microcosms**

Microcosms were prepared in glass serum bottles (approximate volume, 60 mL). All microcosm preparation and sampling was performed in an anaerobic chamber. Approximately 10 g of homogenized site soil and 50-mL of site groundwater were added to each of the bottles. A total of nine bottles were prepared. The bottles were sealed with Teflon<sup>®</sup>-lined butyl rubber stoppers and crimp caps.

Three sets of microcosm treatments were prepared in triplicate as follows.

Treatment 1: LIVE CONTROL: This treatment did not receive any amendments except for deionized water (to simulate addition of amendments performed for the other treatments). This treatment served as a control to monitor VOC loss in the absence of any amendments.

Treatment 2: ZVI 1: Bottles were amended with a nanoscale ZVI (nZVI) at a dosage of 0.2 g/L.

Treatment 3: ZVI 2: Bottles were amended with a microscale ZVI (mZVI) at a dosage of 0.5 g/L.

Microcosm bottles were incubated with gentle shaking at 15°C. At each sampling event, microcosm bottles were removed from the shaker, and sufficient time was allowed for the soils to settle so that the supernatant groundwater could be sampled. Approximately 2-3 ml of groundwater sample was drawn directly from the bottles, and immediately analyzed for VOCs at t= 0, 1 week, 3 weeks, 4 weeks, and 5 weeks. At 6 weeks, samples were analyzed for reduced gases (i.e., methane/ethane/ethene) in order to verify the contaminant mass balance.

## ***4.2 Results and Discussion***

### **Biostimulation/Bioaugmentation Microcosms**

Results of the biostimulation and bioaugmentation study are summarized in **Tables 4-1** through **4-8** and **Figure 4-1**. Both bioaugmentation treatments, as well as biostimulation with lactate, were successful in treating chlorinated ethenes from the microcosms. Biostimulation with EOS was unsuccessful for completely treating the chlorinated PCE, as dechlorination stalled at DCE.

When bioaugmentation with Shaw's dechlorinating culture SDC-9<sup>™</sup> was employed, PCE and TCE were reduced to non-detectable concentrations (i.e. below the PQL of 50 ppb (0.4 mM)) within one week in all samples (**Tables 4-1** and **4-2** and **Figure 4-1**).

**Table 4-1**  
**PCE Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms**

Time (Weeks)	PCE					
	SDC-9™ + Lactate	SDC-9™ + EOS	Lactate	EOS	Live Control	Killed Control
0	1.7±0.5	0.8±0.1	2.3±0.8	1.1±0.1	2.4±0.3	2.7±0.3
1	<0.3	<0.3	ND <sup>a</sup>	ND	3.2±0.3	3.1±0.3
5	<0.7	<0.7	<0.7	<0.7	2.9±0.5	3.3±0.3
9	ND	ND	<0.6	<0.6	2.6±0.3	3.1±0.1
13	ND	ND	<0.2	<0.6	2.5±0.4	2.9±0.3

<sup>a</sup> ND; No data point taken.

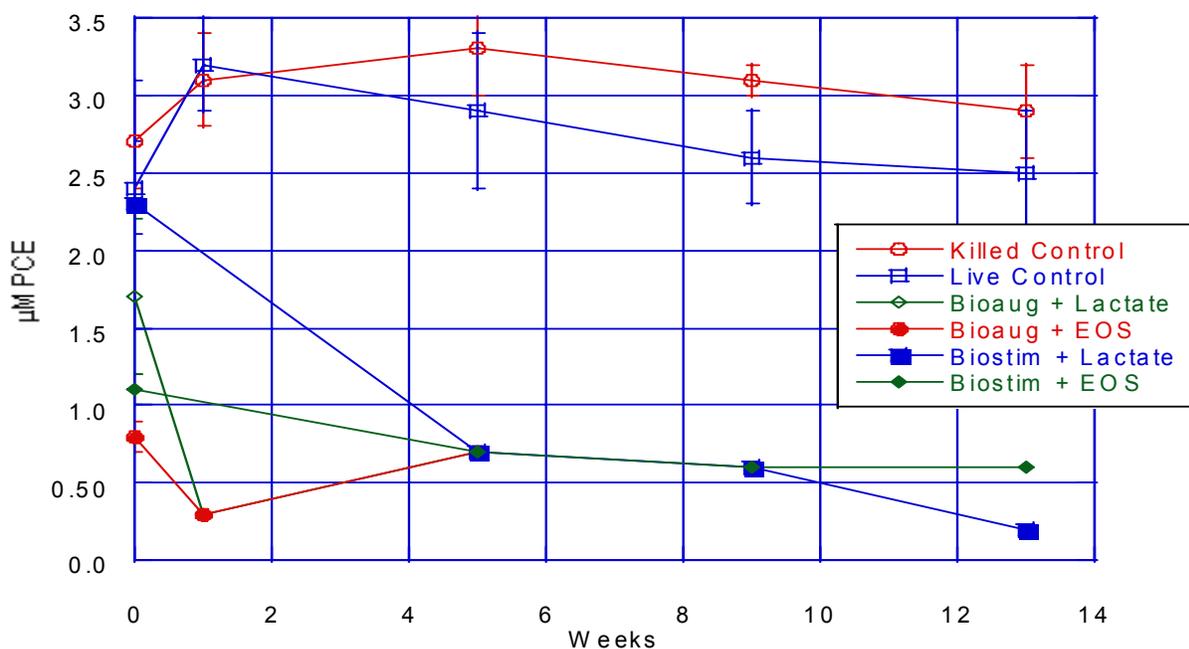
**Table 4-2**  
**TCE Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms**

Time (Weeks)	TCE					
	SDC-9™ + Lactate	SDC-9™ + EOS	Lactate	EOS	Live Control	Killed Control
0	0.8±0.2	0.4±0.1	0.5±0.2	0.5±0.0	0.6±0.1	0.6±0.1
1	<0.4	<0.4	ND <sup>a</sup>	ND	0.7±0.0	0.7±0.0
5	<0.9	<0.9	<0.9	<0.9	0.6±0.1	0.8±0.1
9	ND	ND	<0.8	<0.8	0.6±0.1	0.7±0.0
13	ND	ND	<0.2	<0.8	0.6±0.1	0.7±0.1

<sup>a</sup> ND; No data point taken.

**Figure 4-1**

**PCE Levels in Biostimulation and Bioaugmentation Microcosms**



The PCE and TCE breakdown products DCE and VC were reduced below detection (PQL of 120 ppb (1.9 mM)) within five weeks (**Tables 4-3 and 4-4**).

**Table 4-3**  
**DCE Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms**

Time (Weeks)	DCE					
	SDC-9 <sup>TM</sup> + Lactate	SDC-9 <sup>TM</sup> + EOS	Lactate	EOS	Live Control	Killed Control
0	0.7±0.2	0.5±0.1	0.6±0.2	0.7±0.0	0.6±0.0	0.7±0.0
1	0.6±0.8 <sup>b</sup>	2.9±0.3	ND <sup>a</sup>	ND	0.7±0.1	0.7±0.0
5	<1.2	<1.2	5.2±0.6	4.9±0.3	0.6±0.1	0.7±0.0
9	ND	ND	1.8±2.4 <sup>b</sup>	4.1±0.1	0.5±0.0	0.9±0.4 <sup>b</sup>
13	ND	ND	<0.3	5.2±0.1	0.6±0.1	0.7±0.1

<sup>a</sup> ND; No data point taken. Concentration less than detected limit.

<sup>b</sup> One-half of the detection limit was used for non-detect replicates.

**Table 4-4**  
**VC Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms**

Time (Weeks)	VC					
	SDC-9 <sup>TM</sup> + Lactate	SDC-9 <sup>TM</sup> + EOS	Lactate	EOS	Live Control	Killed Control
0	0.4±0.1	<0.8	<0.8	<0.8	<0.8	<1.1
1	1.3±1.3	0.7±0.2	ND <sup>a</sup>	ND	<0.8	<1.3
5	<1.9	<1.9	<1.9	<1.9	<1.9	<1.9
9	ND	ND	2.1±2.6	<1.6	<1.6	<3.2
13	ND	ND	0.3±0.2 <sup>b</sup>	<1.6	<1.6	<1.6

<sup>a</sup> ND; No data point taken. Concentration less than detected limit.

<sup>b</sup> One-half of the detection limit was used for non-detect replicates.

Measurable concentrations of ethene, the likely degradation end product of biostimulation/bioaugmentation, were present in both bioaugmentation treatments (**Table 4-5**), thus indicating that complete dechlorination was occurring.

**Table 4-5**  
**Ethene Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms**

Time (Weeks)	Ethene					
	SDC-9 <sup>TM</sup> + Lactate	SDC-9 <sup>TM</sup> + EOS	Lactate	EOS	Live Control	Killed Control
0	<0.29	<0.29	<0.07	<0.07	<0.07	<0.07
1	2.0±1.5	0.05±0.01 <sup>c</sup>	ND <sup>a</sup>	ND	<0.07	<0.07
5	6.4±5.1	47±5.3 <sup>b</sup>	1.7±1.9 <sup>c</sup>	<0.07	<0.07	<0.07
7	20.3±14.2 <sup>b</sup>	81.2±23.7 <sup>b</sup>	<71.4 <sup>b</sup>	<3.57	<0.07	<0.07
9	ND	ND	<7.14 <sup>b</sup>	<7.14 <sup>b</sup>	<0.07	<0.07
13	ND	ND	6.5±0.8	<0.36	<0.07	<0.07
16	ND	ND	6.3±2.3	<23.9	<0.07	<0.07

<sup>a</sup> ND; No data point taken. See Note b.

<sup>b</sup> High methane levels in sample masked ethene.

<sup>c</sup> One-half of the detection limit was used for non-detect replicates.

As expected, dechlorination of VOCs via biostimulation took considerably longer than when bioaugmentation was employed. In the biostimulation microcosms, PCE and TCE levels were reduced below the PQL of 120 ppb (1.9 mM) at five weeks, with 500 ppb (5 mM) DCE present at that time. Complete dechlorination to ethene occurred in the lactate treatment, but dechlorination appeared to stall at DCE in the EOS treatment. Ethene was detected in only the lactate treatment.

There was no measurable loss of PCE in both the killed and live controls over the course of the study. Initial PCE concentration in the EOS-amended treatments was substantially less than in the controls and lactate-amended treatments; this is likely the result of PCE partitioning into the oil. For the lactate bioaugmentation treatment, the reduced initial time zero PCE concentration (relative to the controls) may reflect partial biodegradation of the PCE within the 24-hour equilibration period. Evaluation of overall contaminant molar balances was inhibited by elevated methane concentrations, which interfered with the ethene analysis (**Table 4-5**). Ethene analyses for the lactate-amended treatments (biostimulation and bioaugmentation) that were not impacted by methane showed that final ethene levels of approximately 6.4 mM were obtained, which is approximately 1.6-times the stoichiometric ethene concentration that would be expected based on the initial chlorinated ethene concentrations. This discrepancy is likely due to sorbed PCE mass that was initially on the soil.

No ethane was detected in any of the biological treatments (**Table 4-6**).

**Table 4-6**  
**Ethane Levels ( $\mu\text{M}$ ) in the Bioaugmentation and Biostimulation Microcosms**

Time (Weeks)	Ethane					
	SDC-9 <sup>TM</sup> + Lactate	SDC-9 <sup>TM</sup> + EOS	Lactate	EOS	Live Control	Killed Control
0	<0.27	<0.27	<0.07	<0.07	<0.07	<0.07
1	<0.24	<0.07	ND <sup>a</sup>	ND	<0.07	<0.07
5	<0.91	<0.91	<0.91	<0.07	<0.07	<0.07
7	<1.33	<1.33	<66.7	<3.33	<0.07	<0.07
9	ND	ND	<6.67	<6.67	<0.07	<0.07
13	ND	ND	<0.33	<0.33	<0.07	<0.07
16	ND	ND	<0.33	<22.3	<0.07	<0.07

<sup>a</sup> ND; No data point taken. Concentration less than detected limit.

The pH data obtained during the course of this study are presented in **Table 4-7**. There were no significant changes in pH over the course of the study, with pH ranging between 6.7 and 8.0 in all treatments.

**Table 4-7**  
**pH (Standard Units) in the Bioaugmentation and Biostimulation Microcosms**

Time (Weeks)	pH					
	SDC-9 <sup>TM</sup> + Lactate	SDC-9 <sup>TM</sup> + EOS	Lactate	EOS	Live Control	Killed Control
0	7.17	7.35	7.08	7.42	7.75	7.52
1	7.12	7.30	ND <sup>a</sup>	7.40	7.72	7.48
5	6.71	6.49	6.68	6.85	7.59	6.99
9	ND <sup>a</sup>	ND <sup>a</sup>	6.78	7.04	7.99	7.14
13	ND <sup>a</sup>	ND <sup>a</sup>	6.77	6.88	7.11	7.26

<sup>a</sup> ND; No data point taken.

The ORP data obtained during the course of this study are presented in **Table 4-8**. Negative ORP values were observed in the three successful biological treatments (both bioaugmentation treatments and biostimulation with lactate), which is consistent with the success of these treatments. Positive ORP values were observed in the controls, which is consistent with the lack of dechlorination in these treatments.

**Table 4-8**  
**ORP (Millivolts) in the Bioaugmentation and Biostimulation Microcosms**

Time (Weeks)	ORP					
	SDC-9 <sup>TM</sup> + Lactate	SDC-9 <sup>TM</sup> + EOS	Lactate	EOS	Live Control	Killed Control
0	62	5	100	120	120	200
1	-120	-156	ND <sup>a</sup>	ND <sup>a</sup>	50	220
5	-120	-105	-86	18	2	11
9	ND <sup>a</sup>	ND <sup>a</sup>	78	112	126	163
13	ND <sup>a</sup>	ND <sup>a</sup>	31	138	124	177

<sup>a</sup> ND; No data point taken.

### **ZVI Microcosms**

Data from the ZVI testing are presented in **Tables 4-9** and **4-10**. Both ZVI treatments, NZVI and MZVI, were effective at treating the chlorinated ethenes. Contaminant degradation rates in each of the ZVI treatments were comparable. Both ethane and ethene were detected in each ZVI treatment at the final sampling event (t=5 weeks).

The rate of PCE degradation in the ZVI treatments was less than the rate of PCE degradation observed in the bioaugmentation and lactate biostimulation studies. However, no transient accumulation of DCE or VC was observed in the ZVI treatments.

**Table 4-9**  
**Contaminant Levels ( $\mu\text{M}$ ) in Jones Road ZVI Microcosms.**

Time (Weeks)	PCE			TCE		
	NZVI	MZVI	Live Control	NZVI	MZVI	Live Control
0	2.5 $\pm$ 0.6	2.0 $\pm$ 0.4	2.3 $\pm$ 0.5	0.5 $\pm$ 0.1	0.4 $\pm$ 0.1	0.5 $\pm$ 0.1
1	1.5 $\pm$ 0.3	1.1 $\pm$ 0.4	2.2 $\pm$ 0.4	<0.4	<0.4	0.5 $\pm$ 0.1
3	0.6 $\pm$ 0.2	0.3 $\pm$ 0.1	1.7 $\pm$ 0.4	<0.2	<0.2	0.4 $\pm$ 0.1
4	0.4 $\pm$ 0.2	0.1 $\pm$ 0.0 <sup>a</sup>	1.3 $\pm$ 0.2	<0.2	<0.2	0.4 $\pm$ 0.1
5	0.4 $\pm$ 0.2	<0.1	1.2 $\pm$ 0.3	<0.2	<0.2	0.4 $\pm$ 0.1

Time (Weeks)	DCE			VC		
	NZVI	MZVI	Live Control	NZVI	MZVI	Live Control
0	0.5 $\pm$ 0.1	<0.5	0.5 $\pm$ 0.1	<0.8	<0.8	<0.8
1	0.4 $\pm$ 0.0	<0.4	0.5 $\pm$ 0.1	<0.8	<0.8	<0.8
3	0.3 $\pm$ 0.0	<0.2	0.5 $\pm$ 0.1	<0.4	<0.4	<0.4
4	0.2 $\pm$ 0.0	<0.2	0.4 $\pm$ 0.1	<0.4	<0.4	<0.4
5	0.2 $\pm$ 0.0	<0.2	0.5 $\pm$ 0.1	<0.4	<0.4	<0.4

<sup>a</sup> One-half of the detection limit was used for non-detect replicates.

**Table 4-10**  
**Final Ethane and Ethene Values ( $\mu\text{M}$ ) for ZVI Microcosms.**

	NZVI	MZVI	Live Control
Ethene	1.9 $\pm$ 0.3	2.4 $\pm$ 0.2	<0.1
Ethane	0.6 $\pm$ 0.1	0.8 $\pm$ 0.1	<0.1

PCE concentrations in the Live Control decreased by approximately 50 percent during the 5-week study. The reason for this decrease is unclear. Contaminant molar balances in the two ZVI treatments showed greater than an 83 percent molar conversion to ethene (based on initial aqueous phase chlorinated ethene concentrations). No ethene or ethane was detected in the control.

### 4.3 Conclusions

Results of the Lawrenceville Technology Laboratory study indicate the following:

- Bioaugmentation with lactate or EOS, and biostimulation with lactate, resulted in the complete dechlorination of PCE;
- Bioaugmentation with SDC-9<sup>TM</sup> increased the treatment kinetics relative to biostimulation;
- Treatment using both NZVI and MZVI resulted in complete dechlorination of PCE, with no transient accumulation of DCE or VC.

Overall, results of this study show that bioaugmentation, biostimulation with lactate, and NZVI/MZVI are potential treatment options for PCE at the site.

## 5.0 CONCLUSION AND RECOMMENDATION

---

Treatability studies using both microcosm testing of soils and groundwater from the Jones Road site have identified several insitu technologies that successfully degraded PCE and its daughter products. Treatability testing determined that permanganate oxidation was the most effective ISCO technology. Bioremediation treatability testing determined that both bioaugmentation and biostimulation effectively treated PCE and its daughter products in Jones Road soils and groundwater. Biostimulation with lactate had the best reaction kinetics. ZVI also effectively treated the PCE and its daughter products.

As discussed in Section 1.0 of this report, subsurface soils at the Jones Road site are clays, clayey sands, and sandy clays with intermittent sand lenses. Sand layers are discontinuous and at variable depths in the shallow saturated zone (depths of approximately 28-50 feet bgs) at the site. PCE and its daughter products are also present in the vadose zone soils at the site, and at deeper depths in the saturated zone. Due to the presence of low permeability zones, site conditions pose a challenge to implementing an insitu remedial technology at the site. Another challenge, not addressed by this report, are logistics for a pilot study or full-scale implementation, since the facility is occupied and the lot on the south side of the former dry cleaner is an open public area, and the area with the highest shallow groundwater contamination (GP-3A) is a narrow alley with underground utilities. These conditions do not eliminate the possibility of performing a pilot study and full-scale technology application at the Jones Road site. Insitu treatment in the shallow source area is critical for mass VOC destruction and mitigation of the source area. **Figure 1-1**, the Site Plan, shows the potential locations for pilot studies.

Site conditions at Jones Road, including abundant clays, deep contamination migration, and an existing source area, may require the application of remedial technologies in combination. The technology that addresses the shallow source area may not be what is needed at deeper depths. For example, ISCO technologies may be more appropriate in shallower source zones and biotechnologies may be more appropriate at depth or in extended plume areas. An immediate need is to implement a technology that would, in a short amount of time, significantly reduce the mass and mobility of PCE source material. July 2006 Geoprobe<sup>®</sup> studies detected significant concentrations of PCE (i.e., GP-3A = 190,000 µg/L, GP-7A = 43,000 µg/L) near the former Bell Dry Cleaners. An ISCO pilot study, using potassium permanganate, should be performed in this area. Prior to selecting one of the proposed test sites shown on **Figure 1-1**, a conceptual site model (CSM) needs to be developed that includes, as detailed as possible, geologic cross sections and hydraulic information. The CSM will allow for the placement of both injection and monitoring wells and selection of well screen intervals. The CSM will help evaluate where to install pilot study monitoring points to evaluate how the ISCO acts within the various clay and

sand layers. PCE and daughter products have migrated laterally and downward through the subsurface at the site. Applying an insitu technology like ISCO, or a biotechnology, has a good chance of destroying VOCs along preferential flow pathways.

CSM and pilot study results will also allow for an evaluation and planning of a full-scale technology application. CSM information is also critical for developing an appropriate implementation of an ISCO or biotechnology to deeper zones. Although in some areas ISCO should be conducted first, another pilot study to evaluate application and sustainability of a bioaugmentation technology in deeper zones should be considered. In deeper zones, greater than 50 feet and possibly 100 feet, PCE contamination may be addressed by developing zones within sand units where a sustained active bioremediation zone acts as a migration barrier. Such an approach utilizes ISCO in shallower source type areas and biotechnology in deeper migration pathway zones. Because of complex site conditions and the deep nature of the contamination, TCEQ will need to consider a multiple technology approach to the Jones Road site.

More specific details (design) on how to address site-specific conditions would be included in a pilot study work plan. Actions often associated with pilot studies may include short-term aquifer tests (open well and packer studies) to evaluate site hydraulics. Bromide tracer studies are often used with insitu applications to evaluate delivery and distribution pathways. Potassium permanganate with its unique purple color acts as its own tracer.

A pilot test would include a test well network, including injection and extraction wells, and monitoring wells. Insitu technology amendments (ISCO or biotechnology) are placed in the test treatment zone through the injection wells. The pilot test may include single or multiple injections. One or several injection/extraction well pairs may be used during the test. Several monitoring well points may be installed between the injection and extraction wells. Whenever possible, existing monitoring wells are used as monitoring points. The treatment dosage is based on treatability study results and the hydraulic data collected during short-term aquifer tests. Groundwater is recovered from the extraction wells and analyzed on a pre-determined frequency to evaluate PCE and daughter product concentrations. Along with VOCs, natural attenuation parameters and metals are often part of the pilot test analytical program. Extraction well flow rates are based on short-term aquifer test data and tracer test results. Injection, extraction, and monitoring well placement and screen intervals would be based on the CSM and aquifer characteristics.

A report of pilot test results, including a description of the test design and procedures, expected results, and actual results, would be prepared after the test. The report would also include recommendations and a conceptual design for a full-scale (selected area or site-wide) application.

Once a CSM is developed and pilot tests are conducted, a more complete technology assessment and application strategy can be developed which addresses cost, site conditions, and life-cycle engineering for a full-scale remedial technology implementation.

## 6.0 REFERENCES

---

- Block, P. A., R. A. Brown and D. Robinson, 2004, "Novel Activation Technologies for Sodium Persulfate In-Situ Chemical Oxidation," Proceedings of the Fourth International Conference on the Remediation of Chlorinated and Recalcitrant Compounds," Monterrey, CA.
- FMC Corporation, 2001, Persulfates: Technical Information Bulletin
- Hoag, G.E., P. V. Chheda, B. A. Woody and G. M. Dobbs, 2000, "Chemical Oxidation of Volatile Organic Compounds," Patent No. 6,019,548, February 1, 2000.
- Liang, C., C. J. Bruell, M. C. Marley and K. Sperry, 2001, "Kinetics of Thermally Activated Persulfate Oxidation of Trichloroethylene (TCE) and 1,1,1-Trichloroethane (TCA)," The First International Conference on Oxidation and Reduction Technologies for In-Situ Treatment of Soil and Groundwater, Niagara Falls, Ontario, Canada, June 25-29, 2001.
- Neta, P., R. E. Huie and A. B. Ross, 1987, "Rate Constants for Reactions of Inorganic Radicals in Aqueous Solution," Chemical Kinetics Division, National Bureau of Standards and the University of Notre Dame Radiation Laboratory, Document No. NDRL-3028.
- Shaw, 2006, "Jones Road Remedial Investigation Report".
- Shaw, 2006, "Jones Road Site Treatability Study Work Plan", October 12, 2006.
- Shaw, 2007, "July 2006 Geoprobe<sup>®</sup> Investigation", January 24, 2007.
- Yan, Y. Eugene, Frank W. Schwartz, 1999, "Oxidative Degradation and Kinetics of Chlorinated Ethylenes by Potassium Permanganate", Journal of Contaminant Hydrology, V37, 343-365.

## *Appendix A*

### *Soil Acid Buffering Capacity Measurement Data*



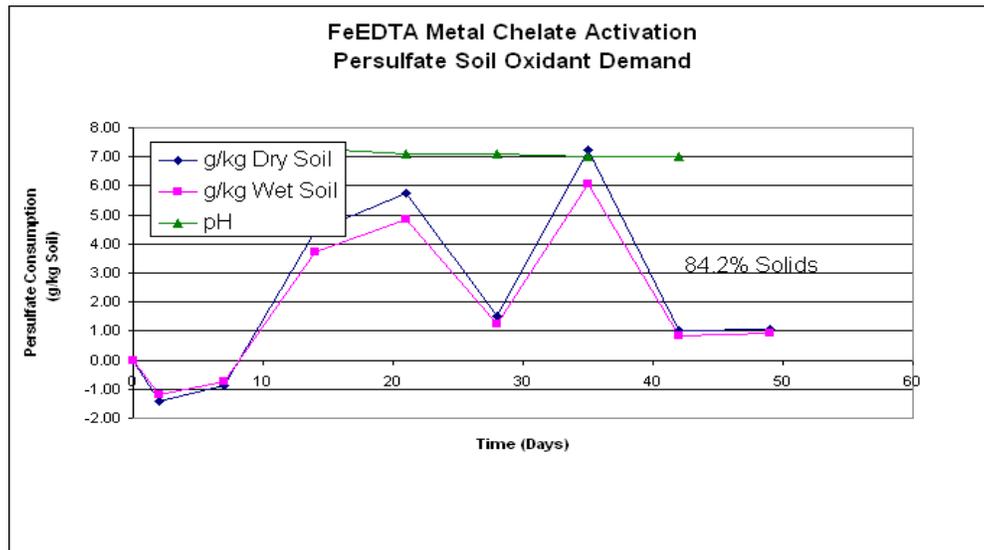
*Appendix B*

*Soil Oxidant Demand Test Data*

Project Name:	<u>Jones Road</u>	Date Started:	<u>8/30/2006</u>
Project Number:	<u>121615.05</u>	Analyst Initials:	<u>XZ</u>
Client Sample No. (Soil):	<u>NA</u>	Client Sample No. (Water):	<u>NA</u>
Description:	<u>Clayey soil</u>	Description:	<u>Groundwater</u>
TAL Sample No.:	<u>10506</u>	TAL Sample No.:	<u>10507</u>
Solids (%):	<u>84.20%</u>	Volume Used (mL):	<u>200</u>
Fraction -4 mm particle size :	<u>NA</u>	Initial Weight $\text{Na}_2\text{S}_2\text{O}_8$ (g):	<u>4.00</u>
Weight Used (g):	<u>200</u>	Initial Conc. $\text{Na}_2\text{S}_2\text{O}_8$ (mg/L):	<u>20,000</u>
Test Temp ( $^{\circ}\text{C}$ )	<u>15</u>		

FeEDTA at 150 mg/L Fe

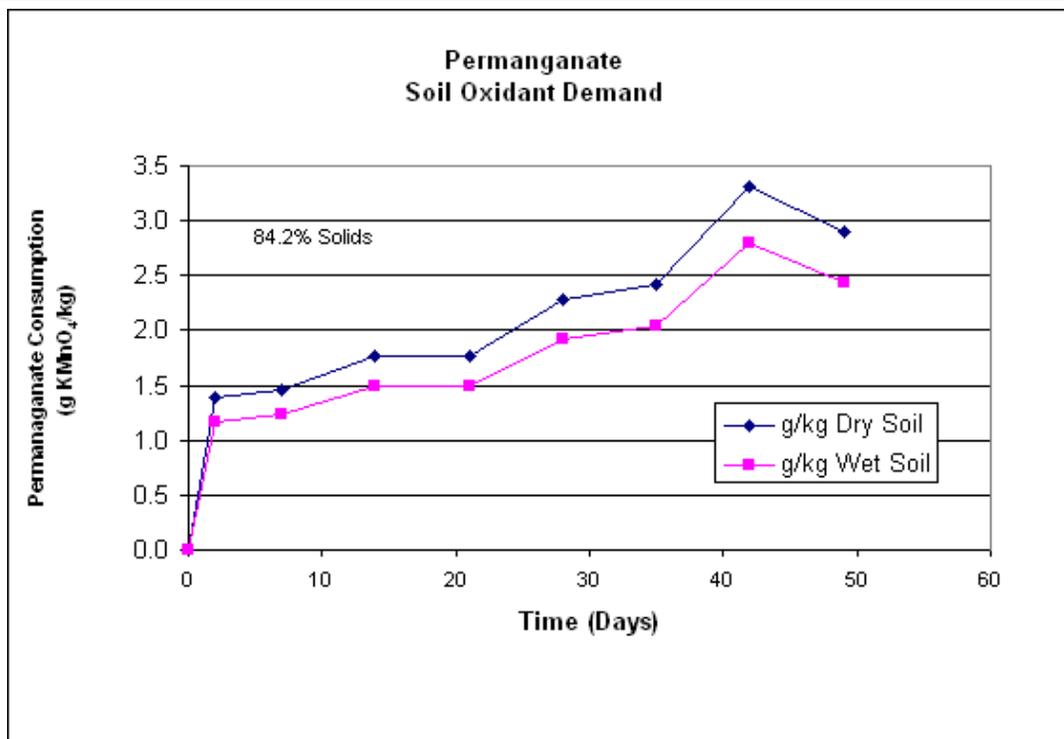
Time (Days)	Persulfate Conc. (mg/L)	Persulfate Addition (g)	Total $\text{Na}_2\text{S}_2\text{O}_8$ Added (g)	pH (SI)	Persulfate Consumed (g/kg Dry Soil)	Persulfate Consumed (g/kg Wet Soil)
0	17,271	0.0	4.00		0.00	0.00
2	18,300	0.0	4.00	7.15	-1.41	-1.19
7	17,900	0.0	4.00	6.99	-0.86	-0.73
14	14,042	0.0	4.00	7.3	4.44	3.74
21	13,090	0.0	4.00	7.1	5.75	4.84
28	16,184	0.0	4.00	7.09	1.50	1.26
35	12,019	0.0	4.00	7.02	7.22	6.08
42	16,541	0.0	4.00	7.02	1.00	0.85
49	16,482	0.0	4.00	7.02	1.09	0.91



Project Name: Jones Road  
 Project Number: 121615.050000  
 Client Sample No. (Soil): NA  
 Description: Clayey soil  
 TAL Sample No.: 10506  
 Solids (%): 84.20%  
 Fraction -4 mm particle size : NA  
 Weight Used (g): 200  
 Test Temp (°C) 15

Date Started: 8/30/2006  
 Analyst Initials: XZ  
 Client Sample No. (Water): NA  
 Description: Groundwater  
 TAL Sample No.: 10507  
 Volume Used (mL): 200  
 Initial Weight KMnO<sub>4</sub> (g): 2.000  
 Initial Conc. KMnO<sub>4</sub> (mg/L): 10,000

Time (Days)	KMnO <sub>4</sub> Conc. (mg/L)	KMnO <sub>4</sub> Addition (g)	Total KMnO <sub>4</sub> Added (g)	Time (Days)	KMnO <sub>4</sub> Consumed (g/kg Dry Soil)	KMnO <sub>4</sub> Consumed (g/kg Wet Soil)
0	8636	0.0	2.00	0	0.00	0.00
2	7625	0.0	2.00	2	1.39	1.17
7	7575	0.0	2.00	7	1.46	1.23
14	7350	0.0	2.00	14	1.77	1.5
21	7350	0.0	2.00	21	1.77	1.5
28	6975	0.0	2.00	28	2.28	1.9
35	6875	0.0	2.00	35	2.42	2.0
42	6225	0.0	2.00	42	3.32	2.8
49	6525	0.0	2.00	49	2.90	2.4



*Appendix C*

*Treatment Effectiveness Test VOC Analysis Data*

**VOC Analytical Data**  
**Laboratory Chemical Oxidation Treatment Study**  
**Jones Road Superfund Site**  
**November 2006**

Treatment	Dosage (g/L)	Sample ID	Water							Soil						
			VC (µg/L)	trans-DCE (µg/L)	Cis-DCE (µg/L)	TCE (µg/L)	PCE (µg/L)	Oxidant (mg/L)	pH	VC (µg/kg)	trans-DCE (µg/kg)	Cis-DCE (µg/kg)	TCE (µg/kg)	PCE (µg/kg wet soil)	Solids content	PCE (µg/kg dry soil)
0 day Control	NA	C1-0	25 U	25 U	34.412	16.687	1243.918	0	7.49	3.43 U	3.43 U	3.43 U	3.43 U	42.583	77.42%	0
	NA	C2-0	25 U	25 U	14.823	8.382	1252.424	0	7.57	4.83 U	4.83 U	4.83 U	4.83 U	39.909	75.51%	0
14 day control	NA	C2-14	25 U	25 U	63.504	57.295	1575.233	0	7.12	5.55 U	5.55 U	5.55 U	5.55 U	91.464	75.46%	0
21 day control	NA	C1-21	2.5 U	2.5 U	2.5 U	2.5 U	95.547	0	7.9	5.67 U	5.67 U	5.67 U	5.67 U	15.009	70.16%	0
1 day, permanganate	3	M1-1	2.5 U	2.5 U	2.5 U	2.5 U	2.5 U	2540		4.63 U	4.63 U	4.63 U	4.63 U	4.63 U	64.90%	0
	5	M2-1	2.5 U	2.5 U	2.5 U	2.5 U	2.5 U	4280		5.2 U	5.2 U	5.2 U	5.2 U	5.2 U	67.55%	0
	10	M3-1	2.5 U	2.5 U	2.5 U	2.5 U	2.5 U	8800		4.43 U	4.43 U	4.43 U	4.43 U	12.481	67.55%	18.48
4 days, permanganate	3	M1-4	2.5 U	2.5 U	2.5 U	2.5 U	2.5 U	2590		4.75 U	4.75 U	4.75 U	4.75 U	4.75 U	68.40%	0
	5	M2-4	2.5 U	2.5 U	2.5 U	2.5 U	2.5 U	5480		4.98 U	4.98 U	4.98 U	4.98 U	4.98 U	67.36%	0
	10	M3-4	2.5 U	2.5 U	2.5 U	2.5 U	2.5 U	8800		5.13 U	5.13 U	5.13 U	5.13 U	5.13 U	70.44%	0
14 days, permanganate	3	M1-14	2.5 U	2.5 U	2.5 U	2.5 U	2.5 U	2630		5.38 U	5.38 U	5.38 U	5.38 U	5.38 U	72.20%	0
	5	M2-14	2.5 U	2.5 U	2.5 U	2.5 U	2.5 U	4240		5.26 U	5.26 U	5.26 U	5.26 U	5.26 U	69.02%	0
	10	M3-14	2.5 U	2.5 U	2.5 U	2.5 U	2.5 U	8360		5.24 U	5.24 U	5.24 U	5.24 U	5.24 U	67.77%	0
4 days, persulfate	2	S1-4	2.5 U	2.5 U	57.938	55.494	1191.344	1785	7.56	9.45 U	9.45 U	9.45 U	9.45 U	118.825	75.50%	0
	5	S2-4	2.5 U	2.5 U	28.352	16.379	795.244	4760	7.64	8.9 U	8.9 U	8.9 U	8.9 U	60.864	69.14%	0
	10	S3-4	2.5 U	2.5 U	18.523	7.973	424.266	9401	7.69	7.0 U	7.0 U	7.0 U	7.0 U	34.79	71.64%	0
8 days, persulfate	2	S1-8	2.5 U	2.5 U	15.388	5.759	251.393	1963.5	7.74	3.9 U	3.9 U	3.9 U	3.9 U	45.111	68.34%	0
	5	S2-8	2.5 U	2.5 U	28.223	15.094	909.551	4760	7.44	4.55 U	4.55 U	4.55 U	4.55 U	52.275	75.35%	0
	10	S3-8	2.5 U	2.5 U	24.851	14.057	438.149	9282	7.4	3.78 U	3.78 U	3.78 U	3.78 U	37.022	72.55%	0
21 days, persulfate	2	S1-21	2.5 U	2.5 U	2.5 U	2.5 U	42.011	1696	7.65	4.83 U	4.83 U	4.83 U	4.83 U	9.069	73.08%	0
	5	S2-21	2.5 U	2.5 U	20.934	11.016	498.767	4641	7.21	4.90 U	4.90 U	4.90 U	4.90 U	27.065	71.44%	0
	10	S3-21	2.5 U	2.5 U	10.819	4.465	154.452	9044	6.94	4.24 U	4.24 U	4.24 U	4.24 U	9.007	74.79%	0

U – Laboratory reporting limits

*Appendix D*

*Treatment Effectiveness Test Metal Analysis Data*

**Metal Analysis Data**  
**Laboratory Chemical Oxidation Treatment Study**  
**Jones Road Superfund Site**  
**November 2006**

Sample ID	Ag (mg/L)	Al (mg/L)	As (mg/L)	Ba (mg/L)	Be (mg/L)	Ca (mg/L)	Cd (mg/L)	Co (mg/L)	Cr (mg/L)	Cu (mg/L)	Fe (mg/L)	K (mg/L)	Mg mg/L)
<i>MDL</i>	0.012	0.086	0.012	0.005	0.005	0.150	0.012	0.026	0.026	0.026	0.150	0.75	0.015
<b>C1-0</b>	<0.012	1.54	<0.012	0.171	<0.005	34.1	<0.012	<0.026	<0.026	<0.026	0.486	<0.75	6.39
<b>C2-0</b>	<0.012	1.35	<0.012	0.162	<0.005	32	<0.012	<0.026	<0.026	<0.026	0.479	<0.75	6.50
<b>C1-21</b>	<0.012	8.59	<0.012	0.162	<0.005	27.2	<0.012	<0.026	<0.026	<0.026	4.7	<0.75	5.86
<b>C2-14</b>	<0.012	1.41	<0.012	0.213	<0.005	40.5	<0.012	<0.026	<0.026	<0.026	0.566	<0.75	8.01
<b>M1-14</b>	0.076	0.519	<0.012	1.61	<0.005	203	<0.012	<0.026	0.232	<0.026	< 0.150	116	35.8
<b>M2-14</b>	0.114	0.863	<0.012	2.19	<0.005	220	<0.012	<0.026	0.288	<0.026	< 0.150	284	44.1
<b>M3-14</b>	0.242	0.788	<0.012	4.5	<0.005	472	<0.012	<0.026	0.472	<0.026	< 0.150	920	68.9
<b>S1-21</b>	0.017	0.936	<0.012	0.438	<0.005	133	<0.012	<0.026	<0.026	<0.026	44.5	<0.75	20.6
<b>S2-21</b>	0.034	0.974	<0.012	0.164	<0.005	220	<0.012	<0.026	<0.026	<0.026	86.4	<0.75	35.1
<b>S3-21</b>	0.044	0.309	<0.012	0.106	<0.005	322	<0.012	0.070	<0.026	<0.026	115	<0.75	48.7

Sample ID	Mn (mg/L)	Mo (mg/L)	Na (mg/L)	Ni (mg/L)	P (mg/L)	Pb (mg/L)	S (mg/L)	Sb (mg/L)	Se (mg/L)	Sn (mg/L)	Ti (mg/L)	V (mg/L)	Zn mg/L)
<i>MDL</i>	0.026	0.026	0.055	0.012	0.026	0.012	0.026	0.012	0.012	0.026	0.012	0.026	0.012
<b>C1-0</b>	<0.026	<0.026	133	<0.012	0.242	<0.012	6.45	<0.012	<0.012J	<0.026	<0.012	<0.026	<0.012
<b>C2-0</b>	<0.026	<0.026	125	<0.012	0.303	<0.012	6.62	<0.012	<0.012J	<0.026	<0.012	<0.026	<0.012
<b>C1-21</b>	<0.026	<0.026	120	<0.012	0.161	<0.012	6.45	<0.012	<0.012J	<0.026	<0.012	<0.026	<0.012
<b>C2-14</b>	<0.026	<0.026	132	<0.012	0.211	<0.012	6.49	<0.012	<0.012J	<0.026	<0.012	<0.026	<0.012
<b>M1-14</b>	574	<0.026	186	<0.012	<0.026	0.015	9.24	<0.012	0.153J	<0.026	0.243	<0.026	<0.012
<b>M2-14</b>	839	<0.026	205	<0.012	<0.026	0.033	10.1	<0.012	0.299J	<0.026	0.496	<0.026	<0.012
<b>M3-14</b>	1163	<0.026	233	<0.012	<0.026	0.107	19.0	<0.012	0.747J	0.031	1.30	<0.026	<0.012
<b>S1-21</b>	0.376	<0.026	403	0.065	0.151	0.357	361	<0.012	<0.012J	<0.026	<0.012	<0.026	0.066
<b>S2-21</b>	0.358	<0.026	736	0.050	0.120	0.350	528	<0.012	<0.012J	<0.026	<0.012	<0.026	0.034
<b>S3-21</b>	1.10	<0.026	1137	0.062	0.102	0.298	552	<0.012	<0.012J	<0.026	<0.012	<0.026	0.047

J Qualifier = Estimated values maybe biased slightly low. Continuing standard outside 80-120% criteria at 79%.