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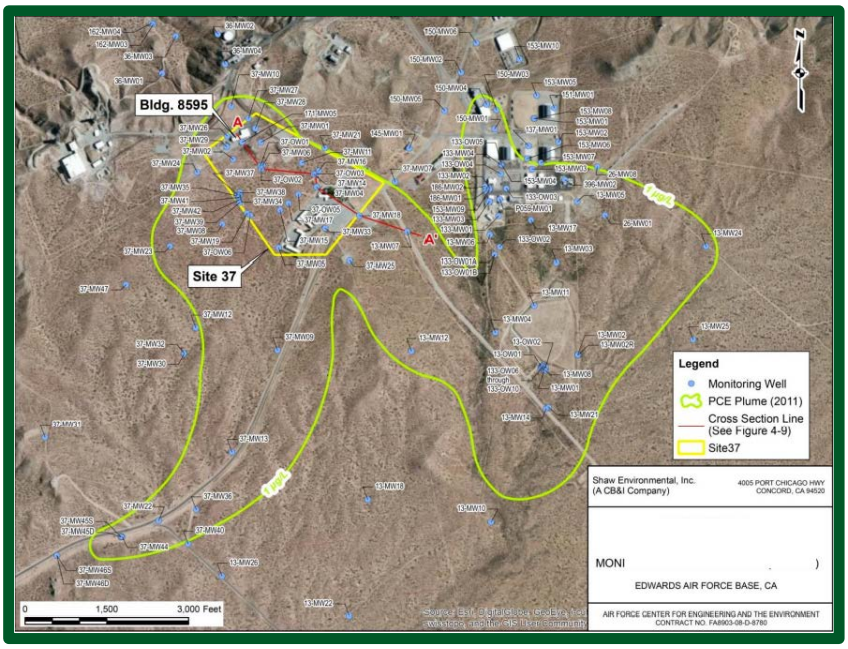

Designing, Assessing, and Demonstrating Sustainable Bioaugmentation for Treatment of DNAPL Sources in Fractured Bedrock

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14. ABSTRACT

Bioaugmentation was applied to treat the DNAPL sources present in the fracture zones that were targeted for investigation using the partitioning tracer testing. Nine months of active treatment (using groundwater re-circulation with electron donor and nutrient delivery) was followed by a 10-month rebound period. While enhanced dissolution of the DNAPL sources was observed in both the shallow and deep fractures intervals, a greater extent of DNAPL mass removal (approximately 100%) was observed in the shallow fracture zone, while only 45% of the DNAPL was removed in the deep zone. The difference in DNAPL mass removal between the two zones was attributed to the DNAPL architecture, as the flow field in the deep zone was more complex, and a greater extent of the DNAPL was present in mass transfer controlled zones. Furthermore, while no increases in chlorinated ethenes or ethene was observed in the shallow zone during the 10-month rebound period, data suggest the sum of chlorinated ethenes and ethene concentrations were increasing during rebound in the deep zone, likely due to the persistence of residual DNAPL sources. This highlights the relationship between DNAPL architecture and remedial performance.

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PCE, DNAPL, bedrock, bioaugmentation, bioremediation

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COST & PERFORMANCE REPORT

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ACRONYMS AND ABBREVIATIONS

µg/L	micrograms per liter
µM	micromolar
AFB	Air Force Base
AFP	Air Force Plant
AFRL	Air Force Research Laboratory
As	Arsenic
bgs	below ground surface
°C	degrees Celsius
CB&I	Chicago Bridge and Iron Federal Services
DAP	Diammonium Phosphate
DCE	*cis*-1,2-Dichloroethene
DHC	*Dehalococcoides* sp.
DMP	2,4-dimethyl-3-pentanol
DNAPL	Dense Non-Aqueous Phase Liquid
DoD	U.S. Department of Defense
ESTCP	Environmental Security Technology Certification Program
EVO	Emulsified Vegetable Oil
ft	foot or feet
GAC	Granular Activated Carbon
GC-FID	Gas Chromatography-Flame Ionization Detector
IPR	In-Progress Review
Kg	kilogram
MCL	Maximum Contaminant Level
mg/L	milligrams per liter
mL	milliliters
mL/min	milliliters per minute
mM	millimolar
Mn	Manganese
MNA	Monitored Natural Attenuation
MOM	Method of Moments
MRF	Mass Recovery Fraction
NPV	Net Present Value
O&M	Operation and Maintenance

ORP	Oxidation-Reduction Potential
OU	Operable Unit
P&ID	Piping and Instrumentation Diagram
P&T	Pump-and-treat
PCE	Tetrachloroethene
PID	Photoionization Detector
PLC	Programmable Logic Controller
PTT	Partitioning Tracer Test
QED	QED Environmental Systems
qPCR	Polymerase Chain Reaction
RDG	Reductive Dehalogenase Genes
SCADA	Supervisory Control and Data Acquisition
SERDP	Strategic Environmental Research and Development Program
SVE	Soil Vapor Extraction
TCE	Trichloroethene
TCH	Thermal Conductive Heating
USEPA/EPA	U.S. Environmental Protection Agency
VC	Vinyl Chloride
VFA	Volatile Fatty Acid
VOA	Volatile Organic Analysis
VOC	Volatile Organic Compound
ZVI	Zero-Valent Iron

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EXECUTIVE SUMMARY

OBJECTIVES

Management of contaminated fractured rock sites remains one of the top environmental challenges for the U.S. Department of Defense (DoD). Use of chloroethene solvents such as tetrachloroethene (PCE) and trichloroethene (TCE) has led to extensive contamination of both soil and groundwater. In particular, chloroethene source zones containing dense non-aqueous phase liquids (DNAPLs) in fractured rock have proven very difficult to remediate. Project ER-201210 was designed to test the ability of bioaugmentation to treat a PCE DNAPL source zone in fractured rock at Edwards Air Force Base (AFB), California.

Bioaugmentation is a relatively low-cost technology to remove and degrade DNAPLs, proven to be highly effective in unconsolidated media but not yet demonstrated in fractured rock. The specific demonstration objectives included: (1) removal of >9% of the DNAPL mass per month, (2) reducing the total chloroethene flux by >90% after treatment, and (3) achieving complete dechlorination of PCE to innocuous products (ethene and ethane). In addition, monitoring was performed ten months after treatment to assess the potential for rebound from untreated contaminants in the treatment zones. The latter two objectives were attained throughout, but removal in the deep zone was slower than desired (about 5% per month). Further, aqueous concentrations rebounded in the deep zone ten months after treatment ceased.

TECHNOLOGY DESCRIPTION

Bioaugmentation involves injecting a mixed culture of bacteria that includes *Dehalococcoides sp.* (DHC) strains capable of dechlorinating all of the chloroethenes, along with a carbon source (lactate) and nutrients. The anaerobic biological activities both increase the solubility of the DNAPL constituents and biodegrade contaminants in place. PCE is degraded through TCE to *cis*-1,2-dichloroethene (DCE), vinyl chloride (VC), and eventually ethene and ethane.

In this case, water containing amendments was recirculated through two target treatment zones, with extraction, treatment, and reinjection into separate depth intervals with discrete fractures. The field scale injections followed a detailed characterization of the target source zone that identified the two fracture intervals and quantified the DNAPL mass within each area through partitioning tracer testing. The amendments were recirculated through each depth interval to degrade PCE and its daughter products over a nine-month period, followed by a ten-month rebound period.

DEMONSTRATION RESULTS

A small portion of a (presumably) much larger DNAPL source area was targeted, and the DNAPL mass and distribution were quantified in two separate depth intervals with discrete fractures. Conventional hydraulic and geophysical tools, along with partitioning tracer testing, were used to quantify the DNAPL distributions in the shallow and deep fracture intervals. The geophysical testing showed that DNAPL was present, that the well capacities within the source area were sufficient to distribute the amendments in conductive fractures, and that there was hydraulic connectivity in both zones in the two wells used for the field test. Initial lab testing was done to verify that bioaugmentation using CB&I's SDC-9 culture could be effective, to assess the need for additional amendments (e.g., nutrients or pH buffer), and to evaluate the potential inhibitory or toxic effects of the partitioning tracers on SDC-9.

Pre-treatment characterization monitoring showed that very low levels of DNAPL (<1% of the fracture volume) persisted in several of the fracture zones, and that DNAPL was present in both the lower and higher transmissivity zones. During biological treatment, enhanced dissolution of the DNAPL sources was observed in both the shallow and deep fractures intervals. In the shallow fracture zone, the measured DNAPL mass removal was approximately 100%. However, the estimated DNAPL removal was only 45% over the same period in the deep zone. The difference in DNAPL mass removal between the two zones was attributed to the DNAPL architecture, as the flow field in the deep zone was more complex, and a greater extent of the DNAPL was present in mass transfer controlled zones.

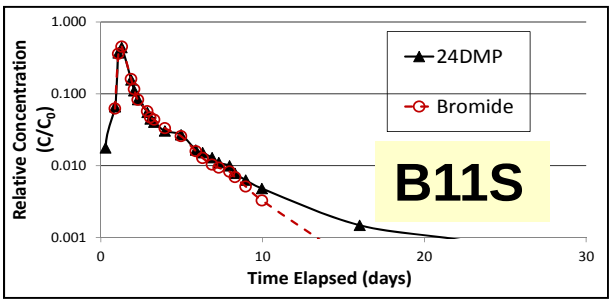
Rebound testing indicated that there was no increase in the sum of chlorinated ethenes and ethene in the shallow zone ten months after active treatment. In contrast, the sum of chloroethenes and ethene concentrations did rebound significantly in the deep zone, probably because residual DNAPL mass was still present. These results highlight the relationship between DNAPL architecture and remedial performance.

The costs were evaluated using a consistent base case for the three most common fractured rock source zone treatment technologies—bioaugmentation, thermal conductive heating (TCH), and active pump-and-treat. The estimated costs for bioaugmentation were considerably less than for the other two technologies, with estimated net present value costs of roughly $1.4M, $5.3M, and $3.7M, respectively.

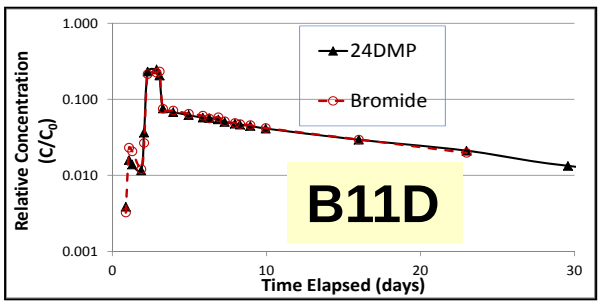
IMPLEMENTATION ISSUES

The challenges associated with DNAPL in fractured rock are similar to those encountered in unconsolidated media. However, these challenges are exacerbated by the complexities associated with the dual porosity nature of fractured rock, as well as the lack of insight into the highly complex DNAPL architecture at the field scale. The primary difficulties identified with implementing bioaugmentation at fractured rock sites were: (1) the complexity of the fracture flow paths, (2) the need for multi-level borehole sampling, and (3) the potential for biofouling at the injection wells.

SHALLOW ZONE – 100% REMOVAL



DEEP ZONE – 45% REMOVAL



1.0 INTRODUCTION

1.1 BACKGROUND

Management of dense non-aqueous phase liquid (DNAPL) tetrachloroethene (PCE) and trichloroethene (TCE) source areas in fractured bedrock is a challenging environmental concern for the U.S. Department of Defense (DoD). Several DoD facilities, including Air Force Plant 4 (AFP4), AFP6, Edwards Air Force Base (AFB), Loring AFB, and Redstone Arsenal, likely contain DNAPL sources in bedrock. These DNAPL sources in bedrock are particularly problematic to treat and manage because defining the nature and extent of the DNAPL source is difficult, DNAPL can sustain groundwater plumes for several decades, and intrinsic mass transfer limitations hinder source removal. Cost-effective treatment technologies for these DNAPL sources in fractured rock are not available. Conventional technologies such as pump-and-treat or chemical oxidation typically are not effective, and the cost and effectiveness of innovative technologies (e.g., thermal, surfactant flushing) have yet to be fully demonstrated. Thus, many DoD fractured bedrock DNAPL sites persist without any active treatment to remove the source.

Another obstacle in addressing DNAPL sources in fractured rock is uncertainty regarding the relationship between contaminant mass removal and the dissolved contaminant flux emanating from the source area. This uncertainty has made it difficult to treat and manage these DNAPL sites, as the extent of mass removal (or "remediation") that is required typically is unknown. Without knowing the extent of mass removal that is required to attain remedial goals for groundwater, or even how to assess this based on pilot scale testing, selecting an appropriate path forward is often difficult.

Because of these difficulties, field applications demonstrating the successful implementation of a selected technology that is both technically and economically effective for treating DNAPL sources in fractured rock have been very limited. As a result, impacts to aquifers from these DNAPL sources continue to occur, and the implementation of long-term containment approaches (e.g., pump-and-treat) for mitigating the downgradient plume are often employed. Demonstration and verification of a cost-effective technology for treating DNAPL sources in bedrock would provide a great benefit to the DoD.

As part of the completed Strategic Environmental Research and Development Program (SERDP) Project ER-1554, the use of bioaugmentation for treatment of PCE DNAPL sources in laboratory scale rock fracture experiments was demonstrated. However, there are currently no demonstrated examples of the successful application of biostimulation or bioaugmentation for treatment of DNAPL sources at the field scale in fractured bedrock so that a final monitored natural attenuation (MNA) remedy can be employed. No field studies have shown that bioaugmentation is effective in fractures containing residual DNAPL. While laboratory studies have demonstrated that bioaugmentation can substantially enhance DNAPL removal in rock fractures and reduce the dissolved flux emanating from the source area, a field scale study demonstrating that bioaugmentation can enhance DNAPL dissolution and mitigate dissolved contaminant flux, both within and downgradient of the DNAPL source has not been performed. Furthermore, methods to optimize implementation (in terms of sustainability, limiting carbon consumption, and minimizing costs) of bioaugmentation in bedrock have not been demonstrated; the ability to target specific fracture zones where DNAPL sources are present would facilitate this.

Thus, a demonstration and assessment of this cost-effective remedial approach is needed to determine the efficacy of this technology for treatment of DNAPL sources at fractured bedrock sites.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objectives of this project were to evaluate the use of bioaugmentation for treatment of PCE DNAPL sources in fractured rock, to assess treatment impacts on the dissolved downgradient plume, to demonstrate effective reductive dechlorination in DNAPL-filled fractures, and develop and verify design parameters to optimize sustainability. Specifically, this evaluation consisted of an assessment of the DNAPL architecture (including identification of specific fracture or fractures zones that contain DNAPL sources), DNAPL dechlorination and dissolution rates in DNAPL-containing fractures, distribution and growth of dechlorinating bacteria both within and downgradient of the DNAPL source area, impact on dissolved contaminant flux emanating from the DNAPL source, and evaluation of electron donor demand during treatment. The relationship between incremental DNAPL mass removal and dissolved PCE concentrations also was assessed, with the ultimate goal of demonstrating that bioaugmentation can facilitate a final MNA remedy in bedrock. This demonstration was performed at the Site 37 PCE source area at Edwards AFB.

1.3 REGULATORY DRIVERS

PCE, along with its reductive dechlorination daughter products TCE, *cis*-1,2-dichloroethene (DCE), and vinyl chloride (VC), are regulated in drinking and ground water by both the U.S. Environmental Protection Agency (USEPA) and the state of California. The applicable groundwater standards are provided in Table 1.1.

Expected PCE concentrations in DNAPL source areas, assuming concentrations of at least 1% solubility, are 300-times above both state and federal regulatory levels. PCE groundwater concentrations in the demonstration source area at Edwards AFB are in excess of 1% solubility. It is significant to note that partial dechlorination of PCE, resulting in near-stoichiometric accumulation of either TCE, DCE, and/or VC, would result in regulatory exceedances of these compounds as well.

Table 1.1. Federal and California State Maximum Contaminant Levels (MCLs)

Constituents	**USEPA MCL** micrograms per liter **(µg/L)**	**California MCL (µg/L)**
Tetrachloroethene (PCE)	5	5
Trichloroethene (TCE)	5	5
cis-1,2-dichlorethene (DCE)	70	6
Vinyl Chloride (VC)	2	5

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

2.1.1 Background – Bioaugmentation

Bioaugmentation involves the subsurface delivery of bacteria, along with an electron donor (e.g., lactate, vegetable oil) and nutrients, which are capable of completely dechlorinating PCE and TCE. For chlorinated ethenes, bioaugmentation typically involves the use of mixed anaerobic cultures that contain *Dehalococcoides* sp. (DHC), or closely related strains, that can reductively dechlorinate the chlorinated ethenes. Bioaugmentation has been successfully applied at several DoD and industrial facilities using both passive (single or periodic injection of amendments) and active (continual or intermittent recirculation of groundwater) *in situ* remedial approaches. Thus, bioaugmentation is a proven and well-demonstrated technology with respect to treatment of chlorinated ethenes in groundwater.

2.1.2 Bioaugmentation for Treatment of DNAPL

While several laboratory and field studies have demonstrated the effectiveness of bioaugmenting with DHC for treating dissolved phase PCE and TCE (*1-5*), the use of this approach for treating DNAPL sources has received far less attention. However, since the treatment of DNAPL source areas has increasingly become a focus at many contaminated sites (*6-8*), there has been a recent increased focus on application of bioaugmentation for DNAPL sources. Batch and column studies have indicated that the presence of PCE DNAPL can have an inhibitory effect on the reductive dechlorination of PCE during bioaugmentation (*9-11*). Adamson et al. (*10*) noted the accumulation of TCE and *cis*-1,2-DCE in the DNAPL source zone, without further dechlorination to VC or ethene until PCE concentrations decreased to approximately 10 micromolar (µM).

Despite this apparent inhibitory effect of DNAPL on the reductive dechlorination of PCE, bioaugmentation has been shown to enhance the rate of PCE DNAPL dissolution in sand columns and flow cells by factors ranging from approximately 1.1 to 21 (*11-13*); enhancement rates generally were on the high end of this range when the dissolved concentration of PCE was less than approximately 300 µM (approximately 30% of the PCE solubility in water) (*11,13*). This enhancement occurs in the DNAPL source zone, despite the fact that (in some cases) only partial dechlorination to DCE occurs, because DCE is approximately 30-times more soluble than PCE. Thus, enhanced solubilization of the DNAPL occurs, with subsequent complete dechlorination of the DCE occurring immediately downgradient of the DNAPL zone.

2.2 TECHNOLOGY DEVELOPMENT

2.2.1 DNAPL in Fractured Bedrock – Discrete Fracture Scale Studies

While application of bioaugmentation for treatment of DNAPL in unconsolidated media has been demonstrated, as well as application of bioaugmentation to treat dissolved phase chlorinated ethenes in fractured bedrock (SERDP Project ER-1555), application of bioaugmentation to treat DNAPL sources in fractured bedrock has not yet been demonstrated. The architecture and dissolution of DNAPL in fractured bedrock can be substantially different than in unconsolidated media.

The role of fracture intersections (*15*), preferential flow in discrete fractures (*16*), and low (relative to sands) DNAPL-water interfacial area and dissolution rates (*17*) are among the factors that differentiate DNAPL dissolution in fractured bedrock from that in unconsolidated media.

As part of the recently completed SERDP project (ER-1554), the use of bioaugmentation for treating PCE in bench-scale discretely fractured sandstone blocks containing residual DNAPL has been evaluated. Bioaugmentation resulted in dechlorination of PCE, as evidenced by generation of DCE, ethene, and chloride; chloride was shown to be the best indicator of dechlorination due to back-partitioning of volatile organic compounds (VOCs) into the DNAPL (*18*). Furthermore, results of the discrete fracture experiments showed that bioaugmentation enhanced DNAPL dissolution by up to 3.5-times (relative to dissolution into groundwater alone) with dissolved PCE concentrations at or near solubility (*18*). Applying these DNAPL dissolution and dechlorination rates to a comparable field scale system (the short length scales in the bench scale systems amplified the importance of abiotic dissolution and masked the importance of biotic dissolution), the estimated DNAPL dissolution enhancement attained via bioaugmentation would be on the order of 30-times greater than via dissolution (e.g., pump-and-treat) alone. In addition, based on the observed DNAPL dechlorination kinetics observed in the bench scale testing, application of bioaugmentation for treatment of DNAPL sources can result in a 98% reduction (without rebound) in dissolved PCE concentration and flux within approximately 2.5 years of bioaugmentation treatment. Bioaugmentation was also shown to be more effective than chemical oxidation with respect to long-term mass removal, due to accumulation of precipitates at the DNAPL-water interface during chemical oxidation.

2.2.2 DNAPL in Fractured Bedrock – Intermediate Scale Fracture Network Studies

In the second phase of the SERDP Project ER-1554, bioaugmentation for treatment of PCE DNAPL in an intermediate scale fracture network was evaluated. DNAPL dissolution studies showed that residual DNAPL in the fracture network was better contacted by groundwater compared to the discrete fractures, likely owing to enhanced contact of DNAPL at the fracture intersections. Furthermore, dissolution was enhanced by a factor of approximately 100 during bioaugmentation in the intermediate scale fracture network. The reason for the relatively large increase in bioaugmentation effectiveness at the fracture network scale, compared to the discrete fracture scale, likely is due to the fact that the dissolved PCE concentrations were lower in the fracture network (due to dilution from flow heterogeneity). Larger fracture apertures in the fracture network also may have enhanced bioaugmentation effectiveness by facilitating biomass growth. Thus, intermediate scale fracture network experiments confirm that bioaugmentation is a potential treatment option for DNAPL sources in fractured bedrock.

2.2.3 DNAPL Source Strength Function in Fractured Bedrock

Several recent studies have evaluated DNAPL source strength (i.e., the relationship between DNAPL mass removed and dissolved flux emanating from the source) in unconsolidated materials (*19*-*22*). These studies have shown that the fraction of DNAPL mass removed is not necessarily proportional to the decrease in dissolved contaminant concentration and flux. The relationship between DNAPL mass removal and dissolved concentration/flux is typically determined by the DNAPL architecture.

As indicated on Figures 2.2 and 2.4, DNAPL source strength can be important for assessing potential effectiveness of a remedial technology, or for determining the longevity of the DNAPL source. Thus, proper assessment of bioaugmentation for treatment of bedrock DNAPL sources requires an assessment of DNAPL architecture within the fracture network, as these coupled physical and biological processes will determine the potential limits of success not only of bioaugmentation, but of most other remedial technologies (including MNA) implemented for treatment of DNAPL in fractured bedrock. It was demonstrated that DNAPL architecture plays an important role in DNAPL dissolution kinetics and during bioaugmentation (*17,18*). It has been shown that much of the DNAPL present in bedrock fractures has limited impact on groundwater quality. This finding has important implications for field scale management of DNAPL sources, as it implies that only a small fraction of the DNAPL mass may need to be removed in order to improve groundwater quality and facilitate an MNA remedy. However, DNAPL architecture in fractured bedrock is poorly understood at the field scale, as the relationship between DNAPL mass and dissolved flux emanating from DNAPL sources has not been evaluated in field scale bedrock fracture systems.

The findings discussed in the paragraphs above suggest that the effectiveness of bioaugmentation is dependent upon DNAPL architecture, and that only partial treatment of DNAPL sources may be sufficient for reducing contaminant flux so that an MNA remedy can be achieved. While the discrete fracture and intermediate fracture network scale studies evaluating DNAPL architecture and dechlorination rates in fractures have demonstrated that bioaugmentation for treatment of DNAPL sources in bedrock (and in factures containing DNAPL) is feasible, there currently are no reported field studies that have focused on assessing bioaugmentation for treating PCE/TCE DNAPL sources in bedrock fractures, particularly as it relates to DNAPL dissolution kinetics, DNAPL architecture, and dissolved plume response. Furthermore, the relationship between partial DNAPL mass removal and contaminant flux in fractured bedrock is unclear, and the extent to which bioaugmentation can reduce contaminant mass and flux has not been demonstrated or assessed at the field scale. As a result, the efficacy of bioaugmentation for addressing DNAPL sources in bedrock has not been demonstrated. In addition, screening and management tools for assessing DNAPL sources in bedrock are lacking, and improved understanding is needed to determine DNAPL source longevity and flux response on the dissolved plume.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.3.1 Advantages

The primary advantages of utilizing an *in situ* approach for treatment of PCE DNAPL sources in fractured bedrock are as follows:

1. Appreciably reduced cost, infrastructure, and timeframe compared to traditional pump-and-treat approaches; and,
2. Transformation to species that do not have maximum contaminant levels (MCLs) (i.e., ethene, ethane) in groundwater, rather than transferred to a secondary medium such as granular activated carbon (GAC).

In addition, the use of an active bioaugmentation approach for treatment of the PCE DNAPL sources provides several advantages over alternate *in situ* approaches, such as:

1. The addition of bacteria capable of enhancing the complete dechlorination of PCE is expected to enhance DNAPL dissolution and mitigate accumulation of daughter products.
2. The biological reactions are slower and longer lasting than other *in situ* approaches (e.g., chemical oxidation), and thus are well suited for treatment under the expected mass transfer controlled conditions in the DNAPL source area.
3. Energy requirements are substantially less than an aggressive *in situ* thermal treatment approaches.
4. Due to residual carbon and biomass, enhanced reductive dechlorination is expected to occur long after active treatment ceases.

2.3.2 Limitations

As with all technologies, there are also limitations with bioaugmentation:

1. Biofouling is a potential concern, especially at the injection well(s). Well re-development and more aggressive methods (e.g., application of a biocide) were required during the demonstration in an attempt to maintain active treatment design flowrates.
2. The groundwater oxidation-reduction potential (ORP) will be significantly reduced, which is necessary to create conditions conducive to reductive dechlorination of PCE. However, such a reduction in ORP also causes secondary geochemical impacts, such as mobilization of metals (e.g., dissolved Fe [II] and Mn [III] from dissolution of Fe and Manganese [Mn] oxides), sulfide production, and other changes in groundwater geochemistry that impact local groundwater quality. Arsenic mobilization is another potential concern.
3. Transient generation of chlorinated ethenes such as DCE and VC was expected and did occur during the demonstration.

3.0 PERFORMANCE OBJECTIVES

Performance objectives are summarized in Table 3.1. A summary of the data analysis to support the assessment of the performance objectives is provided in Section 6.0.

Table 3.1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Effectiveness of bioaugmentation for PCE DNAPL removal	Pre- and post-treatment measurement of DNAPL using partitioning tracer tests, and determination of DNAPL mass removal rates by measuring rates of daughter product generation	>9% DNAPL mass removal per month	This objective was attained for the shallow zone, but fell short (~5% / month) in the deep zone due to mass transfer limitations.
Effectiveness of bioaugmentation for reducing dissolved chlorinated ethene flux from the DNAPL source area	Pre- and post-treatment contaminant concentrations in groundwater wells using EPA Method 8260, and measurement of dissolved chlorinated ethene flux pre-and post-treatment using passive flux meters	>90% reduction in chlorinated ethene flux by the end of active treatment	This objective was attained for both the shallow and deep zones, but chlorinated ethene rebound may have been masked by ongoing reductive dechlorination in the deep zone.
Complete PCE dechlorination	Measurement of ethene and ethane	Ethene and/or ethane detected above background levels within or downgradient of the DNAPL source area	This objective was attained for both the shallow and deep zones.
Distribution and growth of *Dehalococcoides* sp. (DHC) following bioaugmentation	Measurements of DHC via Polymerase Chain Reaction (qPCR) in groundwater	Minimum 100-fold increase in DHC levels at least 20 ft downgradient of bioaugmentation injection point	This objective was attained.
Qualitative Performance Objectives			
Ease of Implementation	Time needed to maintain system during active treatment Amendment delivery rate Feedback from field technician	Biofouling Ability to operate in semi-passive mode Minimal costs	Biofouling in the injection well was a challenge, but otherwise system was operated with ease and minimal Operation and Maintenance (O&M).

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4.0 SITE DESCRIPTION

4.1 SITE SELECTION

A list of potential sites was first developed by CB&I Federal Services (CB&I) during the proposal phase of the project, and was based on CB&I's experience at DoD sites, a literature review, and by discussions with site contractors, regulators, and DoD personnel. After an initial screening of sites, the remaining three sites (Edwards AFB Site 37 source area, AFP4 Landfill 3 area, and Nike Battery PR-58) were evaluated on the basis of the following site selection criteria:

- Confirmed (or very likely) presence of DNAPL;
- Shallow depth to saturated bedrock (<100 ft below ground surface [bgs]);
- Immobile DNAPL (i.e., no recoverable DNAPL from existing bedrock wells);
- No co-contaminants present that would significantly inhibit DNAPL dissolution and PCE/TCE bioremediation;
- pH between 6 and 8;
- Well-connected network of conductive fractures;
- Presence of existing monitoring wells and site data; and
- Site accessibility.

Site selection criteria were applied to PR-58, AFP4, and Edwards AFB, and each site was ranked with respect to attainment of each of these criteria. Table 4.1 below provides an overall assessment of site suitability. Based on the overall ranking, Edwards AFB was the most suitable location for this demonstration. Thus, Edwards AFB, Site 37, was the selected site.

Table 4.1. Site Selection Criteria

Parameter	Preferred Value(s)	Relative Importance (1-5, with 1 being highest)	PR-58	AFP4	Edwards AFB
Likely presence of DNAPL[3]	NA[1]	1	Yes	Yes	Yes
Shallow depth to bedrock	< 100 ft	3	Yes	Yes	80-125 ft[2]
Immobile DNAPL	NA[1]	1	Yes	No	Yes
No inhibitory co-contaminants	NA[1]	1	No	Uncertain	Yes
pH	6<pH<8	3	Yes	Yes	Yes
Well-connected fractures	NA[1]	2	Yes	Yes	Yes
Existing site data and wells	NA[1]	3	Yes	Yes	Yes
Site accessibility	NA[1]	2	Yes	Yes	Yes

[1] NA; Not Applicable

[2] Likely treatment interval where DNAPL and water-bearing fractures are present.

[3] PCE/TCE groundwater concentrations >1% solubility or visual DNAPL observations.

4.2 SITE LOCATION AND HISTORY

Edwards AFB is located approximately 30 miles northeast of the city of Lancaster in the Antelope Valley of the Mojave Desert (refer to Figure 4.1). The Air Force Research Laboratory (AFRL), in the eastern portion of Edwards AFB, has been used as a rocket research and testing facility since the 1950s. The Environmental Restoration Program has divided the base into 10 operable units (OUs); OU4 and OU9 encompass the AFRL on the eastern side of Rogers Dry Lake. The South AFRL includes Environmental Remediation Program Site 37, where facilities are (or were) associated with rocket component maintenance. The groundwater plume associated with this site is located on the southwestern side of Leuhman Ridge, with a regional groundwater flow direction toward the southwest.

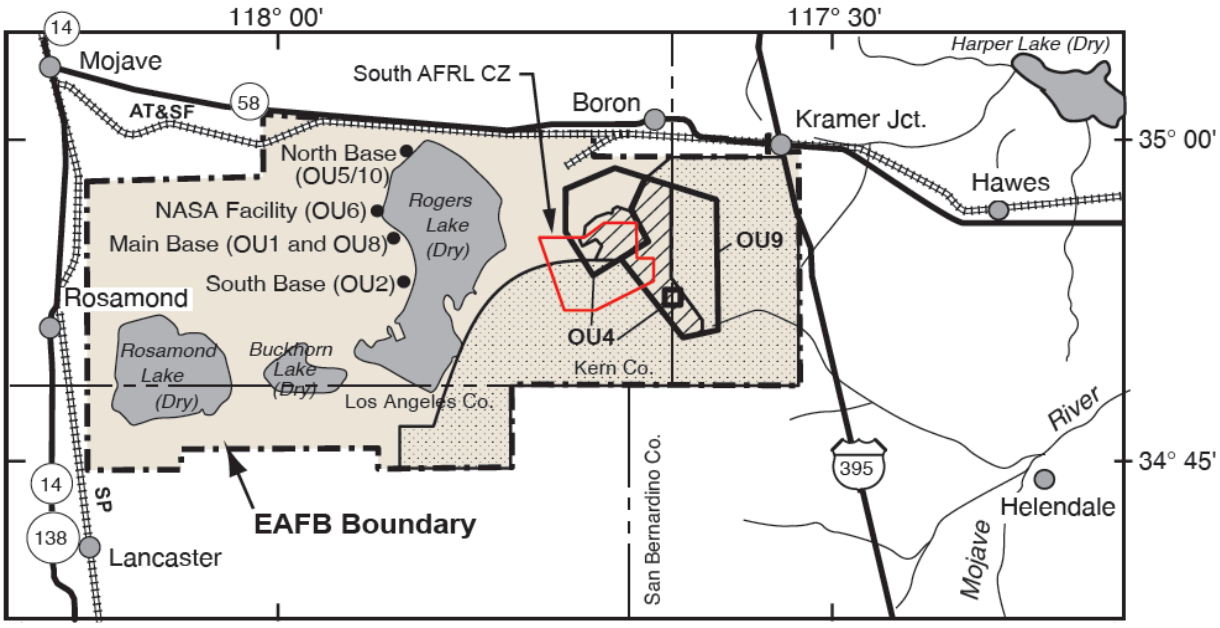


Figure 4.1. Figure 4.1. Edwards AFB Research Laboratory OU4 and OU9

4.3 SITE GEOLOGY AND HYDROGEOLOGY

4.3.1 Site Geology

The subsurface geology at Site 37 is typical of the AFRL with crystalline granitic bedrock overlain by unconsolidated alluvium. The thickness of the alluvium within the treatment area in the vicinity of Building 8595, as observed project drilling to date, ranges from less than 5 to 24 ft. The bedrock beneath the alluvium is below the site and is composed of two types of pre-tertiary plutonic crystalline rock. The first (quartz monzonite) is composed of varying percentages of quartz, plagioclase, and potassium feldspar. The monzonite host rock is intruded in places by a granite that is distinguished from the monzonite by increased percentages of potassium feldspar and decreased plagioclase.

4.3.2 Hydrogeology and Fracture Network

Hydrogeology at the AFRL is characterized by shallow granitic bedrock with low groundwater yields from fracture flow. Groundwater occurs under hydrostatic pressure within fractures in both weathered and competent granitic bedrock. The fracture network does not yield usable quantities of groundwater with typical flow rates of less than 0.5 gallons per minute. The draft *Groundwater Modeling Report for the Northeast AFRL* (*23*) concluded the following based on an evaluation of results from eight boreholes at the AFRL between 1991 and 2009:

- Fracture orientations at the AFRL are highly variable; and,
- Previous fracture mapping has proven ineffective in predicting preferred groundwater flow pathways at the scale of bulk contaminant transport.

On a local scale the movement of groundwater is expected to be fracture-controlled, as confirmed by results of tracer studies conducted in pilot study areas at Site 162 in the AFRL Arroyos and Sites ITI/325 in the Northeast AFRL (*24,25*). Investigations conducted by CB&I during the first phase of this investigation provide additional insight into the character and variation of fracturing at Site 37. The work included geologic coring and borehole geophysical logging, which provide a detailed qualitative and quantitative evaluation of the fracture system (see Section 5.2). Despite the presence of a number of fracture sets within the bedrock, there appears to be one prevalent northeast dipping fracture set that is present across Site 37.

4.3.3 Groundwater Flow

In the South AFRL, groundwater flows ultimately into the Lancaster Subbasin, recharging the aquifer. The flow of groundwater, based the potentiometric contours, is radially outward from the Building 8595 and Main Gate area (i.e., flow to southeast, south and northwest). A groundwater divide appears to be present in the vicinity of Building 8595, which would explain the southeastern migration of contaminants away from the original tank leak location. Based on the potentiometric surface and from the configuration of plumes originating at Site 37, the flow directions appear to be south, southeast, and southwest away from Building 8595.

4.4 CONTAMINANT SOURCE AND DISTRIBUTION

The PCE groundwater plume at Site 37 originates at Building 8595 (Figure 4.2). Past activities that led to the release of chemicals to the groundwater include development and testing of rocket motors using either liquid or solid propellants; and cleaning of rocket components using chlorinated solvents (particularly TCE and PCE). PCE, previously used in a vapor degreaser, is the most widespread contaminant of concern at Site 37.

The lateral and vertical extent of the VOC constituents at Site 37 have been examined through an extensive network of monitoring wells. The lateral extent has been largely defined, reaching roughly 7,000 ft downgradient (south and southwest) of the site. Although the number and complexity of VOC plumes makes the isolation of an individual plume difficult, the plume segment with the most clear relationship to Site 37 (Building 8595) is represented by the smaller (western most) lobe as depicted on Figure 4.2.

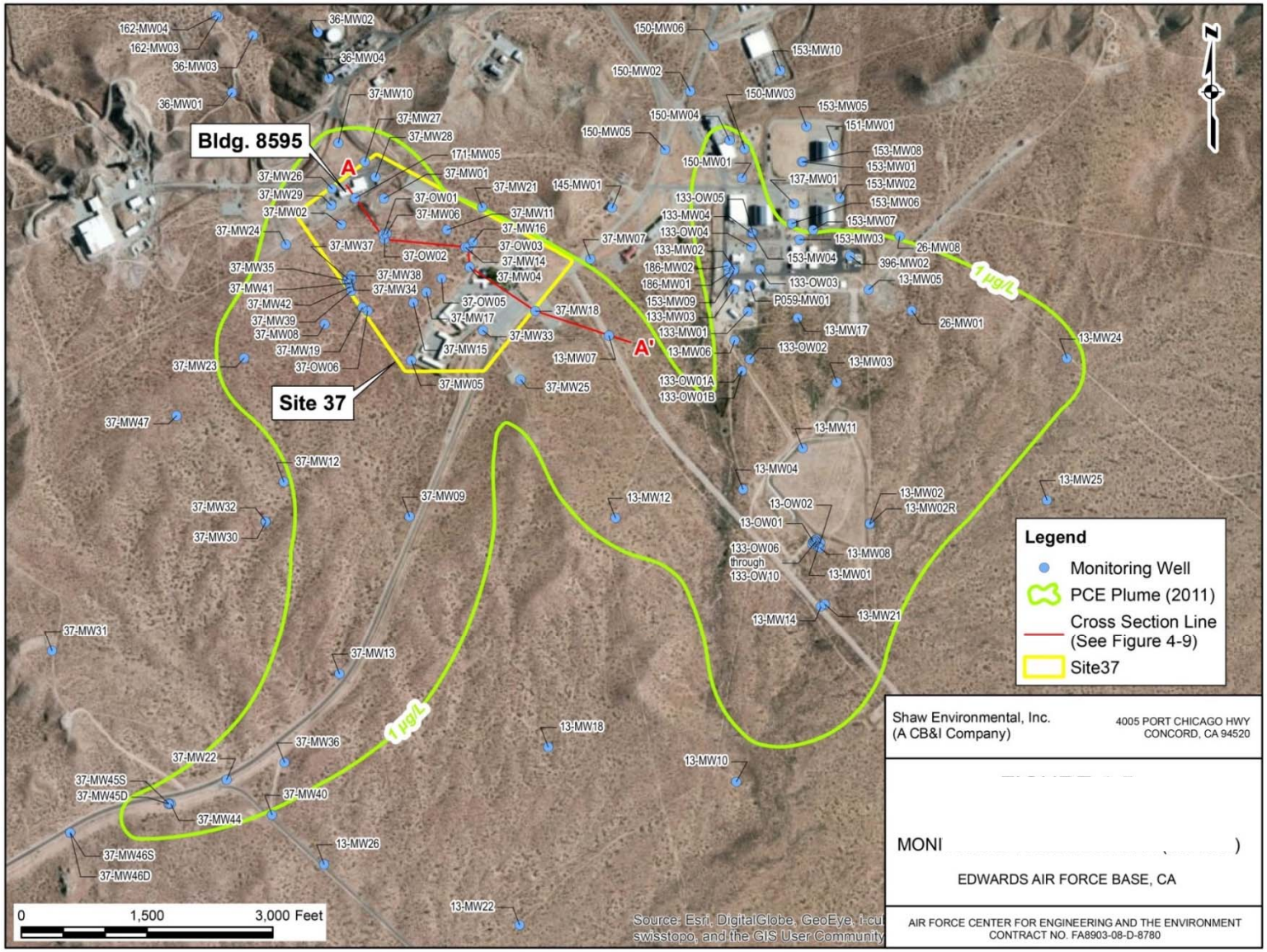


Figure 4.2. Site 37 Bioaugmentation Test Area

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

A demonstration of bioaugmentation to treat DNAPL sources in fractured bedrock was performed to assess overall dissolution and dechlorination rates within targeted DNAPL-filled fractures, to evaluate the overall effectiveness of bioaugmentation for reducing DNAPL mass and reducing dissolved contaminating flux emanating from the source area, to determine the impacts on the downgradient dissolved plume, and to develop and verify design parameters to optimize sustainability (e.g., limit electron donor). Additional bedrock open borehole wells were installed within the DNAPL source area, as determined during the initial DNAPL investigation (Section 5.4). After installation, geophysical testing was performed on the newly installed wells, followed by a series of short-term discrete interval pumping tests to confirm intervals and locations that are hydraulically connected. Discrete interval groundwater sampling was also performed.

Following this initial testing, a Partitioning Tracer Test (PTT) (using conservative tracers and partitioning tracers) was performed across the demonstration area. This testing was used to verify the flow field (i.e., conductive fractures), provide an estimate of the DNAPL mass, and identify the locations of the DNAPL sources.

After baseline characterization was completed, bioaugmentation amendments were distributed through the targeted monitoring zone, which consists of discrete interval sampling points within the array of open borehole bedrock wells, where conductive fractures containing residual DNAPL sources were targeted. Groundwater monitoring was used to measure bioaugmentation effectiveness, as well as dissolved contaminant mass flux and discharge, in the specific fractures (or fracture zones) that contain the DNAPL source. Groundwater monitoring was used to assess the extent and rate of microbially-enhanced reductive dechlorination of PCE, the extent of electron donor distribution, and the extent to which DHC growth and distribution occurs through the fractured bedrock. Daughter product generation (including chloride) was used to determine the extent of DNAPL mass removed during treatment. A rebound assessment was also performed.

5.2 BASELINE CHARACTERIZATION ACTIVITIES

Prior to site selection, CB&I reviewed existing site investigation documents and all available hydrogeologic and contaminant distribution data for the Site 37 source area at Edwards AFB. The screening partitioning tracer test that was performed using an existing monitoring well suggested that DNAPL was likely present in the vicinity of Building 8595 and monitoring well 37-EW07, and the demonstration test plot was selected in this general area (see Figure 5.1). However, as described below, initial characterization activities were performed to verify the suitability of this location, and to confirm the effectiveness of bioaugmentation for treatment of PCE under site biogeochemical conditions.

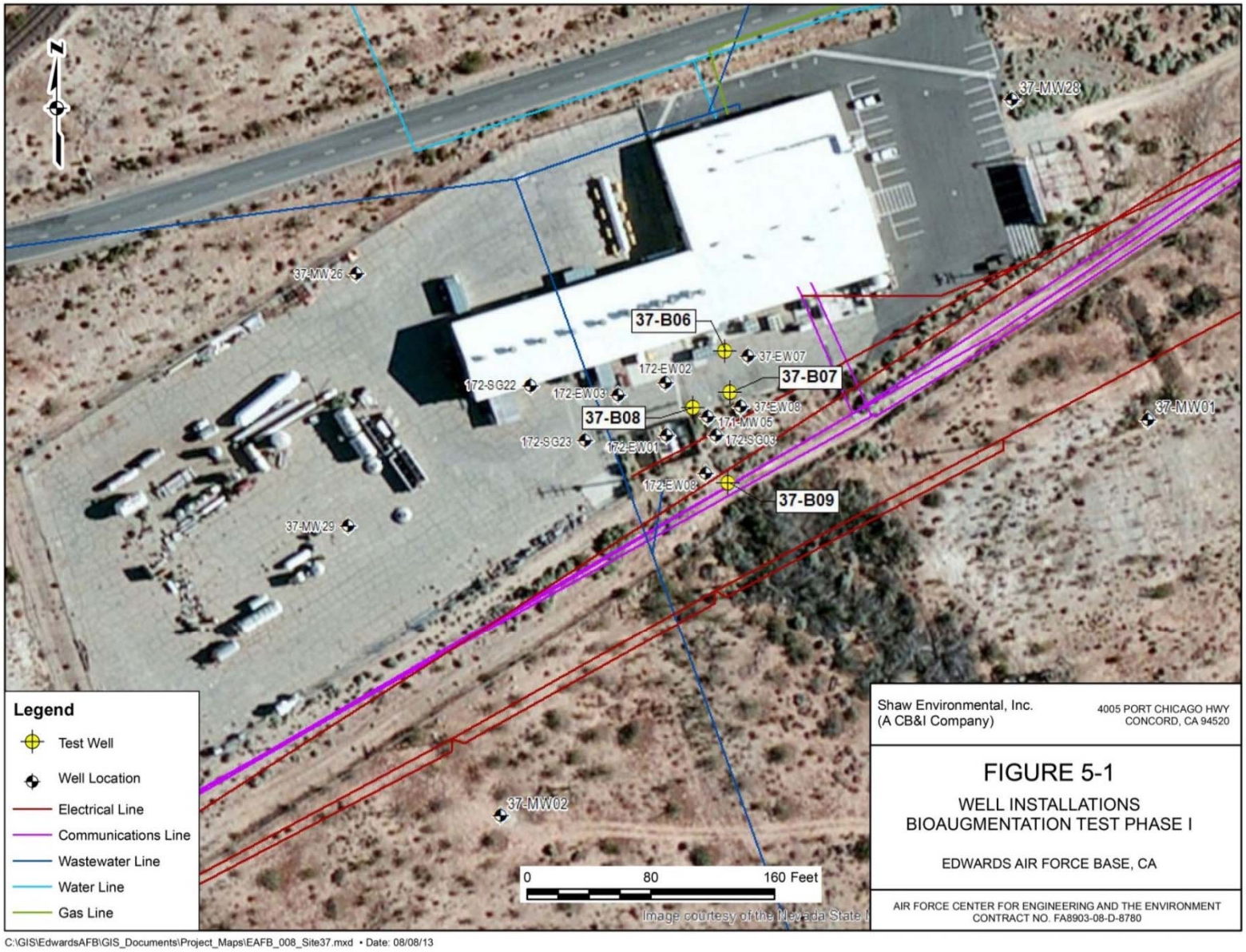


Figure 5.1. Well Installations, Bioaugmentation Test Phase I

An initial investigation was performed in the presumed PCE DNAPL source area in the vicinity of 37-EW07. The overall goal of this preliminary assessment was to verify that the site was suitable for the proposed demonstration, and to provide a design basis for the Demonstration Work Plan that followed this initial testing.

The approach employed was intended to provide a preliminary assessment of DNAPL distribution and bedrock hydrogeology in the suspected DNAPL source area. The approach consisted of collection of rock core from four locations (37-B06, 37-B07, 37-B08, 37-B09; see Figure 5.1), installation of open-borehole bedrock wells at these four locations, geophysical testing, discrete interval rock and groundwater sampling, pump testing, and implementation of partitioning tracer tests (PTTs). Rock core sampling and discrete interval groundwater sampling were used to identify potential DNAPL locations. The geophysical testing and pump testing were used to identify conductive fracture zones, and to assess connectivity among the monitoring wells. PTTs were used to determine which conductive zones contained DNAPL.

The results of these baseline activities are provided in detail in the *Project Final Report*. A summary of the key preliminary characterization results are as follows:

- Well capacities within the source area are relatively low (<250 milliliters per minute [mL/min]), but likely are sufficient for distribution of bioaugmentation amendments in conductive fractures. This was verified by observing the travel times during the interwell tracer test.
- Groundwater flow and solute migration is controlled by a complex fracture flow path, which consists of many fractures at varying orientation and angle.
- Hydraulic connectivity was observed for at least two wells (37-B06 and 37-B07), located 30 ft apart, within the DNAPL source area. This connectivity was attributable to a conductive fracture-plane that intersects these wells at a similar elevation. Less conductive fractures also likely intersect these two well locations.
- DNAPL was identified within the source area. Results of the PTTs indicate that DNAPL was present within the conductive fractures that intersect 37-B06 and 37-B07. Photoionization Detector (PID) and VOC analysis of rock fragments at 37-B07 were consistent with the PTT results. DNAPL also was observed, based on rock VOC fragment analysis, in a low permeable zone at 37-B09.
- PCE groundwater concentrations measured during the preliminary investigation were all consistent with the presence of PCE DNAPL (i.e., greater than 1% solubility).

5.3 LABORATORY TREATABILITY STUDY

5.3.1 Objectives

Laboratory treatability studies were conducted with samples obtained during the initial site characterization and DNAPL investigation, which occurred in January 2013. The overall goal of the laboratory treatability study was to evaluate the effectiveness of bioaugmentation for treatment of PCE under site conditions. The specific objectives of the treatability studies were as follows:

(1) to verify that bioaugmentation using CB&I's commercially available SDC-9 culture will be effective, (2) to assess the need for additional amendments (e.g., nutrients or pH buffer), and (3) to determine the extent to which the alcohols that will be used as partitioning tracer might be inhibitory or toxic to the dechlorinating bacteria in SDC-9 (as this would determine whether or not partitioning tracer tests were performed during the active treatment phase of the field demonstration).

5.3.2 Treatability Study Results.

5.3.2.1 Geochemical Results

Geochemical results for the biodegradation experiments are provided in Table 5.1. Due to elevated background concentrations of chloride, chloride generated via reductive dechlorination could not be determined.

Values for the pH ranged from 7.3 to 8.2, which is within the range where reductive dechlorination of PCE to ethene can occur. It is noted, however, that reported pH values within the demonstration area measured in the field typically were in the range of 6.5 to 7, suggesting that the slightly elevated pH levels measured in the laboratory may be an artifact of sample handling and exposure to the atmosphere. The lack of any decreasing trend in pH in the biostimulation or bioaugmentation treatments suggests that generation of any organic acids are likely being naturally buffered by the rock alkalinity.

Sulfate values in the Killed and Live controls were approximately 350–400 milligrams per liter (mg/L). No sulfate reduction was observed in any treatments that were not amended with lactate. Sulfate reduction was most rapid in the Bioaugmentation treatment (Treatment 5), where sulfate reduction was observed within five weeks. Sulfate reduction for the Biostimulation treatment was observed within ten weeks. The addition of the SDC-9 culture, which is known to contain sulfate-reducing bacteria, likely is the reason why sulfate reduction was more rapid in the bioaugmented treatment. Interestingly, sulfate reduction was delayed until greater than ten weeks when alcohols were present in the bioaugmented treatment. This suggests that the presence of the alcohols may inhibit sulfate reduction.

5.3.2.2 Alcohol Fate

Alcohol concentrations, measured at time 0 and 10 weeks in the biodegradation study, are provided in Table 5.2. Results show negligible (less than approximately 10%) difference in alcohol concentrations between the un-amended and bioaugmented treatments, suggesting that the bioaugmentation culture did not biotransform the alcohols within the ten-week timeframe. However, in both treatments, slight to moderate decreases in the alcohol concentrations were observed. This decrease may be due to slow adsorption of the alcohols into the rock, and/or biodegradation of the alcohols due to indigenous bacteria.

Table 5.1. Geochemical Results for Treatability Study

Chloride (mg/L)						
Time (weeks)	Killed Control	Live Control	Live w/ Alcohols	Biostimulation	Bioaugmentation	Bioaug w/ Alcohols
0	381	367	345	333	348	346
2	411	345	373	360	375	398
5	446	401	402	404	417	424
10	409	366	380	392	429	359
16	418	410	354	383	396	404
Sulfate (mg/L)						
Time (weeks)	Killed Control	Live Control	Live w/ Alcohols	Biostimulation	Bioaugmentation	Bioaug w/ Alcohols
0	327	360	332	322	332	328
2	357	346	359	360	310	362
5	424	418	422	407	4.6	425
10	354	355	379	2.7	1.0	322
16	399	417	362	4.4	1.7	23
pH (SU)						
Time (weeks)	Killed Control	Live Control	Live w/ Alcohols	Biostimulation	Bioaugmentation	Bioaug w/ Alcohols
0	7.3	7.8	8.0	7.9	7.9	7.9
2	7.6	8.0	8.0	8.0	8.0	8.0
5	8.0	8.0	8.1	8.1	8.1	8.0
10	8.2	8.2	8.3	8.2	8.2	8.1
16	8.2	8.1	8.4	8.2	8.2	8.2

Table 5.2. Alcohol Results for Treatments 3 and 6

Methanol (µM)		
Time (weeks)	Live w/ Alcohols	Bioaug w/ Alcohols
0	8.6	8.3
10	7.8	8.0
1-Hexanol (µM)		
Time (weeks)	Live w/ Alcohols	Bioaug w/ Alcohols
0	2.4	2.4
10	1.3	1.6
2-Octanol (µM)		
Time (weeks)	Live w/ Alcohols	Bioaug w/ Alcohols
0	0.6	0.7
10	0.2	0.4

The alcohol concentrations over a time period of two weeks (which was representative of the expected duration of the partitioning tracer tests that would be performed in the field) is provided in Table 5.3. Data from this supplemental experiment show that, for a 14-day duration, no measurable sorption or biodegradation of the tracers occurred. Thus, it was reasonable to assume that these tracers would behave conservatively in the field with respect to sorption to aquifer solids and any biodegradation processes over a two-week period.

Table 5.3. Alcohol Sorption Test Results

Methanol (µM)			
Time (days)	Control	Killed	Live
0	2.6 ± 0.4	2.6 ± 0.1	2.6 ± 0.1
4	2.7 ± 0.2	2.6 ± 0.1	2.6 ± 0.2
14	2.7 ± 0.1	2.5 ± 0.1	2.7 ± 0.1
1-Hexanol (µM)			
Time (days)	Control	Killed	Live
0	0.7 ± 0.1	0.8 ± 0.1	0.8 ± 0.0
4	0.8 ± 0.0	0.8 ± 0.1	0.8 ± 0.1
14	0.8 ± 0.0	0.8 ± 0.1	0.7 ± 0.0
2-Octanol (µM)			
Time (days)	Control	Killed	Live
0	0.2 ± 0.1	0.4 ± 0.1	0.4 ± 0.1
4	0.4 ± 0.1	0.5 ± 0.0	0.5 ± 0.0
14	0.4 ± 0.1	0.5 ± 0.0	0.5 ± 0.0

5.3.2.3 PCE Biodegradation

Results summarizing the PCE biodegradation testing are provided on Figure 5.2. Results showed no evidence of reductive dechlorination in any of the controls or biostimulation treatments. However, evidence of the complete reductive dechlorination of PCE was observed in both (with and without the alcohols) bioaugmentation treatments.

Both bioaugmentation treatments showed substantial decreases in PCE concentration, along with increases in both DCE and VC. Ethene concentrations, although relatively low on a molar basis, were rapidly increasing over the last two sampling events. Surprisingly, transformation of PCE to DCE and VC occurred more rapidly in the treatment where the alcohols were added. The reason for this observation is unclear, but may be due to the fact that sulfate reduction was initially inhibited in the presence of the alcohols, which may have allowed for a greater availability of electron donor for reductive dechlorination. At the very least, comparison between the bioaugmentation treatments with and without the alcohols indicate that the presence of any residual alcohols following completing of the partitioning tracer experiments is not expected to have any adverse effects on biodegradation of PCE.

5.3.3 Treatability Study Conclusions

Results from the treatability study indicate that bioaugmentation is effective for the reductive dechlorination of PCE. Furthermore, the complete dechlorination of PCE to ethene was observed in site groundwater with rock fragments. It is important to note that the previous research has shown that dechlorination of PCE DNAPL in closed microcosm systems may occur much more slowly than in the field or other “open” systems. The fact that substantial PCE dechlorination, and even ethene generation, was observed in this treatability study was very encouraging.

Thus, the results of the treatability study supported the approach to perform the bioaugmentation demonstration at Site 37 at Edwards AFB.

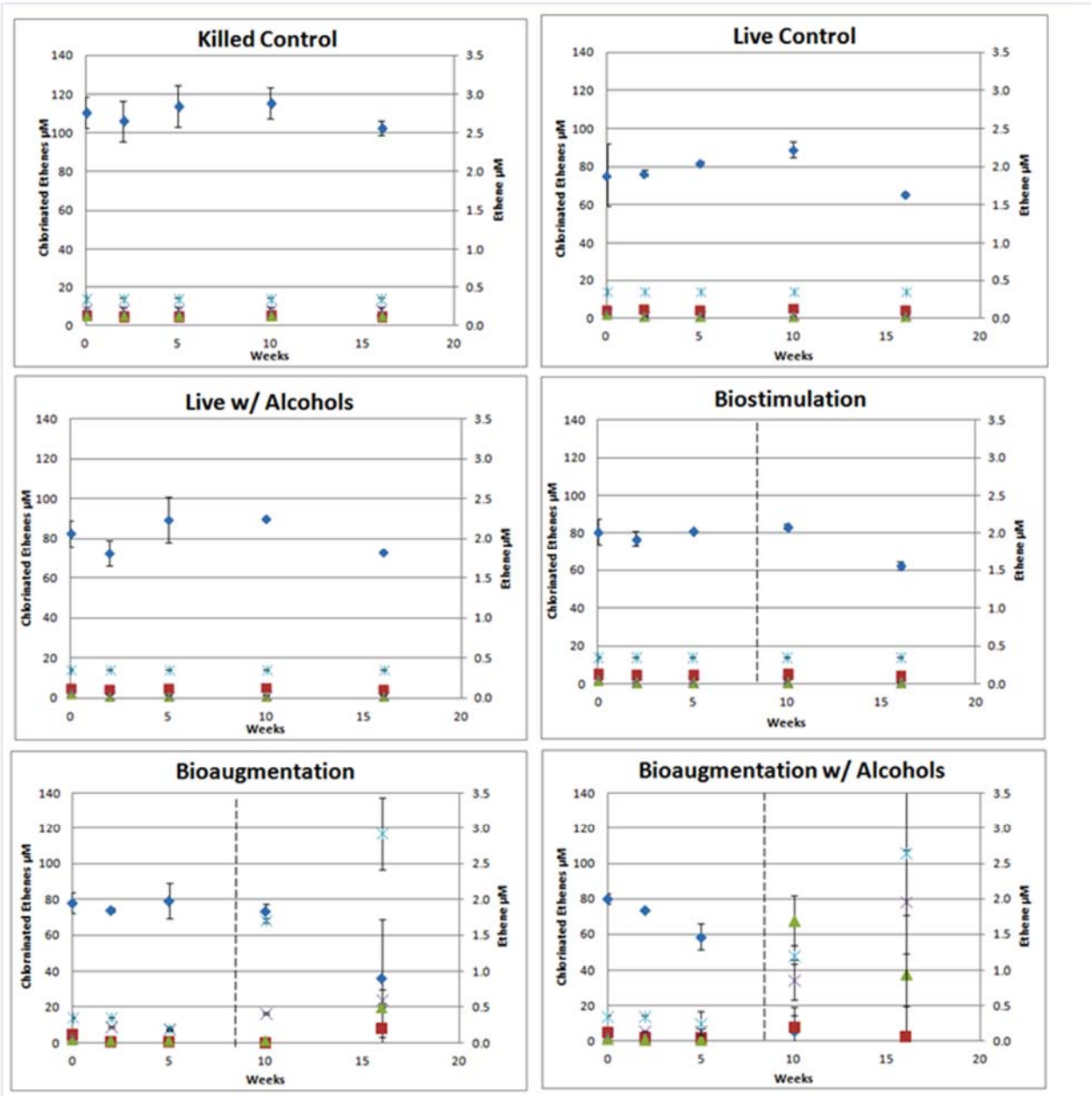


Figure 5.2. Chlorinated Ethenes and Ethene Results for Treatments 1-6 where ◆ = PCE, ■ = TCE, ▲ = cis-1,2-DCE, X = Vinyl Chloride, and * = Ethene. The dotted line represents additional nutrients (yeast extract and lactate), as well as re-bioaugmentation of SDC-9 for treatments 5 and 6, was performed.

5.4 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

During this field demonstration, a series of discreet interval borehole sampling locations were used to assess the effectiveness of bioaugmentation for treatment of PCE DNAPL sources in fractured bedrock. Bioaugmentation treatment was preceded by performance of a partitioning tracer test to assess DNAPL architecture and the fracture flow field. The bioaugmentation amendments were distributed using injection and extraction wells. Bioaugmentation amendments included CB&I's commercially available DHC-containing culture SDC-9, lactate, nutrients, and a bicarbonate buffer. Amendments were distributed across a targeted region within the DNAPL source zone. Amendment distribution, reductive dechlorination rates, microbial growth and transport, and DNAPL dissolution rates were evaluated. By monitoring electron donor and hydrogen levels, efforts were made to limit excess electron donor delivery during the demonstration. Following the almost 12-month demonstration period, rebound testing was performed.

5.4.1 Layout and Well Construction

The treatment test plot includes groundwater extraction, injection, and monitoring wells in an area south of Building 8595. The demonstration layout, which includes open borehole wells installed during the preliminary characterization, as well as more recent wells installed for treatment system operation, is shown on Figure 5.3. The test and treatment system consists of one injection, two extraction, and two monitoring wells. Borehole 37-B06 was used as an injection well for tracer and amendment injection, and boreholes 37-B12 and 37-B13 were used as extraction wells. Borehole 37-B07 and 37-B11 were used as monitoring wells, with multiple sample intervals within each borehole. 37-EW07 is a source area monitoring well that was installed prior to this demonstration, and was periodically sampled, though not included in the monitoring program for the demonstration. The depth intervals that were monitored at each well location are presented in Table 5.4.

Table 5.4. Discrete Intervals for Monitoring, Injection and/or Extraction

Borehole or Well Location	Well Status	Number of Depth Intervals for Monitoring	Sampling or Packered Intervals (feet (ft) bgs)
37-B06	Existing	2	< 59 59-85
37-B07	Existing	3	<70 70-85 85-97
37-B11	Proposed	2	<83 83-105
37-B12	Proposed	1	120-132
37-B13	Proposed	1	79-99
37-EW07*	Existing	1	37.4-57.4

* Existing source area monitoring well. The depth interval is the screen interval of the well.

NOTE: For the initial Stage 1 hydraulic testing described in Section 5.5.1, the isolated intervals were modified to facilitate initial testing.

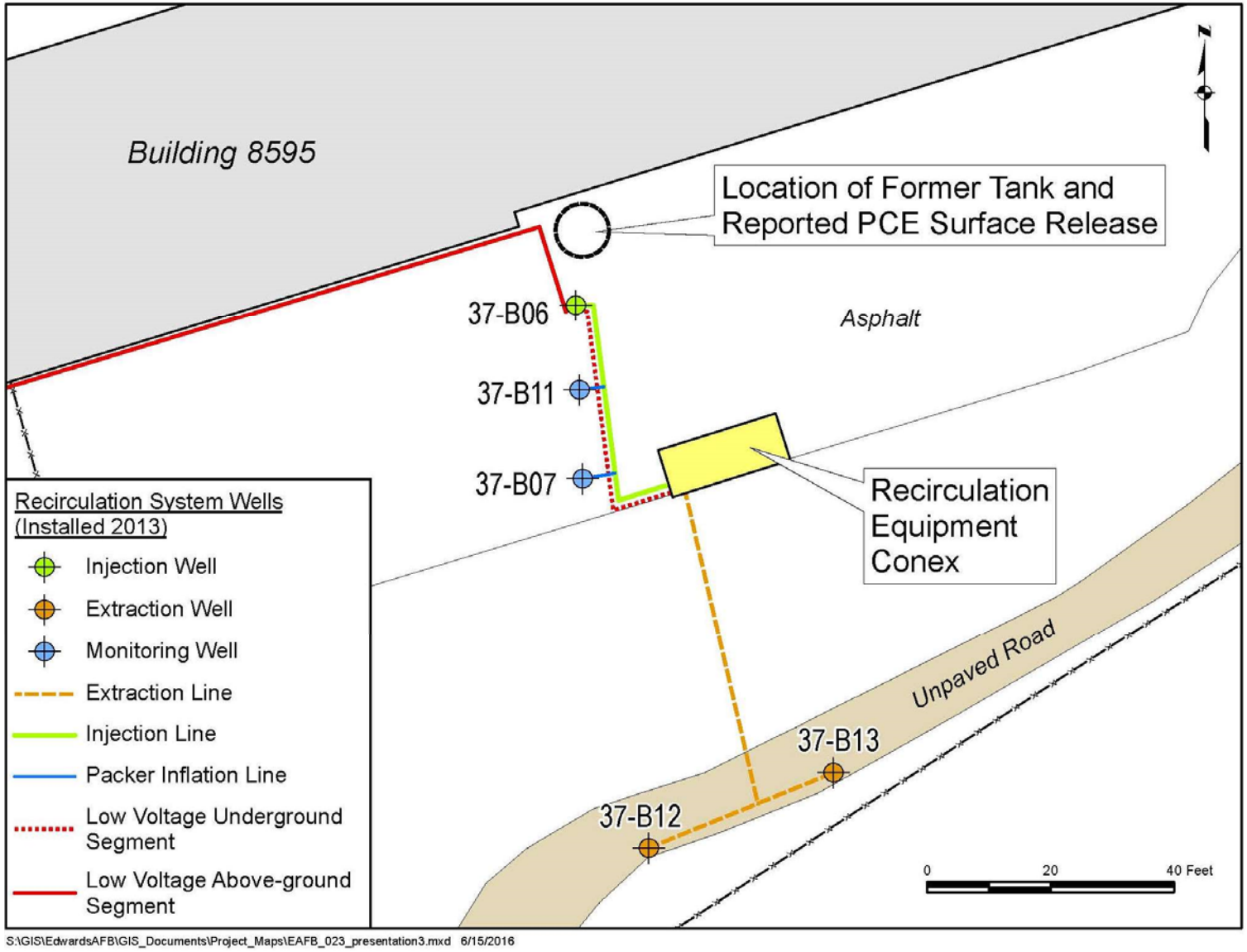


Figure 5.3. Groundwater Recirculation and Amendment Delivery System

5.4.1.1 Well Installation

The installation of the final four demonstration wells (37-B10, 37-B11, 37-B12, and 37-B13) were constructed in a manner similar to those installed during the initial phase of the project: as open borings drilled into the solid bedrock with surface conductor casing installed through the upper sediment interval. Note that 37-B10 was installed at an incorrect location for the demonstration, thus an additional monitoring well (37-B11) was installed and used for performance monitoring.

Slices of the rock matrix were collected adjacent to a PCE containing conductive fracture at 37-B10 (along the conductive fractures at approximately 76 and 98 ft. bgs). These slices were collected immediately upon retrieval in the field. Each slice was approximately 1–2 cm thick, crushed, then placed into capped glass jars containing methanol. Up to five rock slices (i.e., five slices going inwards towards the rock matrix from the conductive fractures) were collected. The methanol was analyzed for PCE at approximately 2 and 5.5 weeks; PCE concentrations did not show an increase going from 2 to 5.5 weeks, thereby confirming equilibrium was attained at 2 weeks. This information was used to assess the extent of contaminant mass present in the rock matrix in close proximity to the fracture interface.

5.4.1.2 Geophysical Testing

Geophysical logging was conducted in five test boreholes to further characterize bedrock fracture zones. The logging was conducted immediately after the well installation activity. The logging was conducted in three of the final demonstration wells (37-B10, 37-B12, and 37-B13) wells and in one well installed in the first phase of the project (37-B07); geophysical logging also was performed in 37-B06 as part of the initial characterization performed. The objective of the geophysical logging was to identify fracture zones that may contain dissolved or DNAPL phase chlorinated solvents.

The key results from the geophysical testing showed that potentially conductive fracture zones were present in 37-B07 at approximately 78 and 90 ft bgs. These fracture zones, based on their depth and orientation, appeared to correspond to fracture zones identified in 37-B06 located at 79 and 83 ft bgs, respectively. Thus, this information was used to determine the discrete interval sampling points discussed in the following sections.

5.4.2 Packer Installation and Sampling Assembly

The pre-installation testing and operation of the treatment system targeted specific intervals within wells containing fracture zones. The drilling and geophysical logging described above provides access to and identifies potentially conductive fracture zones. Based upon knowledge of the connective fracture pathways and DNAPL distribution as determined during the characterization activities described in Section 5.2, as well as the results from additional geophysical and hydraulic testing performed as part of system installation (Sections 5.4.2.2 and 5.5.1, respectively), the intervals for which the packers were used to isolate targeted intervals are listed in Table 5.4. Note that for the initial Stage 1 hydraulic testing described in Section 5.5.1, the isolated intervals were modified to facilitate initial testing.

The basic inflatable straddle packer assembly was used to isolate the intervals. The assembly is constructed of two single inflatable packers ganged together to form a single unit which can be used to isolate specific borehole intervals. The unit also was applied in a single packer mode (where appropriate, as shown in Table 5.4) with the removal of one packer segment. The straddle packer can isolate the borehole into three segments, although the upper and lower borehole segments are open to the entire intervals above and below the straddle packer assembly.

The basic assembly includes the packers, wireline suspension cable, tubing used for inflation of the packer, and additional ports and tubing connectors that facilitate the primary operational functions. The packers were placed via the suspension wire using a manually operated tripod and winch assembly. The packers were inflated through the application or air pressure to the down-hole inflation tube.

5.4.2.1 Injection Well Packers

Groundwater injection in well 37-B06 required the isolation of one zone, though the installation consisted of two packers, the top packers set at 59 ft bgs and the bottom packer at 85 ft bgs (see Figure 5.4). One injection drop-pipe was utilized to inject recirculated water into this interval, through the packer placed at 59 ft bgs.

5.4.2.2 Extraction Well Packers

The groundwater extraction wells (37-B12 and 37-B13) utilized bladder pumps designed for continuous service. The pump mechanism consisted of the following:

- QED Environmental Systems (QED) Well Wizard Model T1200M stainless steel bladder pump with Teflon bladder;
- ¼-inch OD UV protected Nylon 12 air supply tubing; and
- 3/8-inch OD Teflon-lined polyethylene discharge tubing.

Each of the extraction wells withdrew water from one zone, requiring the installation of the pump below a single packer, between the packer and the bottom of the borehole (see Figure 5.4). 37-B12 had a single packer installed at 120 ft bgs, with the pump below, extracting water from the interval from 120 ft bgs to 132 ft bgs. 37-B13 had a single packer installed at 79 ft bgs, with the pump below, extracting water from the interval from 79 ft bgs to 99 ft bgs.

5.4.2.3 Monitoring Well Packers

Dedicated groundwater sampling bladder pumps were installed in treatment system monitoring wells 37-B07 and 37-B11, while portable bladder pumps (decontaminated between sample intervals/wells) were used to sample existing site wells when needed. The pump setups consisted of the following:

- QED Well Wizard Model T1250 stainless steel bladder pump with Teflon bladder;
- ¼-inch OD UV protected Nylon 12 air supply tubing; and
- 3/8-inch OD Teflon-lined polyethylene discharge tubing.

Sampling pumps installed into wells with multiple sampling intervals were installed using packers and were left in place for the entire duration of the demonstration. See Figure 5.4 for the pump and packer placement depths for monitoring wells 37-B07 and 37-B11.

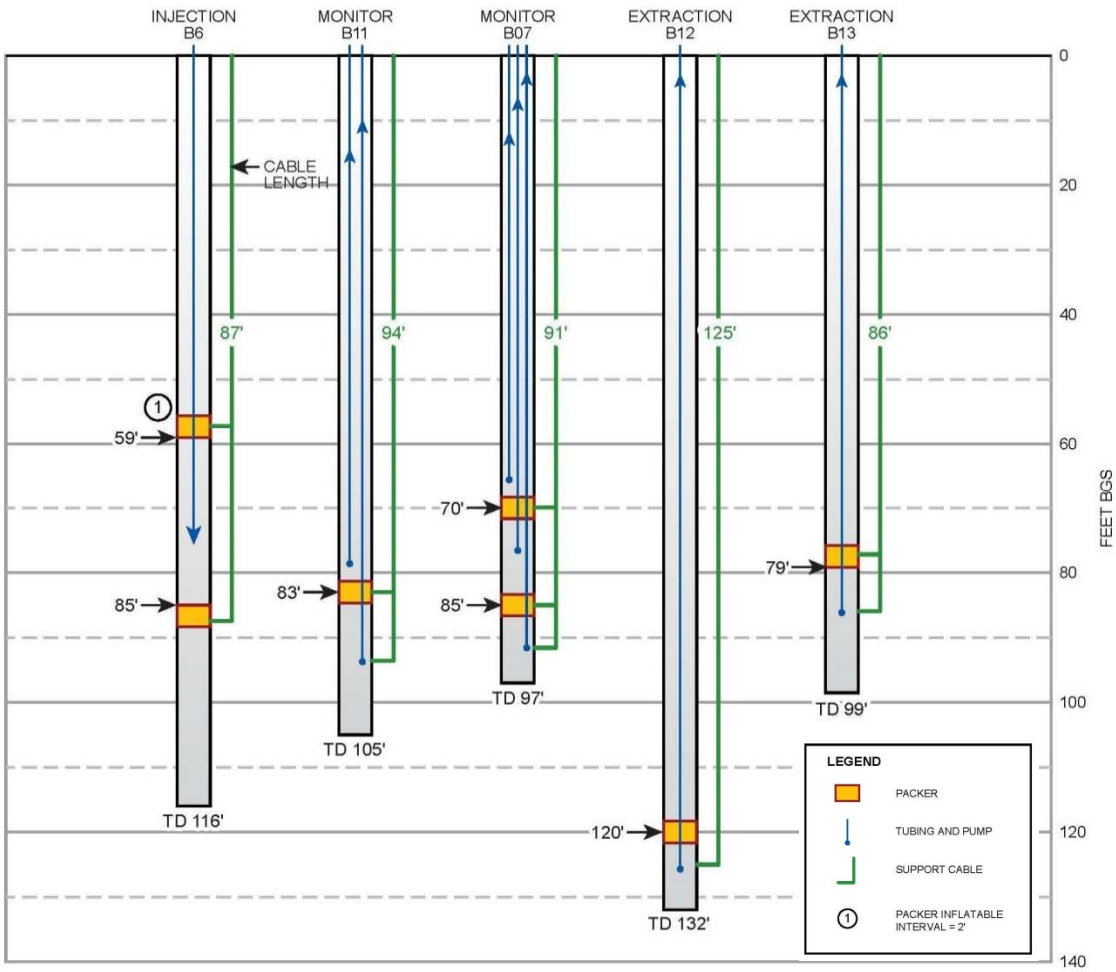


Figure 5.4. Packer and Pump Placement

5.4.3 Enhanced Bioremediation Treatment System

The components of the enhanced bioremediation treatment system include the recirculation system, the tracer and amendment injection system, and ancillary equipment to power the recirculation system. The physical layout of the system is depicted on Figure 5.3, and the components of the system are identified on the piping and instrumentation diagram (P&ID), presented as Figure 5.5. The recirculation system was installed to transport downgradient groundwater and substrate upgradient to the head of the source plume. The design maximum system flow was 300 mL/min; however, flow was dictated by what the injection well could receive (as discussed in Section 5.5.3). The tracer and amendment injection system is a subsystem to the recirculation system. Initially, this sub system was utilized to mix and inject tracer media into the injection wells (see Section 5.5.2). During enhanced bioremediation activities, the sub system was used to inject substrate and amendments to maintain reducing conditions in the treatment area.

The specification and installation of these components are described in detail in the following subsections.

5.4.3.1 Recirculation System

The recirculation system was installed as a single unit housed in a 20-foot long conex box, and included the Tracer and Amendment Delivery System. This unit included a programmable process controller, piping, instrumentation, inline mixers, and manual control valves, as presented in Figure 5.5. Figure 5.5 also shows the process flow of the entire system, including the tracer and amendment delivery subsystem.

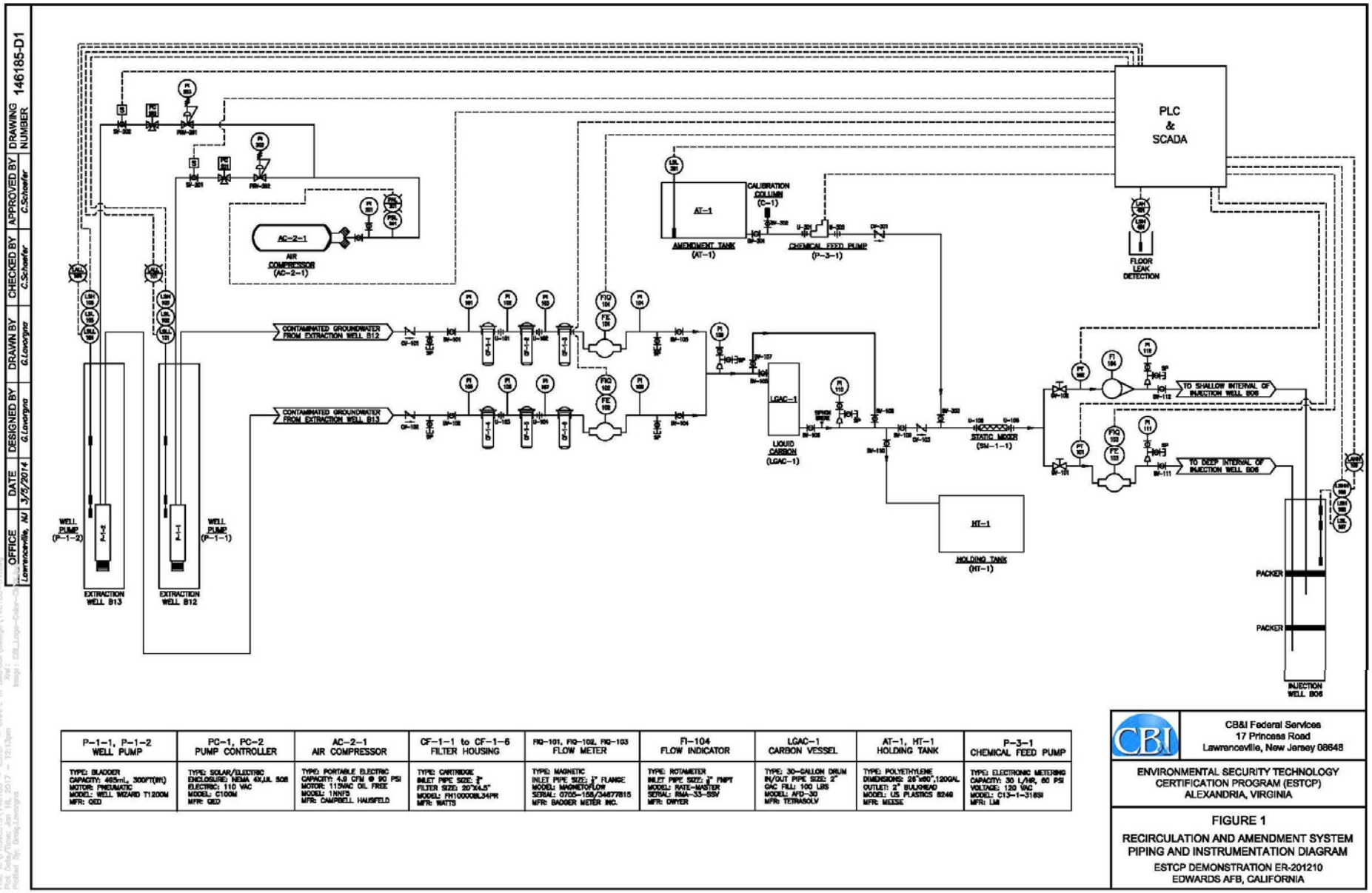
Groundwater extraction occurred through the pneumatic bladder pumps identified in Section 5.4.3.2). Each pump was fully submersible and be capable of maintaining flows over the 300 mL/min design flow for the system. The pumps were controlled through a programmable process controller, which was powered through ancillary equipment. Once groundwater was extracted from the wells, the groundwater was processed through cartridge filters. These filters were utilized to prevent biofouling particulates from entering the system. A lead and a lag filter were included in the system, the lead filter being a 50 micron size and the lag a 20 micron size. The groundwater from the two extraction wells was then combined after the flow meters/totalizers.

During the tracer test, as discussed in Section 5.5.2, groundwater was passed through a liquid GAC unit prior to collection in the holding tank (HT-1) for characterization and proper disposal. The use of GAC and diversion to the holding tank was only employed while the tracer slug was being injected in 37-B06—otherwise the extracted groundwater was re-injected in the injection well (37-B06) without passing through GAC.

During enhanced bioremediation, as discussed in Section 5.5.3, groundwater bypassed the carbon and was directed to the injection wells. Prior to the injection wells, groundwater was mixed with amendments from the amendment delivery system and tank AT-1.

5.4.3.2 Tracer and Amendment Delivery System

The tracer and amendment delivery system was a subsystem to the recirculation system. This subsystem introduced tracer media or amendments at each individual well injection line. The components of the delivery system consisted of a tank, control valves, pressure gauges, and a positive displacement variable speed metering pump. The tank had a capacity of 165 gallons, and the maximum flowrate of the pump was 500 mL/min.



P-1-1, P-1-2 WELL PUMP	PC-1, PC-2 PUMP CONTROLLER	AC-2-1 AIR COMPRESSOR	CF-1-1 to CF-1-6 FILTER HOUSING	FIQ-101, FIQ-102, FIQ-103 FLOW METER	FI-104 FLOW INDICATOR	LGAC-1 CARBON VESSEL	AT-1, HT-1 HOLDING TANK	P-3-1 CHEMICAL FEED PUMP
TYPE: BLADDER CAPACITY: 465mL, 300FT(W1) MOTOR: PNEUMATIC MODEL: WELL WIZARD T1200M MFR: QED	TYPE: SOLAR/ELECTRIC ENCLOSURE: NEMA 4X,UL 508 ELECTRIC: 110 VAC MODEL: C100M MFR: QED	TYPE: PORTABLE ELECTRIC CAPACITY: 4.8 CFM @ 90 PSI MOTOR: 115VAC OIL FREE MODEL: 1NNFB MFR: CAMPBELL HAUSFELD	TYPE: CARTRIDGE INLET PIPE SIZE: 2" FILTER SIZE: 20"X4.5" MODEL: FH100008L34PR MFR: WATTS	TYPE: MAGNETIC INLET PIPE SIZE: 1" FLANGE MODEL: MAGNETOFLOW SERIAL: 0705-155/34677815 MFR: BADGER METER INC.	TYPE: ROTAMETER INLET PIPE SIZE: 1" FNPT MODEL: RATE-MASTER SERIAL: RMA-33-SSV MFR: DWYER	TYPE: 30-GALLON DRUM IN/OUT PIPE SIZE: 2" GAC FILL: 100 LBS MODEL: AFD-30 MFR: TETRASOLV	TYPE: POLYETHYLENE DIMENSIONS: 26"x60",120GAL OUTLET: 2" BULKHEAD MODEL: US PLASTICS 8246 MFR: MEESE	TYPE: ELECTRONIC METERING CAPACITY: 30 L/HR, 80 PSI VOLTAGE: 120 VAC MODEL: C13-1-316SI MFR: LMI

CBI

CB&I Federal Services
17 Princess Road
Lawrenceville, New Jersey 08648

ENVIRONMENTAL SECURITY TECHNOLOGY CERTIFICATION PROGRAM (ESTCP)
ALEXANDRIA, VIRGINIA

FIGURE 1

RECIRCULATION AND AMENDMENT SYSTEM PIPING AND INSTRUMENTATION DIAGRAM

ESTCP DEMONSTRATION ER-201210
EDWARDS AFB, CALIFORNIA

Figure 5.5. Enhanced Bioremediation Treatment System P&ID

During the tracer test, groundwater was extracted from the two extraction wells. Groundwater was processed through filters to remove any particulates in the stream and passed to liquid GAC to remove any VOCs before being stored. While groundwater was being extracted, tracer material was injected from the delivery system into the injection well. Tracer injection volume and mass are described in Section 5.5.2. The mixing will occur in the delivery system tank.

During enhanced bioremediation treatment, the recirculation system bypassed the liquid GAC. Groundwater was recirculated from the extraction wells to the injection wells while pulsed injections of amendments enter the system. Amendment quantities were adjusted based on data received in the field to optimize the system performance.

5.4.3.3 Instrumentation and Monitoring

Process instrumentation including pressure, level, and flow switches were installed at critical locations in the system to ensure safe and controlled operation. The supervisory control and data acquisition (SCADA) system and associated programmable logic controller (PLC) contain all the process control logic to monitor and regulate the operation of the various system components, both locally and remotely through a cellular-based telemetry system. The SCADA/PLC enables the application of power to the pneumatic pump solenoid valves and chemical feed pump, and also monitors the system safety interlocks, calling out when the system is in alarm or offline.

5.5 FIELD TESTING

The field testing was performed in 4 stages, with data from each stage being carefully evaluated prior to proceeding to the next phase. A general timeline of field operations is provided as Table 5.8, with additional details and operations data presented in Appendix B. The first stage consisted of short-term hydraulic testing to verify the extraction well capacity, and to assess hydraulic influence among the injection, monitoring, and extraction wells in the targeted depth intervals. Stage 1 also consisted of baseline sampling (VOC, reduced gases, anions, DHC, metals) at the monitoring and injection wells (Table 5.7) under ambient (no groundwater re-circulation) conditions; this baseline sampling was performed several months after the hydraulic testing. The second stage involved the initiation of groundwater re-circulation, and performance of the partitioning tracer test. This stage continued until groundwater conditions (VOCs, etc.) equilibrated. The third stage was the active bioremediation phase, which lasted nine months. The fourth stage was the rebound period, which lasted ten months.

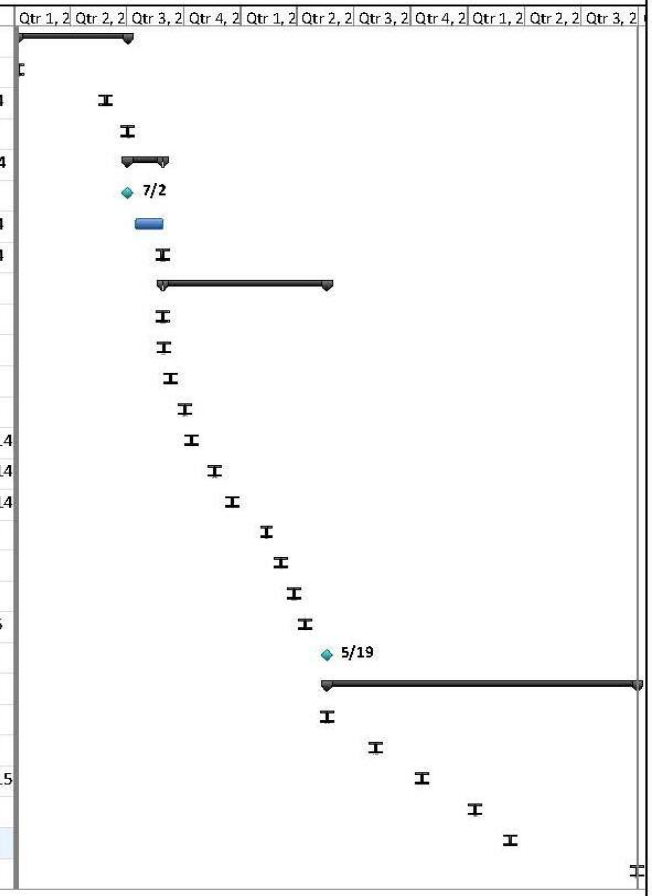
5.5.1 Short-term Hydraulic Testing and Baseline Sampling– STAGE 1

During installation of the monitoring wells used for the Stage 1 testing, a rock core was collected to determine the extent of PCE migration into the rock matrix, as described in Section 5.4.2.1. This was performed during the installation on 37-B10.

Table 5.5. Timeline of Field Operations

Timeline of Field Operations
ESTCP Project ER-201210

ID	Task Name	Duration	Start	Finish
1	**Stage 1 - Short-Term Hydraulic Testing and Baseline Testing**	**128 days**	**Mon 1/6/14**	**Wed 7/2/14**
2	Short-term Pump Testing at 37-B06, 37-B07, 37-B12, 37-B13	4 days	Mon 1/6/14	Thu 1/9/14
3	Baseline Sampling Event No. 1	1 day	Wed 5/28/14	Wed 5/28/14
4	Baseline Sampling Event No. 2	1 day	Wed 7/2/14	Wed 7/2/14
5	**Stage 2 - Groundwater Recirculation and Partitioning Tracer Testing**	**41 days**	**Wed 7/2/14**	**Wed 8/27/14**
6	Start Groundwater Recirculation	0 days	Wed 7/2/14	Wed 7/2/14
7	Partitioning Tracer Test	32 days	Tue 7/15/14	Wed 8/27/14
8	Pre-Bioaugmentation Sampling Event	1 day	Wed 8/27/14	Wed 8/27/14
9	**Stage 3 - Bioaugmentation Treatment and Monitoring**	**188 days**	**Thu 8/28/14**	**Tue 5/19/15**
10	Initial Lactate/Nutrient Pulse Injection	1 day	Thu 8/28/14	Thu 8/28/14
11	Bioaugmentation Injection	1 day	Fri 8/29/14	Fri 8/29/14
12	Post-Bioaugmentation Sampling Event No. 1	1 day	Tue 9/9/14	Tue 9/9/14
13	Redevelope 37-B06 with surge and pumping	1 day	Thu 10/2/14	Thu 10/2/14
14	Post-Bioaugmentation Sampling Event No. 2	1 day	Mon 10/13/14	Mon 10/13/14
15	Post-Bioaugmentation Sampling Event No. 3	1 day	Wed 11/19/14	Wed 11/19/14
16	Post-Bioaugmentation Sampling Event No. 4	1 day	Wed 12/17/14	Wed 12/17/14
17	Redevelope 37-B06 with Nu-Well products	4 days	Mon 2/9/15	Thu 2/12/15
18	Post-Bioaugmentation Sampling Event No. 5	1 day	Thu 3/5/15	Thu 3/5/15
19	Redevelope 37-B06 with surging and wire brush	1 day	Fri 3/27/15	Fri 3/27/15
20	Post-Bioaugmentation Sampling Event No. 6	1 day	Mon 4/13/15	Mon 4/13/15
21	Shut-down Groundwater Recirculation	0 days	Tue 5/19/15	Tue 5/19/15
22	**Stage 4 - Post-Treatment Monitoring and Assessment**	**358 days**	**Tue 5/19/15**	**Thu 9/29/16**
23	Rebound Baseline Sampling Event	1 day	Tue 5/19/15	Tue 5/19/15
24	Rebound Sampling Event No. 1	1 day	Wed 8/5/15	Wed 8/5/15
25	Rebound Sampling Event No. 2	1 day	Mon 10/19/15	Mon 10/19/15
26	Rebound Sampling Event No. 3	1 day	Tue 1/12/16	Tue 1/12/16
27	Rebound Sampling Event No. 4	1 day	Wed 3/9/16	Wed 3/9/16
28	Post-Treatment Rock Core Collection	2 days	Wed 9/28/16	Thu 9/29/16



Date:
Tue 1/17/17

Task | External Tasks | Manual Task | Finish-only
Split | External Milestone | Duration-only | Deadline
Milestone | Inactive Task | Manual Summary Rollup | Progress
Summary | Inactive Milestone | Manual Summary
Project Summary | Inactive Summary | Start-only

Page 1

Initial short-term hydraulic testing was performed to assess the hydraulic connection among the injection, extraction, and monitoring wells, and also to assess the extraction well capacity. The following tests were performed January 8-13, 2014 (one test per day):

- *Pump test at 37-B13 (open borehole for all wells).* The test was performed for approximately 3 hours. Pressure transducers placed in 37-B06 and 37-B07 were used to assess hydraulic influence. Extraction well capacity also was determined.
- *Pump test at 37-B12 (open borehole for all wells).* The test was performed for approximately 3 hours. Pressure transducers placed in 37-B06, 37-B07, and 37-B11 were used to assess hydraulic influence. Extraction well capacity also was determined.
- *Pump test at 37-B06.* The test was performed for approximately 3 hours. Single packers were placed in 37-B06 and 37-B07 so that the top of the packer was at 80 ft bgs. A pressure transducer was placed in 37-B07 above the packer. The pump was placed above the packer in 37-B06 for the pump test.
- *Pump test at 37-B07.* The test was performed for approximately 3 hours. A single packer was placed in 37-B07 so that the bottom of the packer was at approximately 83 ft bgs. A pressure transducer was placed in 37-B06 (no packer in 37-B06). The pump was placed below the packer in 37-B07 to test the connectivity associated with the deeper fracture zone.

Approximately four months following the short-term hydraulic testing, and after placing the packers in the boreholes as shown in Table 5.4, two rounds of baseline groundwater sampling were performed (May 28 and July 2, 2014) for analysis of VOCs, reduced gases, anions, DHC, and dissolved iron.

5.5.2 Groundwater Recirculation and Partitioning Tracer Testing – STAGE 2

This second stage of the field testing was performed using the well network in the demonstration area, and provided baseline (pre-bioaugmentation) conditions with respect to DNAPL mass, flow field, and dissolved contaminant concentrations. Stage 2 testing, except where noted, was performed using the packer intervals described in Table 5.4.

5.5.2.1 Initiation of Groundwater Recirculation

Groundwater recirculation began on July 2, 2014, with an average recirculation rate during the first week of operation of approximately 113 mL/min. Groundwater was extracted from 37-B12 and 37-B13 at approximately 76 and 37 mL/min, respectively. All groundwater was re-injected into 37-B06.

5.5.2.2 Partitioning Tracer Testing

Following nearly two-weeks of groundwater re-circulation, the PTT was initiated. The PTT was used to determine the flow field, verify connectivity between boreholes, determine travel times across the demonstration plot, and estimate the mass of DNAPL present. The PTT was performed similarly to the interwell PTT described in Section 5.2.1.7 of the *Project Final Report*, with 37-B06 used as the injection well and boreholes 37-B12 and 37-B13 used as extraction wells.

PTT activities began the week of July 14, 2014 (conducted by personnel from the University of Florida), with injection of the tracer (mixture of bromide and alcohols) occurring on July 15 and 16, 2014. Addition of the tracer amendments was performed using the amendment delivery system described in Section 5.4.4. Tracer amendments were delivered to the injection interval of 37-B06 (as specified in Table 5.4). The 34 gallon tracer solution was prepared using tap water and the following solute concentrations (verified by sampling the tracer solution during the injection process):

- 517 mg/L bromide (from sodium bromide);
- 1,480 mg/L methanol; and
- 663 mg/L 2,4-dimethyl-3-pentanol (DMP).

The tracer solution was injected into the target interval in 37-B06 over 1.1 days, thereby attaining an average injection flow rate of 83 mL/min, which was similar to that during the previous 10 day recirculation period. During tracer injection, the extracted groundwater from the extraction wells (37-B12 and 37-B13) was directed to a tank in the system Conex box to maintain groundwater flow conditions. The Conex box served as a location to monitor system flows and was ultimately used to facilitate the delivery of remedial amendments for planned bioremediation testing. Groundwater recirculation was reinitiated (i.e., the reinjection of the extracted groundwater from 37-B12 and 37-B13 into 37-B06) after the delivery of the tracer pulse and continued throughout the duration of the tracer test at a combined recirculation rate of approximately 111 mL/min.

Groundwater sampling for bromide and the alcohols commenced just prior to tracer addition and continued throughout the 92-day tracer test. Monitoring locations were sampled by using dedicated pneumatic bladder pumps installed in each of the sampled borehole intervals on Table 5.4. The extraction wells were sampled by diverting the flow to collect 40 mL samples of the recirculating groundwater. The recirculation flow was monitored throughout the tracer test and remained relatively constant at 111 mL/min prior to bioaugmentation (see Section 5.5.3). It is noted that no tracers were detected at any time in the extraction wells; thus, no tracers were reinjected into the injection well following the initial tracer slug.

Upon completion of the PTT, operation of the groundwater recirculation continued with an average flow rate of approximately 115 mL/min through the end of August 2014. Groundwater sampling rounds were conducted on July 31, August 7, August 14 and August 27, 2014, prior to aquifer amendment and bioaugmentation. Sampling was performed at 37-EW07 and all system wells except the injection well 37-B06 (i.e., 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, and 37-B13). This monitoring and continued re-circulation was performed to allow for equilibration throughout the demonstration area, as PCE concentrations were increasing for several weeks after initiating recirculation.

5.5.3 Bioaugmentation Treatment and Monitoring – STAGE 3

Aquifer amendment activities were initiated on August 28, 2014, with personnel from the University of Florida injecting 59 liters of a mixture of sodium lactate and nutrients (diammonium phosphate [DAP] and yeast extract) in water into injection well B06 at approximately 500 mL/min. The mixture was injected with average concentrations of 2,000 mg/L lactate and 100 mg/L DAP and yeast extract.

The following day, August 29, 2014, bioaugmentation was conducted, with 19 liters of CB&I's concentrated SDC-9 bacteria culture injected into injection well 37-B06. Following bioaugmentation, 38 liters of water amended with 2,000 mg/L sodium lactate and 100 mg/L DAP and yeast extract was injected into the injection well as chase water. Groundwater recirculation continued upon completion of chase water injection.

Upon completion of the amendment and bioaugmentation injections, subsequent observations of system performance showed that the water level in the injection well rose significantly, from approximately 30 ft bgs prior to the injections to less than 10 ft-bgs. The recirculation system's automated controls went into an alarm condition when the water level in the injection well became less than 10 ft-bgs, shutting the extraction well pumps down until the water level decreased to 20 ft-bgs, at which time the extraction well pumps were reinitiated. This cycle of the extraction wells operating for a certain period (approximately 7 hours), followed by down-time to let the water levels drop in the injection well continued throughout system operation.

In an attempt to remedy this loss in injection well yield, 37-B06 was redeveloped. Environmental field technicians from AECOM (O&M subcontractor to CB&I) performed the well development on October 2, 2014. The packer string was deflated and removed from the borehole, and the borehole was surged and pumped. Water level recharge was then monitored, calculated to be approximately 0.05-0.06 feet/minute (a little over 100 mL/min). The packer string was then reinserted into the borehole at the proper depth and re-inflated.

System operation continued, and on January 13, 2015, the amendment (lactate, nutrients, bicarbonate) dosage was increased from 60 mL every 2 hours to 60 mL every 30 minutes, as the volatile fatty acid results from the December 17, 2014, groundwater sampling event showed decreased concentrations relative to prior sampling events at monitoring well 37-B11s.

It was also observed on January 13, 2015, that the injection well (37-B06) recharge rate had dropped to less than 10 mL/min. Therefore, a second well development scope of work was generated, consisting of the addition of well development chemicals (Nu-Well 120 Liquid Acid in combination with Nu-Well 310 Bioacid Dispersant, manufactured by Johnson Screens) to remove any scaling or biofouling that may have occurred in the borehole or near fractures. Well surging and pumping were used in combination with the chemicals to develop the borehole and ensure that the low pH water created by the chemicals was removed. 37-B06 well recharge was measured to be approximately 40 mL/min after development, which was considered acceptable for continued system operation. 2 Liters of bioaugmentation bacteria culture (SDC-9), diluted to 19 liters with water, was injected into 37-B06 on February 13, 2015.

By March 1, 2015, the recharge rate in 37-B06 was down to approximately 13 mL/min, and remained at that rate for the next few weeks. An additional well development scope of work was generated, consisting of having a drilling subcontractor mobilize to the site to brush the sides of the borehole with a wire brush, surge the borehole within the injection interval with a surge block and pump the borehole. Upon removal of the packer string (two packers isolating the injection interval) from the borehole to complete the development work on March 27, 2015, the glands of both packers were observed to be bulging, which did not allow their reinsertion back into the borehole. One spare packer was located on-site, and was set in the borehole at the same elevation as the original bottom packer, and the injection tubing was lowered to the same depth as the original. The only difference is that the new configuration did not include a top packer.

Upon packer replacement and inflation, the recharge rate was again measured in the borehole. Very little improvement was observed following the recent well development activities. Therefore, the decision to deflate the bottom packer was made on March 28, 2015, to allow the recirculation system to operate at a more reasonable (higher) flow. Recharge rates of greater than 200 mL/min were observed upon packer deflation. Careful consideration was taken when evaluating the results of subsequent groundwater sampling events, to determine the connectivity of the deeper portion of the 37-B06 to the monitoring well depth intervals.

System operation continued through May 19, 2015, at which time the system was shut-down and the rebound assessment phase of the project began. Groundwater monitoring was performed on that day, to serve both as the final Stage 3 groundwater results and as a baseline for post-treatment monitoring. Data justifying shut-down of the system was presented to the Environmental Security Technology Certification Program (ESTCP) in a technical memorandum dated May 7, 2015.

5.5.4 Post-Treatment Monitoring and Assessment – STAGE 4

To assess the feasibility of performing a final partitioning tracer test at the site, an injection well recharge test was performed on January 13, 2016. The water column in injection well 37-B06 was pumped down to just above the inflated packer (approximately 80 ft-bgs), and the well recharge rate was observed by measuring depth to water periodically during borehole recharge. The test duration was approximately 2.5 hours, with well recharge measurements ranging from 8.68 mL/min near the beginning of the test to 3.67 mL/min at the end of the test. These low borehole recharge measurements provide sufficient data to conclude that performing a final partitioning tracer test at the site is not feasible, as initial well capacity for injection (used during the initial tracer testing) was approximately 100 mL/min.

As mentioned above, the post-treatment monitoring baseline groundwater samples were collected on May 19, 2015. Four additional sampling events were conducted during the post-treatment assessment phase, as presented in Table 5.5.

One final post-treatment rock core was also collected during this Stage. The borehole was located between the injection well (37-B06) and the first monitoring well (37-B11), as shown in Figure 5.6.

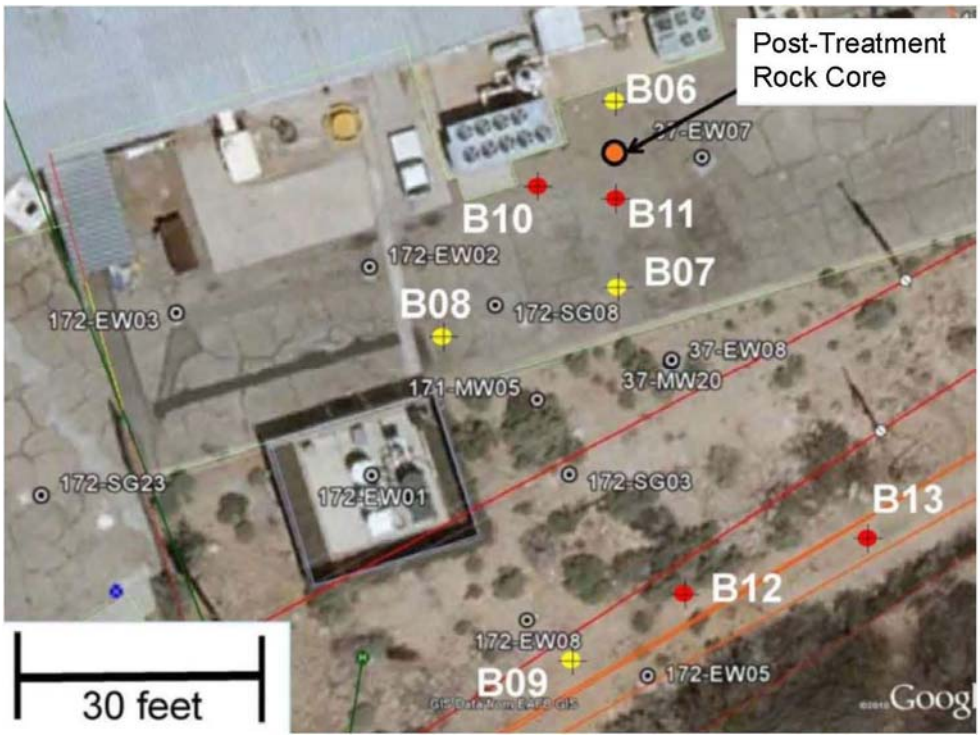


Figure 5.6. Post-Treatment Rock Core Location

The focus of the rock core collection was centered on the conductive fractures observed in nearby injection well 37-B06 at approximately 78 and 83 ft bgs. The observed fractures in the new borehole (37-B14), which may be connected to the fractures observed in 37-B06, were located approximately 81.4 ft-bgs and 86.4 ft-bgs. Slices of rock (approx. 1 cm thick) were cut in the field with a diamond blade saw, adjacent to both fractures, from the fracture interface into the rock matrix (up to 8 cm distance). The rock was crushed and immediately placed into soil jars with methanol for extraction. The methanol was to be analyzed as a function of time (up to three sampling events over a three-month period) for VOCs to ensure extraction equilibration, and to assess the concentration profile within the rock. On the other face of each of the two fractures, samples were collected for mineral analysis (ferrous iron using the 1,10-phenanthroline method, which was employed in the recently completed SERDP project ER-1685). Samples were collected as a function of distance from the fracture interface (up to 5 cm distance). This allowed for assessing the extent to which reducing conditions impacted the rock matrix. The borehole was abandoned with neat cement upon completion of coring and rock sample collection.

5.6 SAMPLING METHODS

Groundwater sampling was conducted in order to characterize the distribution of chemical constituents in groundwater, to evaluate the hydrochemistry of the aquifer, and to determine formation travel times (tracer testing). The varied objectives of the sampling required multiple sampling schemes: each analytical suite and sequencing reflecting the individual goals. The completion of wells at multiple levels with single wells also necessitated variations in sampling protocol.

The procedures used in collecting groundwater samples during the demonstration, including quality assurance sampling and analysis, are described in detail in the *Project Final Report*. The analytical methods and sample preservation used for the analyses that were part of this demonstration are summarized in Table 5.6 below.

Table 5.6. Analytical Methods, Preservation, and Containers -Groundwater

Analyte	Method/ Laboratory	Preservative	Bottle
VOCs	EPA 8260 CB&I	4 degrees Celsius (°C) with HCl	40 mL Volatile Organic Analysis (VOA) vial (x2)
Reduced Gases	EPA 3810 CB&I	4°C with HCl	40 mL VOA vial (x2)
Anions	EPA 300.0 CB&I	4°C	100 mL polyethylene screw-cap (x1)
Alcohols	Gas Chromatography-Flame Ionization Detector (GC-FID) Univ. Florida	4°C with HCl	40 mL VOA vial (x2) cap (x2)
***Dehalococcoides* sp. (DHC)**	qPCR (Schaefer et al. [*1*]) CB&I Microbial Insights	4°C	1 L glass bottle
Reductive dehalogenase genes (RDG) **(*tceA*, *vcrA* and *bvcA*)**	qPCR Microbial Insights	4°C	1 L glass bottle
Volatile Fatty Acids	EPA 300m CB&I	4°C	40 mL VOA vial (x2)
Hydrogen	RSK175 CB&I	4°C with HCl	125 mL glass serum bottle with Teflon-lined cap and crimp seal
Metals (Fe, As)	EPA 200.7 Chemtech	Capsule filter, 4°C with HNO_3	100 mL polyethylene screw-cap (x1)
Bromide	Field Meter	--	--
pH	Field pH Test Strips	--	--

The analytical sampling described in Sections 5.5.1 through 5.5.4 was performed, in general, at the locations and frequency described in Table 5.7. Sampling locations were, in large part, based upon the results of the tracer test.

Table 5.7. Groundwater Sampling Schedule

Stage	Analyte	Locations	Frequency
Stage 1 (Section 5.5.1)	VOCs	B10, B11, B12, B13	1 event
Stage 2 (Section 5.5.2)	VOCs	B06, B07, B10, B11, B12, B13	1 event
	Alcohols	B06, B07, B10, B11, B12, B13, 37-EW07	Multiple events (up to 27)
Stage 3 (Section 5.5.3)	VOCs Reduced Gases Anions Volatile Fatty Acids (VFAs) DHC	B07, B11, B12, B13, 37-EW07*	2 baseline, 2, bi-weekly, 5 monthly events
	Hydrogen	B07, B11, B12, B13	1 baseline, 1 bi-weekly, 2 monthly
	RDG	B07, B12, B13 B11	1 baseline event Stage 3 - Month 8
	Total/Dissolved Fe As	B07, B11, B12, B13	1 baseline, 1 bi-weekly, 3 monthly
Stage 4 (Section 5.5.4)	VOCs Reduced Gases Anions VFAs DHC Total/Dissolved Metals (Fe, Ar, Na, K)	B07,B11	4 events (3, 5, 8, and 10 months post-Stage 3 treatment)

* Select sampling frequency at this location (pre-bioaugmentation baseline, post-bioaugmentation round no. 1)

5.7 SAMPLING RESULTS

5.7.1 Results of STAGE 1 Testing

5.7.1.1 Rock Matrix Assessment

Results of the rock matrix assessment are provided in Figure 5.7. The results clearly show PCE diffusive uptake into the rock matrix. Although there are scatter in the data, no clear gradient of PCE migration (high concentration to low concentration) emanating from the fracture face is observed. These results suggest that there is a high storage potential of PCE within the rock matrix. It is noted that the rock matrix porosity was 4.9%, as measured using the water uptake method (*32*).

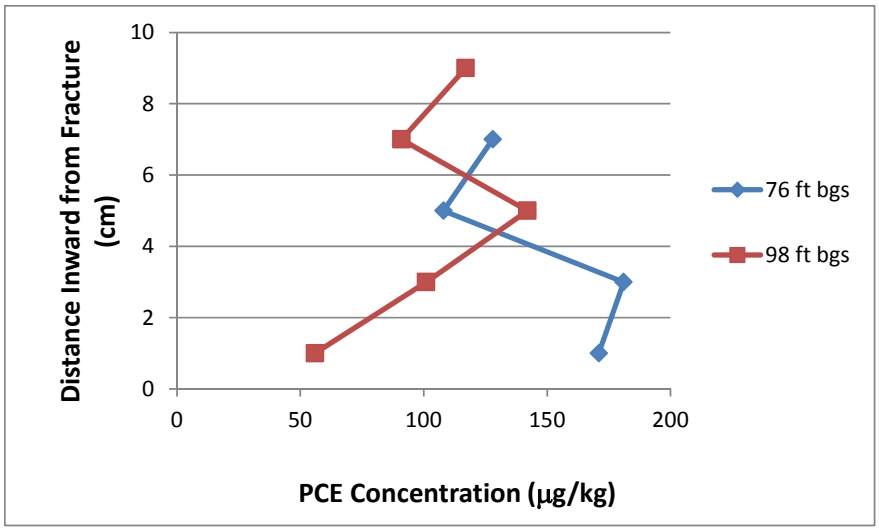


Figure 5.7. PCE Concentration within the Rock Matrix at 37-B10.

Adjacent to fracture zones at approximately 76 and 98 ft bgs.

5.7.1.2 Short-Term Hydraulic Testing

Results of the short-term hydraulic testing yielded the following qualitative and quantitative results:

- *Pump test at 37-B13.* Test results showed that the open borehole extraction capacity was approximately 70 to 90 mL/min, based on steady draw-down testing and the rate of recharge observed within the borehole after the pump test was completed. No measureable drawdown was observed in 37-B06 or 37-B07 during the test, suggesting that a strong hydraulic connection between the test well and the injection/monitoring wells was not present.
- *Pump test at 37-B12.* Test results showed that the open borehole extraction capacity was approximately 110 to 130 mL/min, based on steady draw-down testing and the rate of recharge observed within the borehole after the pump test was completed. No measureable drawdown was observed in 37-B06 or 37-B07 during the test, suggesting that a strong hydraulic connection between the test well and the injection/monitoring wells was not present.
- *Pump test at 37-B06.* Test results showed that the open borehole extraction capacity was approximately 25 to 50 mL/min, based on steady draw-down testing and the rate of recharge observed within the borehole after the pump test was completed. Due to decreases in water table elevation in 37-B07 prior to the test, the extent of hydraulic influence in the shallow (above 80 ft bgs) fracture zone could not be assessed.
- *Pump test at 37-B07.* Test results showed that the open borehole extraction capacity was approximately 400 mL/min, based on steady draw-down testing. Rapid drawdown was observed at 37-B06 during testing, indicating a strong hydraulic influence in the deep (below 80 ft bgs) fracture zone.

5.7.1.3 Baseline Sampling

Results of the baseline groundwater sampling under ambient (no re-circulation) conditions indicated significant (>1% solubility) PCE concentrations at all the monitoring locations shown in Table 5.4. Ambient (prior to recirculation) dissolved groundwater PCE concentrations ranged from 4 to 25 mg/L in the monitoring wells and as high as 85 mg/L in the extraction wells. Further results of the baseline sampling are presented and discussed in the context of the initiation of groundwater recirculation and bioaugmentation treatment in Section 5.7.3.

5.7.2 Results of STAGE 2 Testing

5.7.2.1 Partitioning Tracer Test

Results showed that only 37-B11s and 37-B11d had appreciable quantities of tracer, indicating complete breakthrough of the tracer pulse. No tracer was observed at either of the extraction wells (37-B12 and 37-B13), or in the shallow and intermediate intervals of 37-B07. Very low levels (less than 1% of the injected tracer concentrations) were measured in 37-B07d, making any meaningful interpretation of results with respect to DNAPL architecture difficult at this location. Thus, assessment of DNAPL architecture and flow field is focused on the strong tracer signatures observed at 37-B11s and 37-B11d. The lack of hydraulic influence observed at B06 and B11 (shallow and deep intervals) while pumping at the extraction wells likely limited the tracer zone of influence to the immediate vicinity of the injection well (which included 37-B11s and 37-B11d), where the tracer flow was largely controlled by the hydraulic gradient emanating from the injection well. It is suspected that the fracture plane that was shown to hydraulically connect the deep zone between 37-B06 and 37-B07 is likely intersected by another fracture plane that diverted most of the tracer flow.

Tracer breakthrough curves for 37-B11s and 37-B11d are shown in Figures 5.8 and Figure 5.9, respectively. For both 37-B11s and 37-B11d, and also for 37-B07d, methanol concentrations are lower than bromide (bromide concentrations were normalized to the background bromide concentration of 1.3 mg/L). If both methanol and bromide were conservative tracers, they would co-elute, even in the presence of DNAPL. These observations suggest that slow biodegradation of methanol was likely, which is consistent with previous observations of methanol biodegradation in groundwater *(28)*. Thus, bromide was likely the only conservative tracer in this study.

Observation of the tracer elution data shows a distinct pulse of tracer breakthrough at 37-B11s, an initial small pulse of tracer at 37-B11d (located at 1.1 days), followed by a second much larger pulse of tracer (located at 2.5 days), and a final slowly eluting tracer mass (or, “tail”) late in 37-B11d. Qualitative observations also show that the conservative bromide tracers have lower peak concentrations and/or show less tailing than the hydrophobic alcohol tracer at 37-B11s, the initial small peak at 37-B11d, and slightly in the “tail” at 37-B11d, suggesting that partitioning into DNAPL is occurring along the flow path in these flow regimes. In contrast, the bromide appears to co-elute with the hydrophobic tracer at the primary pulse in 37-B11d, suggesting that DNAPL is not present along this flow path. The absence of any measureable difference in the elution of bromide and hydrophobic tracers at the large pulse in 37-B11d also confirms that hydrophobic tracer sorption to the aquifer solids is negligible, thus DMP uptake (where observed) is assumed attributable to DNAPL in the fractures.

5.7.2.2 Assessment of Flow Field

Applying the method of moments (MOM) model, the fracture volume and the fraction of the injected flow associated with each of the regimes depicted in Figures 5.8 and 5.9 are presented in Table 5.8; other model regressed parameters also are provided in Table 5.8. The mass of bromide eluting through 37-B11s and d is consistent (within approximately a factor of 2) with the radial fracture flow assumption, thus indicating that this assumption is reasonable given the conditions of the tracer experiment.

The distribution of flow among the four fracture zones is proportional to the transmissivity of each of these zones. Results show that most of the tracer mass, and flow, that reached the target 37-B11 intervals eluted through 37-B11s and the tracer tail at 37-B11d. The relatively large fracture porosity, and associated low tracer velocities, is responsible for the tailing peak at 37-B11d. In contrast, the initial peak at 37-B11d has a relatively low transmissivity (compared to the other 3 fractures), but has a low fracture porosity; these factors are what cause the low flow and short elution time relative to the other fracture zones. The implications of this immobile porosity and DNAPL architecture and dissolution are discussed in the following sections.

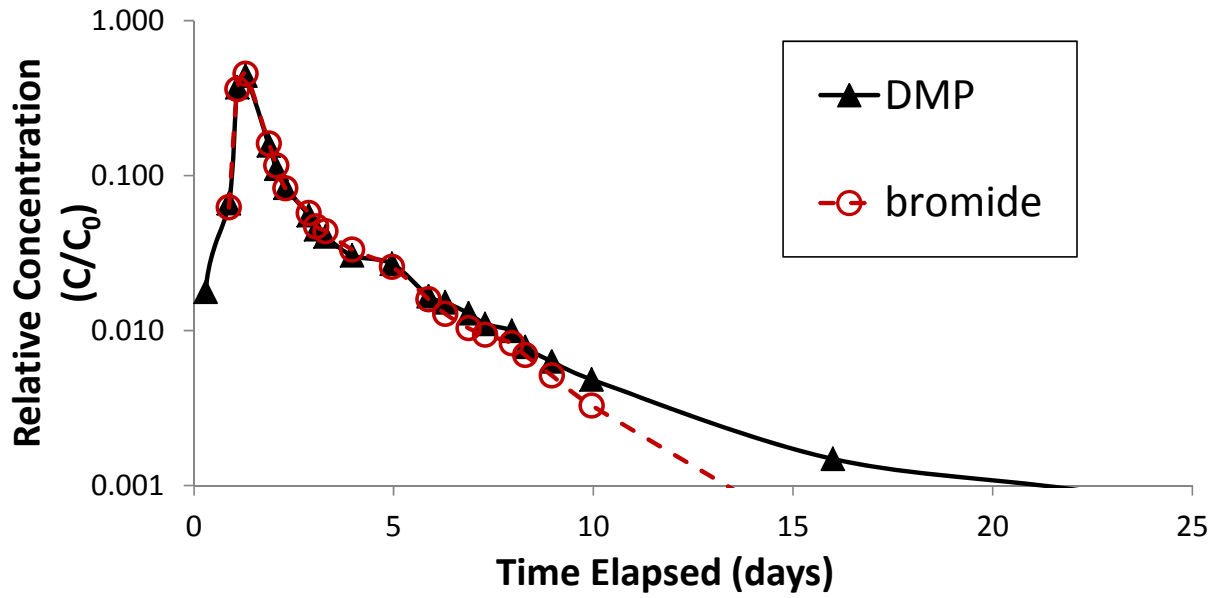


Figure 5.8. Bromide and DMP Tracer Elution in 37-B11s

Bromide and DMP tracer elution through the 37-B11s monitoring interval. Concentrations are plotted relative to the injection concentration. A semi-log plot is used to show the difference in tracer behavior.

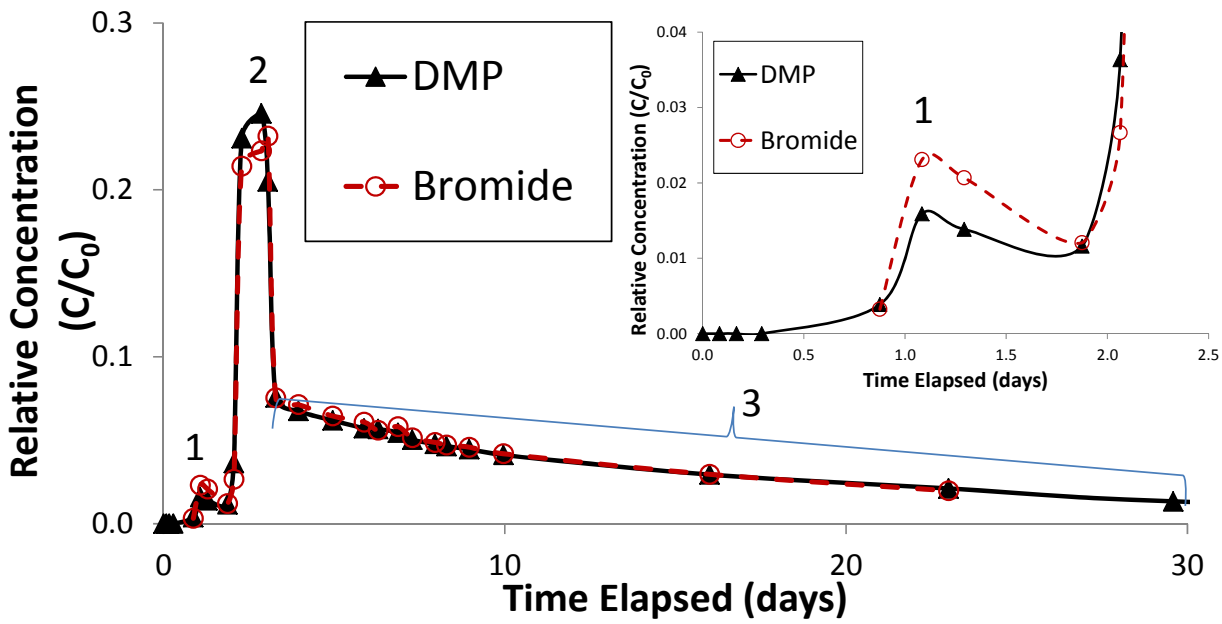


Figure 5.9. Bromide and DMP Tracer Elution in 37-B11d

Bromide and DMP tracer elution through the 37-B11d monitoring interval. Concentrations are plotted relative to the injection concentration. Early and middle peaks are observed (denoted by the 1 and 2, respectively), followed by the late tail (denoted by the 3). The inset figure highlights the initial peak.

Table 5.8. Modeling Results Based on the PTT

The relative flow for each fracture zone is calculated as the fraction of eluted bromide mass through each zone divided by the eluted bromide mass for the sum of the 4 zones.

Parameter	37-B11s	37-B11d (initial)	37-B11d (middle)	37-B11d (last)
Relative Flow Mass Recovery Fraction (MRF)	0.50	0.011	0.087	0.40
Velocity (m/day)	1.5	7.5	1.6	0.2
Mean residence time (days)	2.7	0.6	2.5	21
Fracture Porosity	0.00069	3.0×10^{-6}	0.00080	0.0042
R	1.08	1.24	0.99	1.02
S_n	0.002	0.007	0.0	0.0004
DNAPL volume (m^3 x 1000)	0.66	0.0091	0.0	0.82
DNAPL Dissolution Time (ambient) (years)	44	200	0.0	13

5.7.2.3 DNAPL Architecture

The DNAPL fracture saturation associated with each zone is presented in Table 5.8. The DNAPL saturation in each of the fracture zones is quite low, ranging from 0 (no measureable DNAPL) to a maximum of 0.007. These saturations are likely 1 to 2 orders of magnitude below levels needed for DNAPL mobility (*13,21*). DNAPL is observed in both high and low transmissivity (or flow) zones within the fracture network. The majority (55%) of the DNAPL resides in the relatively transmissive zone in 37-B11d (final peak), which also is associated with the largest fracture porosity. The greatest DNAPL saturation is located in the low transmissivity fracture zone (initial peak in 37-B11d), but only 0.6% of the DNAPL mass is present in this zone due to its low fracture porosity.

5.7.3 Results of STAGE 3 Testing: Bioaugmentation Treatment and Monitoring

5.7.3.1 Recirculation Flow and Amendment Distribution

The groundwater recirculation flow rate prior to and after bioaugmentation is shown in Figure 5.10. Immediately after adding the bioaugmentation culture, the re-circulation flow rate diminished by approximately 40% without any recovery in the flow rate as groundwater re-circulation continued. The reason for this immediate and sustained decrease is unclear, but it is unlikely that any biofouling impacts would have occurred so quickly based on prior experience using similar bioaugmentation approaches *(2)*. It is possible a physical blockage of the fractures occurred during injection, perhaps due to instability or crumbling along the borehole wall, or any solids potentially present in the injection. Following the culture injection, slow decreases in re-circulation flow rate were observed over time following bioaugmentation and during delivery of biological amendments. These slow decreases in flow, in contrast to the step-decrease observed during the initial bio-amendment delivery, were due to slowly diminishing capacity of the injection well, and were likely due to biomass growth and/or microbially-enhanced mineral precipitation. The re-circulation flow rate decreased to as low as approximately 10 to 20% of the original flow rate for several months of the demonstration. Attempts to re-develop the injection well only resulted in marginal improvement to the well capacity; the relatively large improvement at 303 days was primarily due to deflating the packer in the injection well.

PCE concentrations within the two extraction wells 37-B12 and 37-B13 remained elevated during the duration of the demonstration, with PCE concentrations averaging 0.7 and 0.4 millimolar (mM) (120 and 70 mg/L), respectively. Analytical results are presented in tabular form in Appendix C. These dissolved PCE concentrations were several times greater than the dissolved PCE concentrations observed (under ambient conditions prior to initiation of groundwater re-circulation) at the injection well or monitoring wells 37-B11 and 37-B07. The elevated PCE concentrations in the two extraction wells suggest that PCE DNAPL potentially may also be present further downgradient in the vicinity of the extraction wells.

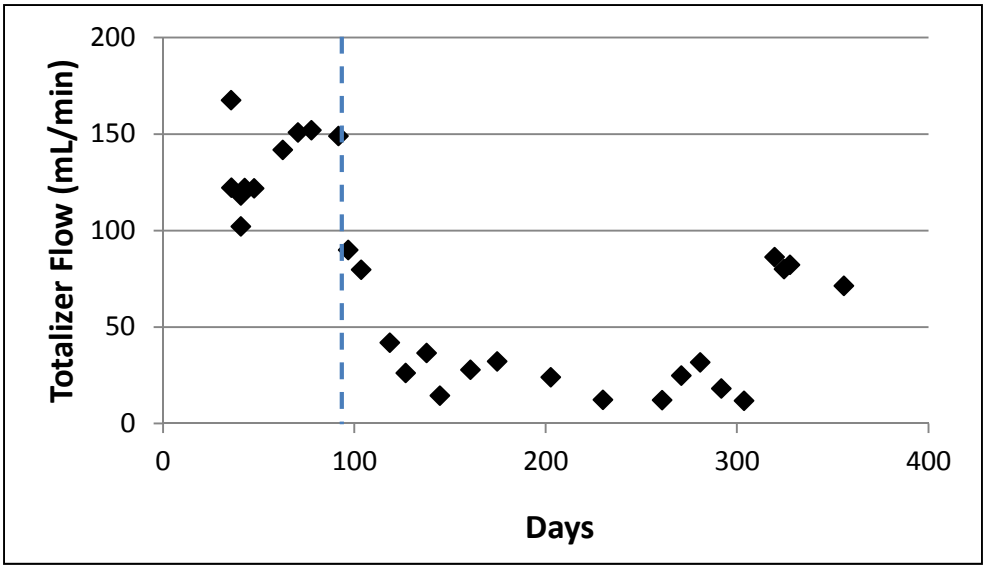


Figure 5.10. Groundwater Re-circulation Flow Rate.

The vertical dashed line indicates the start of biological amendment addition. Attempts to re-develop the well were performed on days 127, 256 and 303.

No remedial amendments or biodegradation impacts (e.g., decreases in PCE, chlorinated ethene daughter products, lactate fermentation products, increases in DHC) were observed at either of the extraction wells during the demonstration. These results are consistent with the previously performed tracer tests, where no tracers were observed at the extraction wells *(27)*. In addition, no remedial amendments or biological impacts were observed at the shallow and intermediate intervals of 37-B07 (although one sample at the shallow interval of 37-B07s did show a 1 to 2-log increase in DHC). Trace impacts of biological treatment were observed at the deep interval in 37-B07d, located approximately 5 m downgradient from 37-B11. Lactate fermentation products typically were between 50 and 200 mg/L, which were approximately 10-times less than what was observed in the 37-B11 intervals. As shown in Figure 5.11, DCE generation, decreases in PCE concentration, and DHC increases were minimal at 37-B07d; all of these data indicate that no bioremediation of PCE occurred at this location due to insufficient delivery of remedial amendments. By the end of the demonstration, sulfate levels also had decreased by approximately a factor of 2, suggesting that sulfate reduction was only starting to occur. The sum of detected volatile fatty acids at 37-B07d never exceeded 200 mg/L. The minimal impacts observed at 37-B07d (as well as the other shallower 37-B07 intervals) were consistent with the previous tracer testing, which indicated that this monitoring location was not along the primary fracture flow paths emanating from the injection well. The lack of a strong amendment response at 37-B07, located only 8.8 m downgradient of the injection well, highlights the complexity of fracture flow at this site.

Consistent with the pre-remedial tracer test, migration of remedial amendments and biological impacts were most clearly observed at both the shallow and deep monitoring intervals of 37-B11. Figures 5.12 and 5.13 show the relatively high levels of propionic acid (a lactate fermentation daughter, and also a fermentable volatile fatty acid) observed in the shallow and deep intervals of 37-B11 throughout the demonstration; propionic acid typically was the most abundant volatile fatty acid detected. Other biological impacts at 37-B11, including an assessment of PCE dechlorination and DNAPL removal, are discussed in the following subsections.

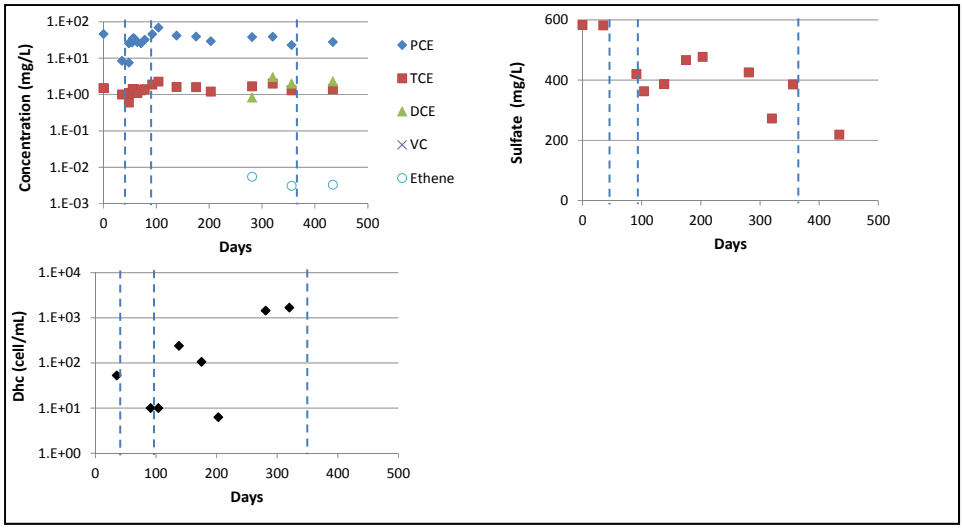


Figure 5.11. Chlorinated Ethene+Ethene, Sulfate, and DHC Levels at 37-B07d

Vertical dashed lines represent the start of groundwater re-circulation, the initiation of bioremediation amendment addition, and the cessation of groundwater recirculation. For the chlorinated ethenes, only detections are shown. For the DHC, data at 10 cell/mL represent the analytical detection limit.

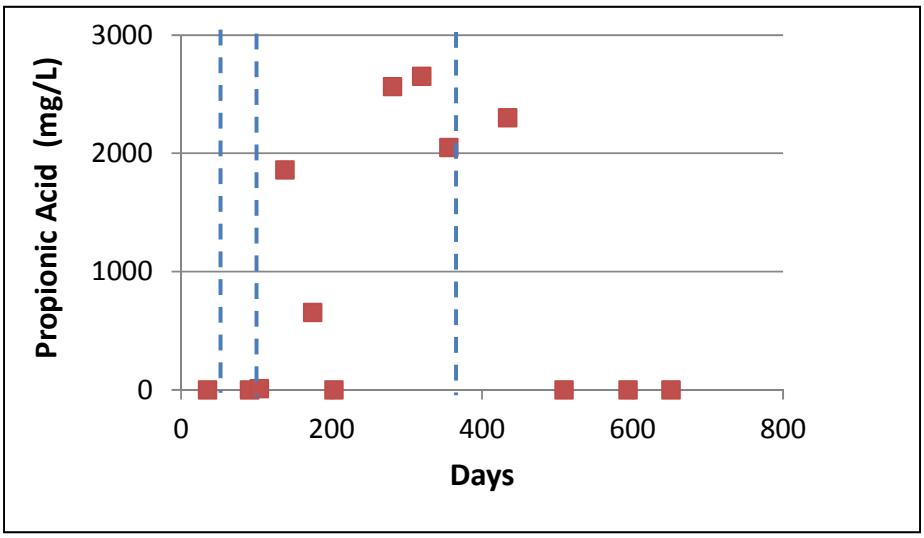


Figure 5.12. Propionic Acid Concentration Measured in the Shallow Interval of 37-B11

Vertical dashed lines represent the start of groundwater re-circulation, the initiation of bioremediation amendment addition, and the cessation of groundwater re-circulation.

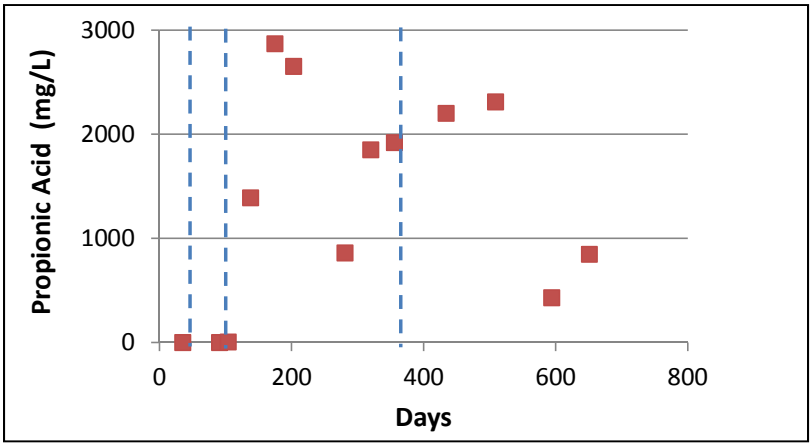


Figure 5.13. Propionic Acid Concentration Measured in the Deep Interval of 37-B11

Vertical dashed lines represent the start of groundwater re-circulation, the initiation of bioremediation amendment addition, and the cessation of groundwater re-circulation.

5.7.3.2 Reductive Dechlorination

Figures 5.14 and 5.15 summarize the chlorinated ethenes and ethene observed at 37-B11s and 37-B11d, respectively. The increases in PCE concentrations after initiating groundwater re-circulation were due to the elevated PCE concentrations in the downgradient extraction wells. Results indicate that, within seven weeks following bioaugmentation and biological amendment delivery, PCE concentrations showed a substantial (~90%) decrease, with an approximate stoichiometric increase in DCE (although the DCE concentrations in 37-B11s at 46 days following bioaugmentation appear anomalously low). These results are consistent with previous studies that show DCE as the primary dechlorination daughter product when PCE DNAPL is present *(18,29,30)*. The increases in chloride concentrations, particularly between 130 and 205 days, also confirm reductive dechlorination is occurring (Figure 5.16).

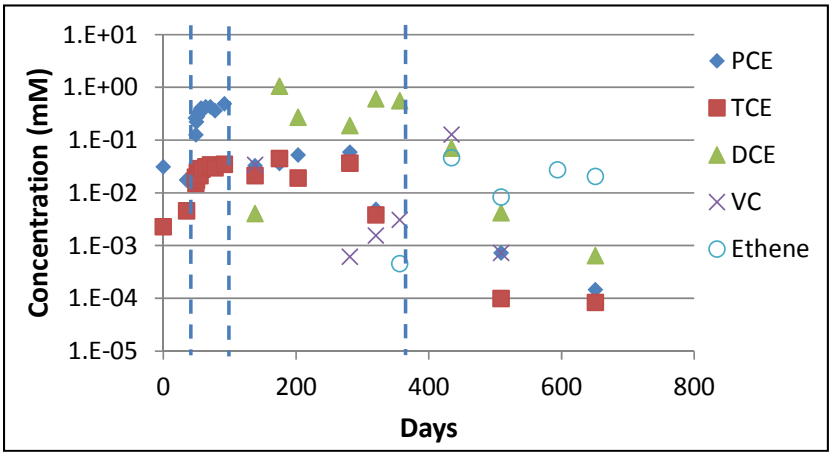


Figure 5.14. Chlorinated Ethene and Ethene Concentrations at 37-B11s

Only detections of chlorinated ethenes and ethene are shown. Vertical dashed lines represent the start of groundwater re-circulation, the initiation of bioremediation amendment addition, and the cessation of groundwater re-circulation.

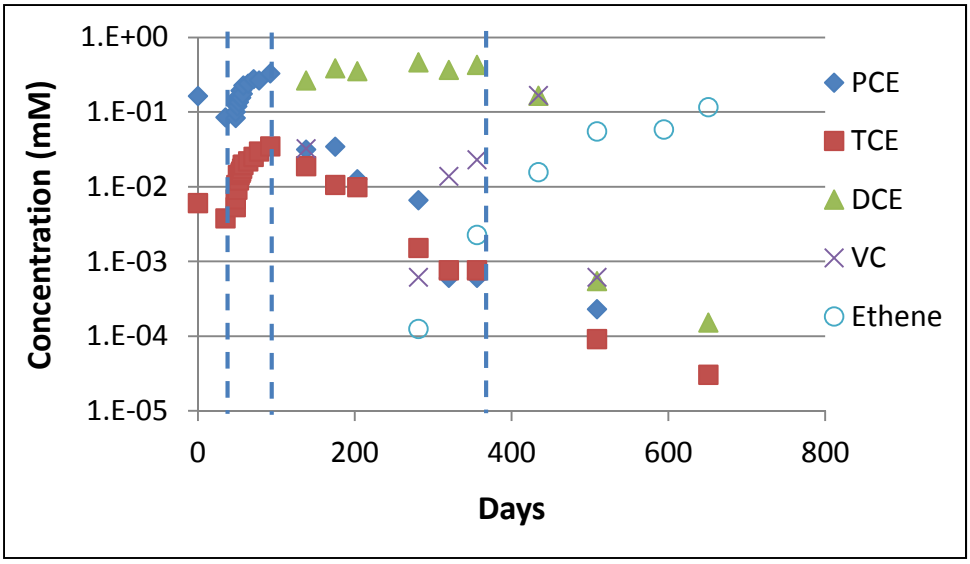


Figure 5.15. Chlorinated Ethene and Ethene Concentrations at 37-B11d

Only detections of chlorinated ethenes and ethene are shown. Vertical dashed lines represent the start of groundwater re-circulation, the initiation of bioremediation amendment addition, and the cessation of groundwater re-circulation.

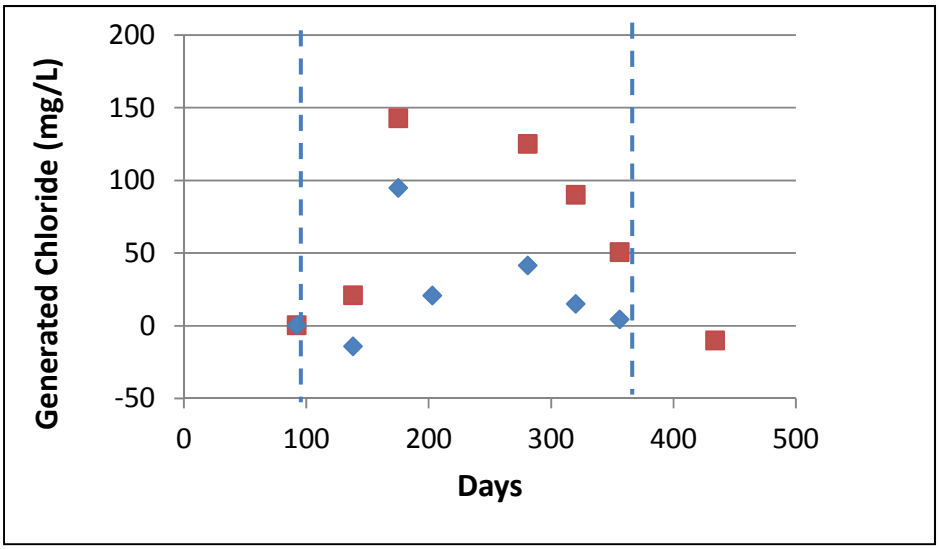


Figure 5.16. Generated Chloride (above background chloride levels) at 37-B11.

37-B11s (■) and 37-B11d (◆). Vertical dashed lines represent the initiation of bioremediation amendment addition and the cessation of groundwater re-circulation. Dilution and mixing from extraction wells are accounted for in determining the generated chloride.

5.7.3.3 Microbial Growth and Geochemical Impacts

Figure 5.17 shows the sulfate and dissolved iron levels for 37-B11s and 37-B11d. Results indicate that sulfate reduction occurred in both zones. Increases in dissolved iron also occurred. Methane levels typically were non-detect or less than 5 µg/L, suggesting that bulk methanogenic conditions likely were not attained during active treatment.

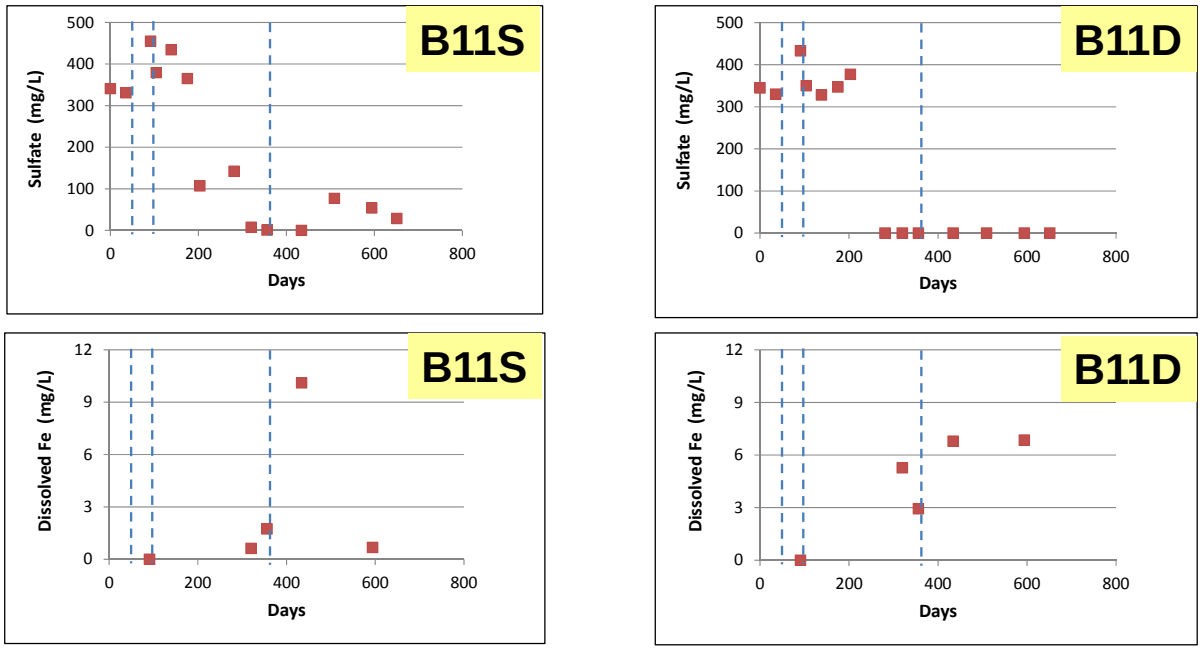


Figure 5.17. Sulfate and Dissolved Iron Concentrations Measured in 37-B11s and 37-B11d

Vertical dashed lines represent the start of groundwater re-circulation, the initiation of bioremediation amendment addition, and the cessation of groundwater re-circulation.

Figure 5.18 shows the DHC concentrations for 37-B11s and 37-B11d as a function of time. Results indicate that the DHC were able to migrate to this well. The increasing DHC levels overtime also indicate that DHC growth occurred. DHC concentrations on the order of 10^3 DHC/mL were observed at 37-B07d. However, because the primary fracture flow path beyond 37-B11 was not well defined, the downgradient extent of DHC migration could not be determined.

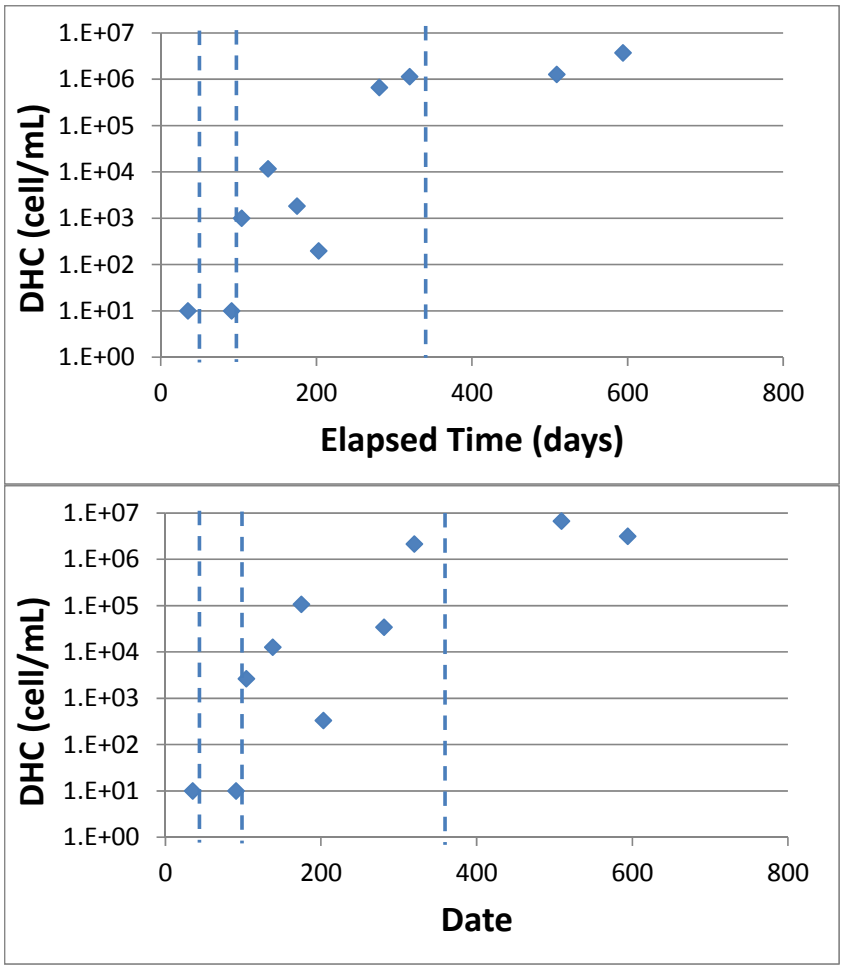


Figure 5.18. DHC Concentrations Measured in 37-B11s (top) and 37-B11d (bottom).

Vertical dashed lines represent the start of groundwater re-circulation, the initiation of bioremediation amendment addition, and the cessation of groundwater re-circulation.

5.7.4 Results of STAGE 4 Testing: Post Treatment Monitoring and Assessment

5.7.4.1 Groundwater Monitoring

After cessation of the groundwater re-circulation and amendment delivery at 356 days, DCE concentrations in 37-B11(s and d) began to rapidly decrease, with a transient increase in VC and increased ethene generation (Figures 5.14 and 5.15). An increasing trend in total molar chlorinated ethene + ethene was observed over the rebound period for 37-B11d, while no increasing trend was observed for 37-B11s. Sulfate levels remained low (Figure 5.17) and ferrous iron levels remained elevated at 37-B11d; volatile fatty acid levels also remained elevated (Figure 5.13). These data indicate that strongly reducing conditions favorable to the complete dechlorination of PCE were maintained at 37-B11d throughout the rebound period. In contrast, by 5 months into the rebound period at 37-B11s, volatile fatty acids became depleted, sulfate levels had increased from non-detect levels (Figure 5.17), and dissolved iron levels decreased, which together suggest that strongly reducing conditions were not maintained throughout the rebound period at this location.

5.7.4.2 Post Treatment Rock Core Collection

Results of the rock core collection for ferrous iron content are shown in Figure 5.19. These ferrous mineral contents are orders of magnitude below those previously observed in rock matrices that showed abiotic dechlorination of chlorinated ethenes (*40*). Consistent with this observation, abiotic reactivity on the rock matrix using collected rock core showed no abiotic dechlorination. The ferrous iron content showed a decreasing trend going into the rock matrix, particularly for the shallow zone. It is unclear if this trend existed prior to bioremediation, or if bioremediation facilitated the formation of ferrous mineral phases at or near the fracture interface.

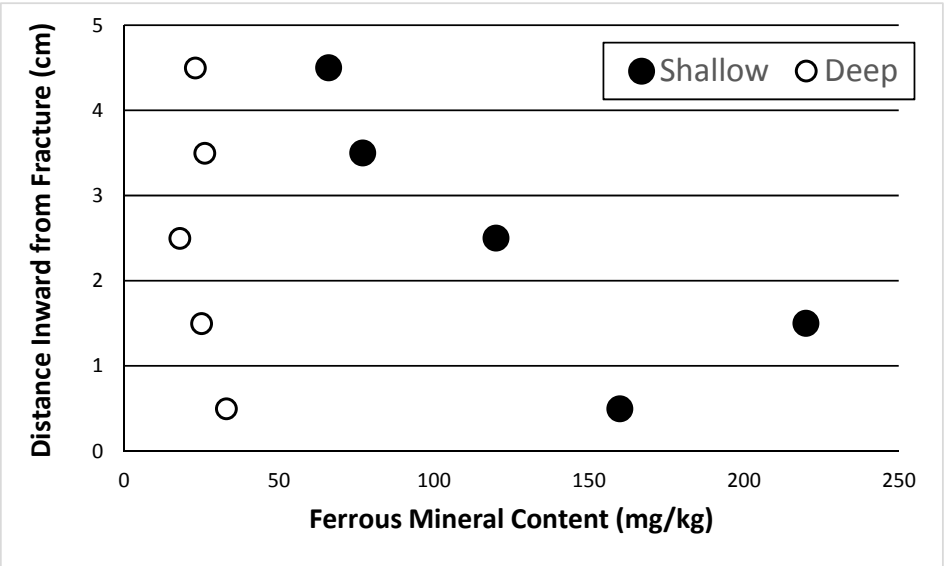


Figure 5.19. Ferrous Mineral Content within the Rock Matrix at 37-B14.

Shown as a function of distance from the fracture interface. Both the shallow (~76 ft bgs) and deep (~85 ft bgs) fracture zones were evaluated.

PCE concentrations within the rock matrix (up to 8 cm into the rock matrix) were below the analytical detection limit (<80 µg/kilogram [kg]). Thus, in comparison to the PCE concentrations within the rock matrix prior to bioremediation, the concentrations decreased by at least a factor of 2. Based on the conceptual model of rapid treatment and removal of PCE in the fractures by biological treatment, and corresponding removal of PCE from the rock matrix via aqueous diffusion, impacts of treatment would not have been expected beyond 1–2 cm. Thus, the absence of measureable PCE in the rock matrix is not readily explained. One possibility is that the presence of microfractures in vicinity of the fracture zone may have allowed remedial amendments to migrate into what appeared to be a competent rock matrix (see Figure 5.20); this would have greatly reduced the diffusion length, and would explain how PCE removal occurred at such relatively large distances from the primary fracture interfaces.

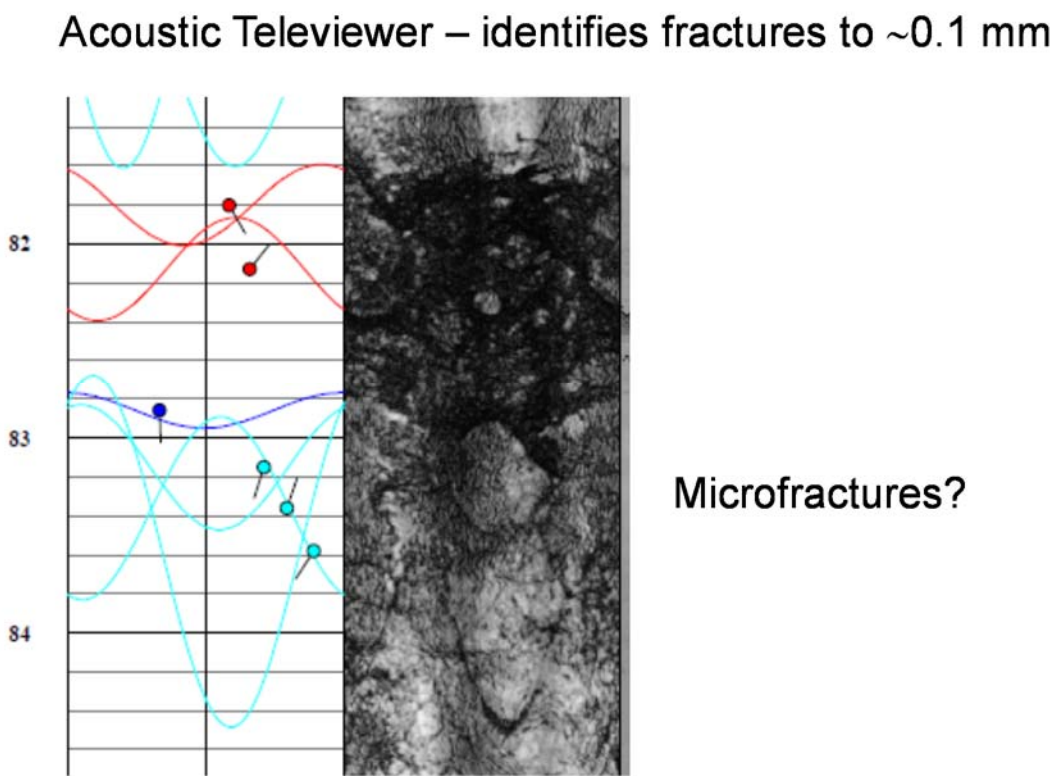


Figure 5.20. Acoustic Televiewer Results Focusing on the Deep Fracture Zone at 37-B06

Microfractures may exist adjacent to the primary fracture. These microfractures may have allowed remedial amendments to distribute further into the rock matrix than what would have been predicted based on diffusion alone.

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6.0 PERFORMANCE ASSESSMENT

6.1 DNAPL ARCHITECTURE

Due to high groundwater velocities and low matrix porosity, tracer elution likely was controlled by convection through the fractures, with limited impacts from matrix diffusion. Using the DMP tracer pulse at 37-B11s, the ratio of convective tracer migration through the fractures to diffusive uptake into the rock matrix (F_{frac}/F_{matrix}) for 37-B11s is 65, indicating that matrix diffusion effects are minimal. A similar result (150) is attained for the tail of 37-B11d.

The impacts of matrix diffusion on mean retention time (or retardation) is related to the tracer diffusion coefficient, where tracers with large diffusion coefficients show more retardation due to uptake into the rock matrix than tracers with small diffusion coefficients *(34)*. For the system, where the aqueous diffusion coefficient for bromide is approximately 2-times greater than that of DMP *(33,35)*, matrix diffusion would lead to a potential underestimation of DNAPL mass, as the difference in mean retention time between bromide and DMP would be greater if bromide exhibited enhanced retardation due to matrix diffusion. However, because the impacts of matrix diffusion in the system is small, a factor of two difference for the aqueous diffusion coefficient has minimal impact on the mean residence time, resulting in less than a 10% error in the DNAPL estimates calculated via the MOM.

While the role of matrix back diffusion in sustaining groundwater plumes in fractured bedrock has been examined *(36,37)*, the role of DNAPL in low permeability fracture zones on plume longevity has received little attention. The ambient (prior to initiating groundwater recirculation) PCE concentrations in 37-B11s and 37-B11d were 4 mg/L and 21 mg/L, respectively. The 21 mg/L dissolved PCE concentration is associated primarily with the dissolved PCE concentration in the "tail" portion of the facture zone, as the majority of the fracture flow and porosity is associated with this fracture zone. The difference in dissolved PCE concentration between 37-B11s and 37-B11d is approximately proportional to the difference in residence time (i.e., travel time between 37-B06 and 37-B11), as increased residence time allows for more DNAPL dissolution. Assuming the dissolved PCE concentration is approximately proportional to the residence time, the dissolved concentration in the low transmissivity zone associated with the initial tracer peak in Figure 5.9 is estimated as 0.6 mg/L, which is calculated by multiplying the 21 mg/L concentration by the ratio of the velocity in the initial fracture zone divided by the velocity in the "tail" portion of the fracture zone.

The calculated DNAPL dissolution timeframes are provided in Table 5.8. It is noted that these time frames do not account for any dechlorination reactions, additional uptake into the rock matrix, or decreases in aqueous concentration as the DNAPL mass diminishes; thus, these timeframes are for screening and comparative purposes only. The two findings of note are that (1) despite the very low DNAPL saturations in the fractures, dissolution timeframes are very long, and (2) DNAPL present in the low transmissivity fractures appears to be responsible for sustaining the contaminant plume. These results suggest that the presence of DNAPL in low permeability fractures can sustain plumes for timeframes similar to that of contaminants present in the rock matrix *(38)*. The persistence of DNAPL in the low flow fractures is similar to the persistence of DNAPL in low permeability zones observed in unconsolidated materials *(39)*.

PCE under ambient flow conditions results in F_{frac}/F_{matrix} values >1 for times in excess of 1 year. This suggests that DNAPL sources, rather than matrix back-diffusion, are controlling the sustained mass discharge from the source area. PCE concentrations in the rock matrix adjacent to conductive fractures showed constant concentrations of approximately 120 µg/kg moving inwards from the fracture interface. If matrix back-diffusion was sustaining the elevated PCE levels in the fractures, then a gradient in increasing PCE concentrations into the rock matrix would be expected. Thus, removal of DNAPL sources likely will result in a decrease in mass discharge from the source area. It is also notable that the mass of PCE DNAPL in the fractures (Table 5.8) is conservatively 10-times greater than that estimated in the rock matrix (assuming a uniform 4.9% matrix porosity and 120 µg/kg PCE in the matrix).

Given the long DNAPL dissolution timeframes described in the previous paragraphs and shown in Table 5.8, dissolution into bypassing groundwater was not responsible for reducing the residual saturation from levels of DNAPL mobility to the current levels. Reductive dechlorination daughter products typically observed during biodegradation of PCE were not observed during baseline sampling of groundwater, thus it is unlikely that enhanced DNAPL removal via biodegradation facilitated DNAPL removal to any appreciable extent. Testing to assess abiotic dechlorination reactions within the rock matrix, using batch testing methods previously described *(40)*, also indicated that abiotic process had minimal impact on DNAPL dissolution. Examination of the simulation work performed by Parker et al. *(31)* shows that diffusive uptake into the rock matrix alone could not account for depletion of the DNAPL source. The PCE mass within the rock matrix, based on a uniform PCE concentration of 120 µg/kg, confirms that matrix diffusion alone could not have accounted for such a large decrease in DNAPL saturation. It is speculated that the value of DNAPL saturation originally entrapped within the fractures was much lower than the range of residual DNAPL saturation observed in laboratory studies *(17,41)*, as very discrete fingers of DNAPL may have entered the fracture planes targeted in this field study. Alternately, or perhaps in addition, it is plausible that only a very small fraction of the DNAPL mass is near the flow path of the tracers, and much of the DNAPL resides in low- or no-flow zones within the fracture planes. This alternate possibility is consistent with previous bench-scale studies using fractured sandstone blocks that showed most of the residual PCE DNAPL in a single fracture plane was located in low flow zones *(18)*. While it is possible that DNAPL in such very low-flow (or no-flow zones, such as dead-end fractures) may be present and not detected via the partitioning tracer technique, the impact of such DNAPL on the groundwater plume also would be limited by the same diffusional mass transfer processes that “hide” these sources from the partitioning tracers. Thus, in this respect, the partitioning tracer tests in fractured bedrock likely identify and quantify the DNAPL sources that most readily impact the dissolved plume, which are those along a measureable flow path. However, diffusional mass discharge from DNAPL in these stagnant zones could still have a measureable (albeit significantly less than DNAPL present along the measureable flow path) long-term impact on the dissolved plume.

6.2 BIOAUGMENTATION TREATMENT

6.2.1 DNAPL Mass Removal

Based on the PCE present in the extracted groundwater, and assuming conversion of this PCE to DCE, 25 mg/L of chloride would be generated. The chloride generation observed at both the shallow and deep intervals at 37-B11 (Figure 5.16) exceeded this value by 2- to 6-times, indicating the dechlorination of PCE DNAPL. Assuming the excess chloride is the result of PCE DNAPL dissolution and subsequent conversion to DCE, the maximum observed chloride generation (143 mg/L) at 37-B11s represents approximately 2.1 mM PCE, which indicates a dissolution enhancement of the PCE DNAPL of approximately 5 when compared to the PCE molar concentrations measured prior to bioaugmentation at 37-B11s (Figure 5.14).

While the measured increases in chloride provide useful information regarding DNAPL dissolution, the molar increases in DCE were approximately equal to the dissolved PCE concentrations prior to bioaugmentation, and thus were not indicative of any DNAPL dissolution enhancement. Previous studies have suggested that DCE generated at the DNAPL-water interface likely back-partitions into the DNAPL, and is not observed in the bulk aqueous phase *(18,26)*. Once partitioned into the DNAPL, DCE may diffuse through thin DNAPL layers/ganglia into the rock matrix or other low permeability zones.

Based on the chloride generation observed during active treatment, 1.1 and 0.6 kg of DNAPL were removed in 37-B11s and 37-B11d, respectively. Thus, treatment was effective for removing the DNAPL in the shallow zone, but only about 45% of the DNAPL was removed from the deep zone. Due to the scatter in the chloride data, the DNAPL mass removal for the deep interval is only an estimated value, with an estimated error of up to 50%. The estimated DNAPL mass in each of these zones was based on partitioning tracer testing, which only accounts for the DNAPL mass that is in close proximity to the fracture flow paths. Thus, DNAPL may still remain within the shallow fracture zone, but in zones that are not hydraulically conductive relative to the primary flow path and that minimally impact groundwater quality.

6.2.2 Rebound

The behavior during the 10-month rebound period was similar for both 37-B11s and 37-B11d. Both the shallow and deep zones showed an increased conversion to VC and ethene after cessation of groundwater recirculation and amendment addition, and both zones showed a substantial decrease in the molar balance (of chlorinated ethenes and ethene) as accumulation of VC and ethene occurred. The decrease in the molar balance after rebound is explained by (1) eliminating the re-injection of high concentration PCE groundwater from the extractions wells as ambient flow conditions were resumed, and (2) VC and ethene diffusive uptake into the rock matrix. Assessment of elevated sodium levels (from addition of sodium lactate during the re-circulation phase), showed that approximately half of the sodium was depleted by 8 months into the rebound period in both the shallow and deep zones. Thus, the decrease in the elevated chlorinated ethenes + ethene is only partially explained by dilution due to ambient groundwater flow. Comparison of the relative importance of matrix diffusion effects on solute transport has been previously performed for both the shallow and deep fracture zones *(27)*.

Using this approach, but applying a mean residence time of 8 months, dimensional analysis suggests that matrix diffusion effects in the shallow zone will be significant. Due to the complex flow paths present in the deep zone (Table 5.8), a similar assessment is not possible, but the mass transfer limitations observed during the tracer test in the deep zone suggests diffusive controls on solute migration are likely. Thus, dissipation of the generated VC in both the shallow and deep zones is likely due to both dilution and diffusion into low flow zones.

While rebound behavior in 37-B11s and 37-B11d were similar, there were some important differences. In the shallow zone, the increase in sulfate, decrease in ferrous iron, and depletion of volatile fatty acids suggests that strongly reducing conditions did not persist throughout the rebound period. The shallow zone may have been more exposed to low levels of dissolved oxygen during rainfall events than the deep zone, which may explain why strongly reducing conditions were not maintained in the shallow zone, but yet were maintained in the deep zone. With conditions no longer supporting sulfate and iron reduction five months into the rebound period, it is unlikely that conditions were favorable for continued ethene generation in the shallow zone. The continued decreases in ethene and the lack of observed increases in any of the chlorinated ethenes are consistent with DNAPL source removal. The ethene remaining in the shallow zone likely persists because it has not yet been fully flushed from the system and/or due to matrix back diffusion.

In contrast, as indicated by the persistence of volatile fatty acids and continued sulfate depletion, strongly reducing conditions persisted in the deep zone. Such conditions support the continued dechlorination of chlorinated ethenes to ethene. The increasing trend in both ethene and the total molar balance suggest that an ongoing chlorinated ethene source is present. Based on the fact that only 45% of the PCE DNAPL was removed during active treatment, it is plausible that this ongoing source is residual PCE DNAPL, but it is also plausible that the continued ethene generation is from matrix back-diffusion and/or back-diffusion from other mass transfer limited zones.

6.2.3 Implications for Groundwater Quality

Overall, considering the specific fracture intervals targeted for this study, treatment in the shallow zone was more effective than in the deep zone with respective to DNAPL removal. In addition, while the shallow and deep zones showed decreases in chlorinated ethenes of 97 and 99.9%, respectively, the increasing ethene concentrations in the deep zone suggest that continuing microbially-enhanced dechlorination may be “masking” PCE rebound. This rebound process has been described conceptually and mathematically by Chambon et al. (2010) *(42)* and Manoli et al. (2012) *(43)*. The difference in behavior, with respect to both the DNAPL removal and rebound, between 37-B11s and 37-B11d is likely due to the DNAPL architecture. For the shallow zone, DNAPL sources were along a flow path that did not show any mass-transfer limited behavior during the partitioning tracer test, while the DNAPL sources located in the deep zone showed “tailing” behavior that is indicative of mass transfer controlled processes *(27)*. These mass transfer limitations likely inhibited the dissolution and removal of the PCE DNAPL sources in the deep zone during active treatment.

7.0 COST ASSESSMENT

7.1 COST MODEL

In order to evaluate the cost of a potential full-scale bioremediation program, and compare it against other remedial approaches, costs associated with various aspects of the demonstration were tracked throughout the course of the project. Table 7.1 summarizes the various cost elements and total cost of the demonstration project. The costs have been grouped by categories as recommended in the Federal Remediation Technologies Roundtable Guide to Documenting and Managing Cost and Performance Information for Remediation Projects *(44)*. Many of the costs shown on this table are a product of the innovative and technology validation aspects of this project, and would not be applicable to a typical site application. Therefore, a separate "discounted costs" column that excludes or appropriately discounts these costs has been included in Table 7.1 to provide a cost estimate for implementing this technology at the same scale as the demonstration (i.e., pilot scale).

Costs associated with the bioaugmentation for treatment of DNAPL in fractured bedrock demonstration were tracked from April 2012 to November 2016. The total cost of the demonstration was $1,217,300, which included $371,500 in capital costs, $255,100 in operation and maintenance (O&M) costs, and $590,700 in demonstration-specific costs (cost related to ESTCP requirements, site selection and characterization). A total of approximately 2,618 cubic yards (based on a 30-foot radius of influence from the single injection well and a 25-foot vertical treatment interval), or 2,115 gallons (assuming a 0.4% fracture porosity) of DNAPL-impacted contaminated aquifer were treated during the demonstration. This corresponds to a unit cost of approximately $465 per cubic yard or $575 per gallon of contaminated aquifer (Table 7.1). By excluding an estimated $638,700 of research-oriented costs (primarily the costs associated with the installation and sampling of extra monitoring wells, down-hole geophysical surveys, contaminant flux investigations, molecular biology studies and ESTCP reporting requirements), unit costs are estimated at approximately $221 per cubic yard, or $274 per gallon of DNAPL-impacted contaminated aquifer for a project of this scale (Table 7.1).

7.1.1 Capital Costs

Capital costs (primarily system design and installation) accounted for $371,500 (or 31%) of the total demonstration costs. As indicated in Table 7.1, these costs exceed what would be expected during a typical remediation project due partially to the larger number of performance monitoring wells (8) installed within the relatively small demonstration area versus those anticipated to be required for a more typical project of this scale.

7.1.2 O&M Costs

O&M costs accounted for $255,100 (or 21%) of the total demonstration cost. These costs consisted primarily of groundwater monitoring (including labor, materials and analytical), system O&M, reporting, and travel costs. System O&M costs were $106,000, or 9% of total demonstration costs. The cost of the 605 pounds of sodium lactate product added during the demonstration was $2,900, or 0.2% of total demonstration costs. Treatment dosage during the demonstration is estimated at approximately 0.23 pounds of sodium lactate product per cubic yard of treated aquifer. Extensive performance monitoring activities were conducted to effectively validate this technology; including 14 groundwater sampling events (2 baseline and 12 performance).

Table 7.1. Demonstration Cost Components

Cost Element	Details	Tracked Demonstration Costs	Discounted Costs[1]
CAPITAL COSTS			
System Design	Labor	$41,500	$41,500
Well Installation, Development & Surveying[2]	Labor	$49,500	$37,000
	Materials	$16,500	$12,500
	Subcontracts (driller/surveyor)	$76,000	$57,000
System Fabrication & Installation (recirculation system)	Labor	$75,500	$75,500
	Equipment & Materials	$54,500	$54,500
	Subcontracts (electrical, Conex box/PLC)	$45,500	$45,500
	Travel	$12,500	$12,500
	Subtotal	**$371,500**	**$336,000**
OPERATION AND MAINTENANCE COSTS			
Groundwater Sampling[3]	Labor	$54,500	$27,250
	Materials	$7,500	$3,750
Analytical	In-House Labor	$10,500	$0
	Outside Labs	$20,600	$15,500
System O&M (including testing & start-up)	Labor	$61,500	$46,125
	Materials	$44,500	$33,375
Utilities	Electric	$0	$3,600
Reporting & Data Management	Labor	$47,500	$23,750
Travel		$8,500	$4,250
	Subtotal	**$255,100**	**$157,600**
OTHER TECHNOLOGY-SPECIFIC COSTS			
Site Selection	Labor & Travel	$24,600	$0
Site Characterization (pump testing, downhole geophysical surveys, microbiological studies, and tracer testing)	Labor (including in-house analytical)	$46,000	$20,000
	Materials	$15,000	$5,000
	Subcontractors (driller, geophysical, tracer)	$255,000	$0
	Travel	$3,500	$0
Treatability Testing	Labor (including in-house analytical)	$24,500	$0
IPR Meeting & Reporting	Labor & Travel	$10,500	$0
Technology Transfer (presentations, papers)	Labor & Travel	$11,000	$0
Demonstration Plan/Work Plan	Labor	$96,500	$30,000
Final Report	Labor	$85,600	$30,000
Cost and Performance Report	Labor	$18,500	$0
	Subtotal	**$590,700**	**$85,000**
	TOTAL COSTS	**$1,217,300**	**$578,600**
	ESTIMATED TREATMENT VOLUME (cubic yards)	**2,618**	**2,618**
	ESTIMATED TREATMENT VOLUME (gallons)	**2,115**	**2,115**
	APPROXIMATE TREATMENT COST (per cubic yard)	**$464.97**	**$221.01**
	APPROXIMATE TREATMENT COST (per gallon)	**$575.56**	**$273.57**

Notes:

[1]Discounted costs are defined as estimated costs to implement this technology at the same scale as the demonstration. These costs do not include extensive groundwater sampling, demonstration reporting, interim progress reviews, and preparation of technical and cost and performance reports.

[2]Demonstration includes 8 bedrock wells to 100 feet (includes 1 injection and 2 extraction wells). 5 bedrock wells are asumed for discounted costing.

[3] Two baseline and twelve performance monitoring events were performed during the demonstration. Six sampling events are assumed for discounted costing.

7.1.3 Demonstration-Specific Costs

Other demonstration-specific costs (a portion of which are not expected to be incurred during non-research-oriented remediation projects for the most part) accounted for $590,000 (or 49%) of the total demonstration cost. These costs included site selection, laboratory treatability studies, down-hole geophysical surveys, tracer testing to determine DNAPL architecture, molecular biology studies, ESTCP demonstration reporting and meeting (IPR) requirements, and preparation of extensive technical and cost and performance reports.

7.2 COST DRIVERS

7.2.1 General Considerations

The expected cost drivers for installation and operation of a bedrock groundwater recirculation and amendment delivery system for the remediation of contaminated groundwater, and those that will determine the cost/selection of this technology over other options include the following:

- Depth of the DNAPL source below ground surface;
- Width, length, and thickness of the DNAPL source area;
- Aquifer lithology and hydrogeology;
- Regulatory/acceptance of groundwater extraction and re-injection;
- Regulatory considerations concerning secondary groundwater impacts (i.e., metals mobilization, sulfate reduction, etc.);
- Length of time for clean-up (e.g., necessity for accelerated clean-up);
- The presence of indigenous bacteria capable of degrading Chlorinated Volatile Organic Compounds.
- Concentrations of contaminants and alternate electron acceptors (e.g., NO_3^-, SO_4^{2-} and O_2);
- The type(s) of co-substrates determined to be effective at promoting the biodegradation at a given site (i.e., those that are packaged in soluble form vs. those that need to be mixed into solution prior to injection); and
- O&M costs.

As discussed in detail in Section 5.3, microcosm screening and column treatability testing showed that sodium lactate was an effective substrate for promoting biological reduction. Based on the laboratory studies, sodium lactate was chosen as the substrate for field injection.

7.2.2 Competing Treatment Technologies

The two other technologies (in addition to bioaugmentation with groundwater recirculation) that have been shown to treat DNAPL in fractured bedrock at the field scale include (1) Thermal Conductive Heating (TCH) and (2) Active Pump-and-treat (P&T) with air stripping and carbon treatment.

TCH vaporizes volatile contaminants, and when coupled with Soil Vapor Extraction (SVE) may be an effective means to remove contaminants as shown by ESTCP Project ER-200715 *(45)*. The technology may be limited by the ability to achieve targeted temperature and the ability to remove contaminant from the rock matrix. Important parameters include the type of rock and its fracture porosity and heat capacity. Fracture patterns and connectivity are also important.

Pump-and-treat technologies provide capture of contaminated groundwater, and above-ground treatment of the extracted water prior to discharge or re-injection into the subsurface. While these systems can provide protection to downgradient receptors if designed properly, they are inefficient at removing contaminant mass from a plume and/or source zone, and often require operation for decades, leading to high overall costs.

Zero-valent iron (ZVI) permeable reactive barriers, biowalls, and biobarriers treat contaminated groundwater as it flows through the wall/barrier. While these approaches can provide protection to downgradient receptors, they are even less effective than P&T at removing contaminant mass from the plume and/or source zone. These technologies are impractical at bedrock sites due to the difficulty of trenching through bedrock.

As previously discussed, bioremediation approaches can be either "active," where distribution of amendments is achieved using groundwater recirculation, or "passive," where distribution is accomplished during initial injection and/or via ambient groundwater flow. Active groundwater treatment approaches often involve pairs or groups of injection and extraction wells to recirculate groundwater and effectively distribute injected amendments within the subsurface. Passive treatment approaches generally involve injection of amendments via closely-spaced injection wells or direct-push technology. In each of the above three approaches, a carbon source is typically added in order to promote and maintain the reducing, anoxic conditions and supply carbon needed for *in situ* growth of bacteria capable of degrading target contaminants. A slow-release carbon source such as an emulsified vegetable oil (EVO) is often utilized with passive treatment approaches to reduce injection frequency.

Bioremediation (either active, passive, or semi-passive approaches) can be utilized to treat source areas and diffuse plumes or as a barrier to protect downgradient receptors. For deeper plumes (e.g., >50 ft. bgs) or those that are large or very thick, passive approaches are often not technically feasible and are cost-prohibitive (e.g., injecting passive substrates at closely spaced intervals to >50 ft bgs). Active or semi-passive treatment systems may be technically and economically more attractive under these conditions. Active or semi-passive treatment approaches may also be better suited for heterogeneous geologies or sites where pH adjustment is required, as groundwater recirculation improves mixing and distribution of injected amendments within the subsurface. Longer treatment time frames, high contaminant concentrations, and secondary reactions may also present conditions favorable for utilizing an active approach, since amendment addition and mixing rates can be adjusted more easily then with passive approaches which often utilize less frequent injection of amendments at high concentrations. However, these approaches may be limited where re-injection of contaminated water with amendments is either prohibited or subject to regulatory injection permits.

7.3 COST ANALYSIS

A thorough cost analysis of various *in situ* treatment approaches, including active-pumping systems, passive systems, and semi-passive designs is provided in Chapter 10 of Krug et al.*(46)*. Various approaches are compared technically and economically with each other and under a variety of different contamination scenarios. The base case and cost analysis presented in the publication referenced above was modified as a template for the cost analysis of the technology tested during this demonstration, as well as the other technologies discussed above. A cost analysis for the base case was performed for the following technologies:

1. Bioremediation Recirculation System
2. Thermal Conductive Heating
3. Active Pump-and-treat

The cost analyses comparing the above approaches are presented below based on a 30-year operating scenario. It should be noted that detailed characterization activities, particularly the partitioning tracer tests discussed earlier in this report, are an important precursor to remediation technology selection and implementation, particularly at fractured bedrock sites. This characterization will allow a more focused remedial approach in specific fracture zones where DNAPL sources reside, reducing the treatment area and ultimately shortening remedial timeframes and potentially realizing significant cost savings for any treatment approach selected.

7.3.1 Base Cost Template

As discussed above, the base case presented in Krug et al. *(46)* is modified as a template for the cost analysis of the above technologies/approaches. The base case presents a situation where a bedrock aquifer is contaminated with residual TCE DNAPL (not exceeding 1% of the fracture volume) in the source. The TCE source area plume extends to 150 ft bgs, and is 150 ft long and 60 ft wide, perpendicular to groundwater flow (**Figure 7.1**). The specific base case site characteristics, including aquifer characteristics and design parameters for each of the remedial approaches analyzed are summarized in **Table 7.2**.

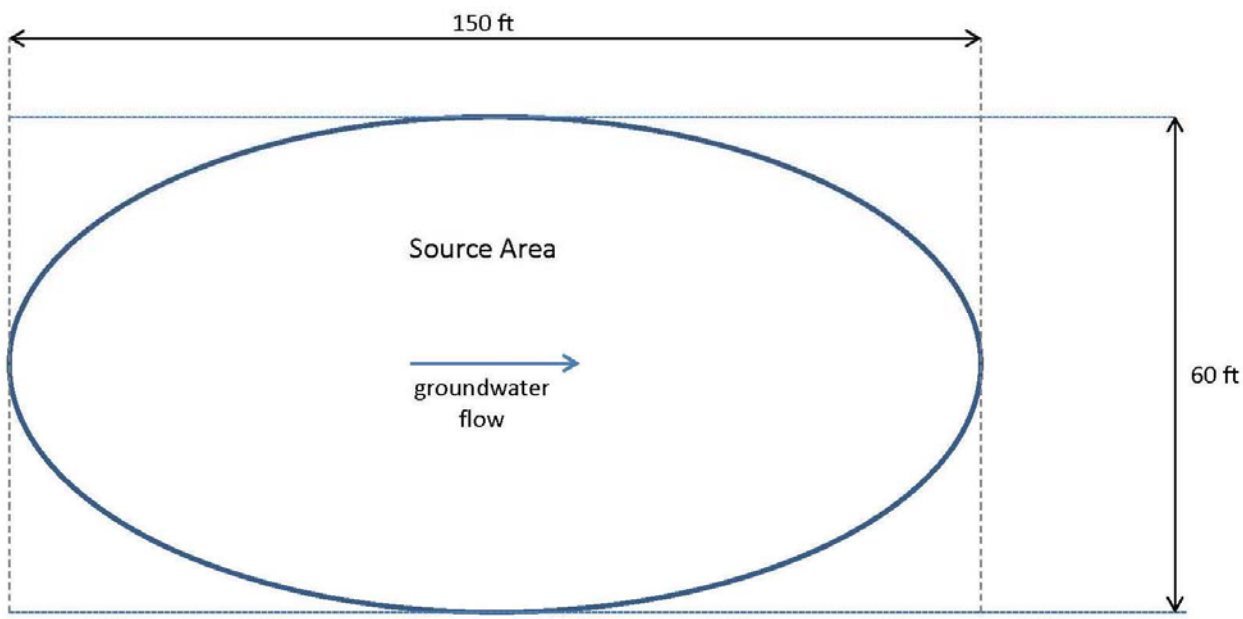

Figure 7.1. Base Plume Characteristics

The following subsections provide cost estimates for implementation of each the three treatment approaches for the base case. The cost estimates provide insight into the comparative capital, O&M, and long term monitoring costs to better identify cost drivers for each technology/ approach. Total costs and the Net Present Value (NPV) of future costs were calculated for each of treatment approaches. Future costs (O&M and long term monitoring costs) are discounted, using a 2% discount rate, to determine the NPV estimates of these costs. Specifically excluded from consideration are the costs of pre-remedial investigations and treatability studies, assuming the costs for these activities would be similar for each alternative.

Table 7.2. Summary of Base Case Site Characteristics and Design Parameters

Design Parameter	Units	Alternative		
		Bioremediation Recirculation System	Thermal Conductive Heating	Pump and Treat
Width of Plume	feet	60	60	60
Length of Plume	feet	150	150	150
Treatment area	square feet	9000	9000	9000
Upper depth of treatment	feet	0	0	0
Lower depth of treatment	feet	150	150	150
Thickness of overburden	feet	50	50	50
Thickness of bedrock	feet	100	100	100
Porosity	dimensionless	0.05	0.05	0.05
Number of extraction wells	each	6	2	6
Number of injection wells	each	7	0	8
Number of Monitoring Wells	each	6	10	6
Number of heater borings	each	0	52	0
Number of SVE Wells	each	0	52	0
Number of steam injection wells	each	0	8	0
Number temperature monitoring wells	each	0	12	0
Number of pressure monitoring wells	each	0	5	0

7.3.2 Bioremediation Recirculation System

The Bioremediation Recirculation System alternative assumes that two rows of three extraction wells and three row of two or three injection wells will be installed in the source area as shown in Figure 7.2. Groundwater will be recirculated between the rows of extraction and injection wells, and substrate added every two months for a period of three years, after which time the system will be shut down and decommissioned. This alternative also assumes 30 years of associated long term monitoring costs.

As summarized in Table 7.3, the estimated total costs for this alternative over 30 years are $1,400,725 with a total NPV of lifetime costs of $1,299,777. The capital cost including design, work plan, installation of recirculation and monitoring wells, construction of the groundwater recirculation and amendment mixing systems, and system start up and testing are approximately $511,000. The NPV of the O&M is estimated at approximately $388,000 for the three years of treatment. The O&M costs include the labor costs associated with regular rounds (every two months) of substrate mixing and injection, labor for system O&M, costs for equipment repair and replacement, and cost for substrate. The NPV of the 30 years of monitoring and reporting costs is estimated to be $401,000.

This alternative ranks lowest in estimated total remedy cost and also lowest in NPV of lifetime costs (see Table 7.6). This technology has both lowest capital costs and the lowest long term O&M costs of the alternatives evaluated.

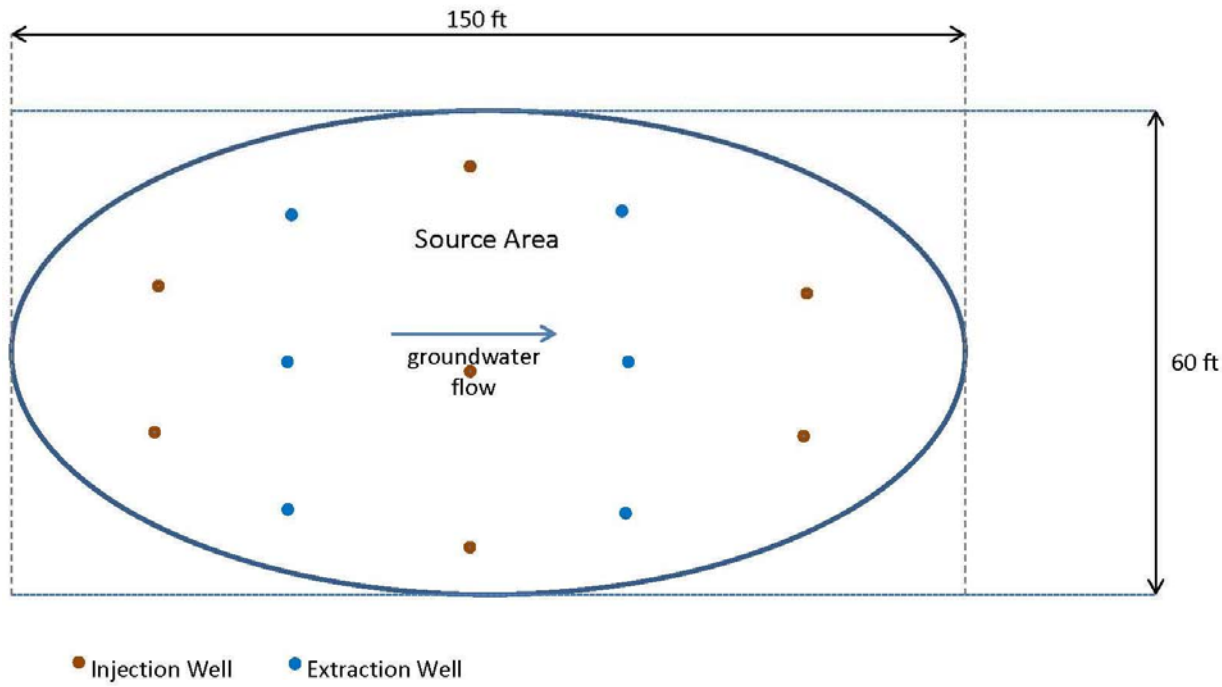

Figure 7.2. Bioremediation Recirculation System Alternative

Table 7.3. Cost Components for Bioremediation Recirculation System

	Year Cost is Incurred							NPV of Costs*	Total Costs
	1	2	3	4	5	6	7 to 30		
CAPITAL COSTS									
System Design	67,142	-	-	-	-	-		67,142	67,142
Well Installation	237,738	-	-	-	-	-		237,738	237,738
System Installation	188,133	-	-	-	-	-		188,133	188,133
Start-up and Testing	17,978	-	-	-	-	-		17,978	17,978
SUBCOST ($)	510,990	-	-	-	-	-		**510,990**	**510,990**
OPERATION AND MAINTENANCE COSTS									
System Operation and Maintenance	131,833	131,833	131,833	-	-	-		387,796	395,500
Decommisioning	-			117,629					
SUBCOST ($)	**131,833**	**131,833**	**131,833**	**117,629**	**0**	**0**		**387,796**	**395,500**
LONG TERM MONITORING COSTS									
Sampling/Analysis/Reporting (Quarterly through 5 years then Annually)	37,002	37,002	37,002	37,002	37,002	12,369	12,369 every year	400,991	494,235
SUBCOST ($)	**37,002**	**37,002**	**37,002**	**37,002**	**37,002**	**12,369**		**400,991**	**494,235**
TOTAL COST ($)	**679,826**	**168,835**	**168,835**	**154,631**	**37,002**	**12,369**		**1,299,777**	**1,400,725**

Notes:
NPV - Net Present Value

7.3.3 Thermal Conductive Heating

The conceptual design and cost estimate for the Thermal Conductive Heating alternative are derived from the Cost and Performance Report for ESTCP Project ER-200715 (ESTCP, 2013). The alternative assumes the installation of 51 heater borings and 51 SVE wells installed in an array throughout the source area plume (Figure 7.3). The system will be maintained for a period of one year. This alternative also assumes 30 years of associated O&M and long term monitoring costs.

As summarized in Table 7.4, the estimated total costs for this alternative over 30 years are $5,256,000 with a total NPV of lifetime costs of $5,150,000. The capital cost including design, work plan, installation of steam injection wells, SVE wells and system infrastructure are approximately $3,024,000. The NPV of the O&M is estimated at approximately $1,725,000 for the 1 year of active treatment. The O&M costs primarily include the labor and material costs associated the labor required for system operations. Electrical consumption is a major component of the cost with an estimated cost of $533,000 over the one-year operating period. The NPV of the 30 years of monitoring and reporting costs is estimated to be $401,000.

This alternative ranks highest in estimated total remedy cost and also the highest in NPV of lifetime costs (see Table 7.6). The estimated capital costs for this approach are the highest of the three alternatives because of the extensive infrastructure required. The estimated long term O&M costs associated with operating the system make this one of the highest expensed alternatives, with total remedy costs like the pump-and-treat alternative. As with the other approaches, total remedy costs will increase if the treatment needs to extend beyond one year.

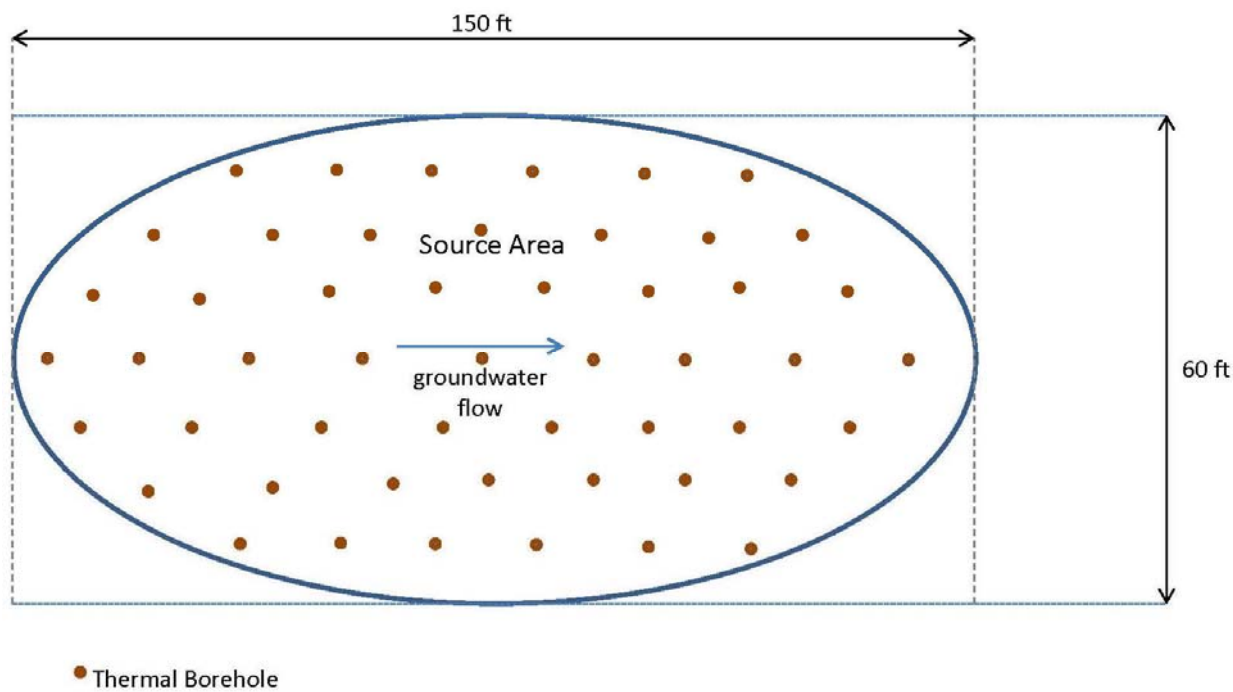

Figure 7.3. Thermal Conductive Heating Alternative

Table 7.4. Cost Components for Thermal Conductive Heating

	Year Cost is Incurred							NPV of Costs*	Total Costs
	1	2	3	4	5	6	7 to 30		
CAPITAL COSTS									
System Design	365,426	-	-	-	-	-	-	365,426	365,426
Well Installation (30 1" PVC Wells)	1,559,000	-	-	-	-	-	-	1,559,000	1,559,000
System installation	1,054,858	-	-	-	-	-	-	1,054,858	1,054,858
Start-up and Testing**	45,000	-	-	-	-	-	-	45,000	45,000
SUBCOST ($)	3,024,284	-	-	-	-	-	-	**3,024,284**	**3,024,284**
OPERATION AND MAINTENANCE COSTS									
System Operation and Maintenance	1,091,485	646,000	-	-	-	-	-	1,724,819	1,737,485
Decommisioning				-					
SUBCOST ($)	1,091,485	646,000	-	-	-	-		**1,724,819**	**1,737,485**
LONG TERM MONITORING COSTS									
Sampling/Analysis/Reporting (Quarterly through 5 years then Annually)	37,002	37,002	37,002	37,002	37,002	12,369	12,369 every year	400,991	494,235
SUBCOST ($)	**37,002**	**37,002**	**37,002**	**37,002**	**37,002**	**12,369**		**400,991**	**494,235**
TOTAL COST ($)	**4,152,771**	**683,002**	**37,002**	**37,002**	**37,002**	**12,369**		**5,150,094**	**5,256,004**

Notes:
NPV - Net Present Value

7.3.4 Active Pump-and-treat

The P&T system alternative would include ten source area extraction wells and four injection wells outside the pumping zone of influence (Figure 7.4). In this case the extracted groundwater would be treated above ground by air stripping and passing it through GAC; and the treated groundwater is re-injected providing hydraulic control and mass removal. The pump-and-treat system will be maintained for a period of 30 years. This alternative also assumes 30 years of associated O&M and long term monitoring costs.

As summarized in Table 7.5, the estimated total costs for this alternative over 30 years are $3,705,000 with a total NPV of lifetime costs of $3,019,000. The capital cost including design, work plan, installation of extraction/injection and monitoring wells, construction of the groundwater treatment system, and system start up and testing are approximately $791,000. The NPV of the O&M is estimated at approximately $1,826,000. The O&M costs include the labor costs associated with system O&M, costs for equipment repair and replacement, electrical costs, and cost for the replacement and disposal of the GAC. The NPV of the 30 years of monitoring and reporting costs is estimated to be $401,000.

This alternative ranks second in both estimated total remedy cost and NPV of lifetime costs (Table 7.6). The estimated capital costs for this alternative are higher than those of the bioremediation alternative because of the higher costs associated with constructing a groundwater treatment system, compared to constructing the recirculation system.

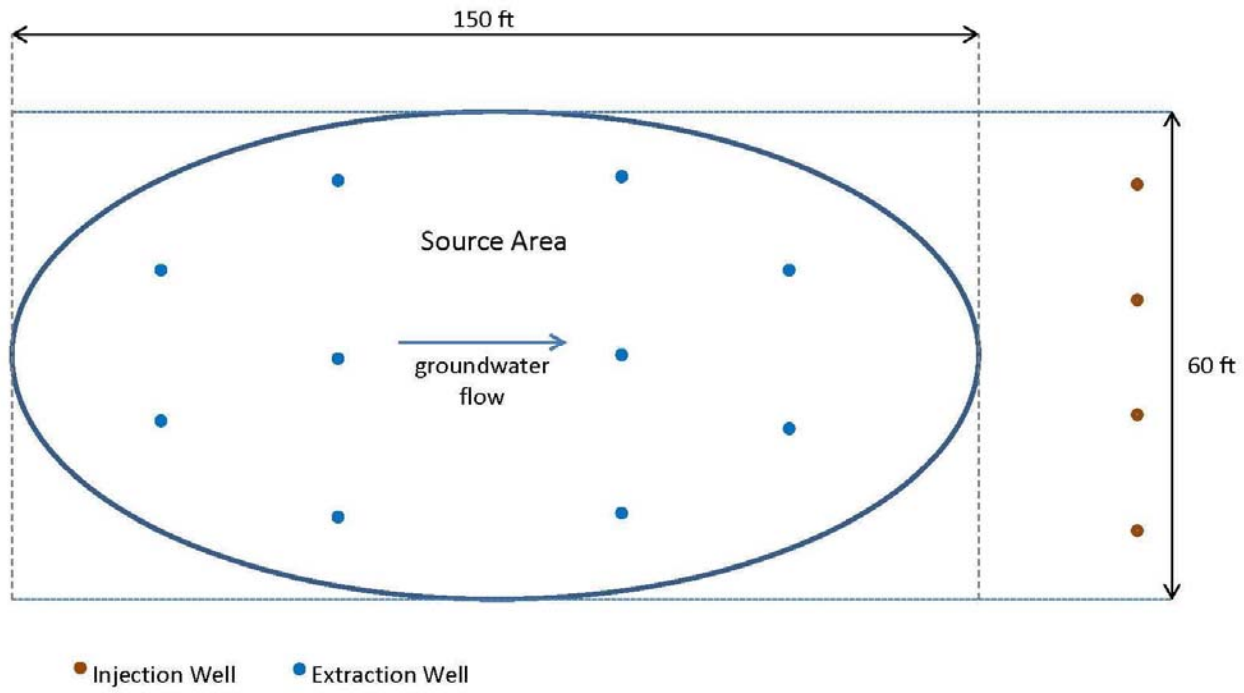

Figure 7.4. Active Pump-and-treat Alternative

Table 7.5. Cost Components for Active Pump-and-treat

	Year Cost is Incurred							NPV of Costs*	Total Costs
	1	2	3	4	5	6	7 to 30		
CAPITAL COSTS									
System Design	95,142	-	-	-	-	-		95,142	95,142
Well Installation	264,738	-	-	-	-	-		264,738	264,738
System Installation	405,300	-	-	-	-	-		405,300	405,300
Start-up and Testing	26,250	-	-	-	-	-		26,250	26,250
SUBCOST ($)	791,430	-	-	-	-	-		**791,430**	**791,430**
OPERATION AND MAINTENANCE COSTS									
System Operation and Maintenance	55,809	82,059	82,059	82,059	82,059	82,059	82,059 every year	1,826,527	2,419,834
SUBCOST ($)	**55,809**	**82,059**	**82,059**	**82,059**	**82,059**	**82,059**		**1,826,527**	**2,419,834**
LONG TERM MONITORING COSTS									
Sampling/Analysis/Reporting (Quarterly through 5 years then Annually)	37,002	37,002	37,002	37,002	37,002	12,369	12,369 every year	400,991	494,235
SUBCOST ($)	**37,002**	**37,002**	**37,002**	**37,002**	**37,002**	**12,369**		**400,991**	**494,235**
TOTAL COST ($)	**884,241**	**119,061**	**119,061**	**119,061**	**119,061**	**94,428**		**3,018,947**	**3,705,498**

Notes:

NPV - Net Present Value

* - NPV calculated based on a 2% discount rate

Table 7.6. Summary of Costs for Treatment Alternatives

Alternative	Capital Costs	NPV of 30 Years of O&M Costs	NPV of 30 Years of Monitoring Costs	NPV of 30 Years of Total Remedy Costs	Total 30-Year Remedy Costs
Bioremdiation Recirculation System	$510	$390	$400	$1,300	$1,400
Thermal Conductive Heating	$3,020	$1,720	$400	$5,150	$5,260
Active Pump and Treat	$790	$1,830	$400	$3,020	$3,710

Notes:

All costs are in thousands of dollars

NPV - Net Present Value; current value of future costs based on a 2% annual discount rate

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8.0 IMPLEMENTATION ISSUES

The primary issues related to implementation of the DNAPL architecture characterization and bioaugmentation treatment of the DNAPL sources were:

- ***Complexity of the fracture flow paths.*** Despite considerable efforts to characterize the fracture flow field (e.g., hydraulic testing, borehole geophysical testing), anticipating the distribution of tracers and amendments proved challenging. Thus, most of the interpretation of results from this study were limited to within 15 ft of the injection well. Improved methods to cost-effectively determine fracture flow paths remain a high priority for addressing contaminated groundwater in fractured rock.
- ***Multi-level borehole sampling***. Inflatable packers were used to facilitate multi-level sampling, targeting specific fracture zones, for this demonstration. While this approach worked, the ability to examine more than 3 zones becomes impractical due to the number of packer pass-throughs. Also, there is always concern that the packers become deflated due to leakage (the packers were connected to a gas tank). While FLUTe has developed a multi-level sampling system for bedrock borehole wells that offers some significant benefits, its use is not always cost effective or practical. Development of improved tools for multilevel borehole sampling would be beneficial to bedrock investigation and treatment.
- ***Biofouling within injection wells***. Biofouling has often been an issue for active bioremediation systems. Not surprisingly, biofouling was a challenge in this demonstration. Unfortunately, the intrinsically low transmissivity of the fracture system limited the effectiveness of well regeneration techniques. Approaches using automated or periodic biocide treatment to limit microbial biomass accumulation within injection wells is likely needed to mitigate this issue in future bioremediation applications.

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9.0 REFERENCES

(1) Adamson, D.T., J.M. McDade, and J.B. Hughes. Inoculation of a DNAPL source zone to initiate reductive dechlorination of PCE. *Environ. Sci. Technol*. **2003**, 37, 2525-2533.

(2) Amos, B.K., E.J. Suchomel, K.D. Pennell, and F.E. Löffler. Microbial activity and distribution during enhanced contaminant dissolution from a NAPL source zone. *Water Res*. **2008**, 42, 2963-2974.

(3) Amos, B.K., E.J. Suchomel, K.D. Pennell, and F.E. Löffler. Spatial and temporal distributions of *Geobacter lovleyi* and *Dehalococcoides* spp. during bioenhanced PCE-DNAPL dissolution. *Environ. Sci. Technol*. **2009**, 43, 1977-1985.

(4) AECOM. *Environmental Restoration Program, Groundwater Modeling Report for the Northeast AFRL, Air Force Research Laboratory, Operable Unit 4 and 9, Edwards Air Force Base, California.* Draft. Prepared for 95 ABW/CEVR, Edwards AFB, CA and AFCEE/EXEW, Lackland Air Force Base, TX. Orange, CA, **2011**.

(5) Cápiro, N.L., F.E. Löffler, and K.D. Pennell. 2015. Spatial and temporal dynamics of organohalide-respiring bacteria in a heterogeneous PCE-DNAPL source zone. Journal of Contaminant Hydrology 182:78-90.

(6) Chambon, J.C., M.M. Broholm, P.J. Binning, and P.L Bjerg. 2010. Modeling multi-component transport and enhanced anaerobic dechlorination processes in a single fracture–clay matrix system. Journal of Contaminant Hydrology 112:77–90.

(7) Cho, H.J., R.J. Fiacco Jr., and M. Daly. Characterization of crystalline bedrock contaminated by dense nonaqueous liquid. *Ground Water Monitoring and Remediation.* **2008**, 28, 49-59.

(8) Difilippo, E.L. and M. Brusseau. Time-continuous analysis of mass flux reduction as a function of mass removal at two field sites. SERDP/ESTCP Symposium, **2008**.

(9) Earth Tech. *Environmental Restoration Program, Site 162 and Site 177/325 In Situ Bioremediation Treatability Study Report, Air Force Research Laboratory, Operable Units 4 and 9, Edwards Air Force Base, California.* Prepared for 95 ABW/EMR, Edwards Air Force Base, CA and AFCEE/EXEW, Brooks City-Base, TX. Long Beach, CA, **2008b**.

(10) Earth Tech. *Environmental Restoration Program, Site 162 and Site 177/325 In Situ Bioremediation Treatability Study Work Plan Addendum, Air Force Research Laboratory, Operable Units 4 and 9, Edwards Air Force Base, California*. Prepared for 95 ABW/EMR, Edwards Air Force Base, CA and AFCEE/EXEW, Brooks City-Base, TX. Long Beach, CA, **2008c**.

(11) ESTCP, January 2013, ESTCP Cost and Performance Report (ER-200715) Dense Non Aqueous Phase Liquid (DNAPL) Removal form Fractured Rock Using Thermal; Conductive Heating (TCH).

(12) Federal Remediation Technologies Roundtable. 1998. Guide to Documenting and Managing Cost and Performance Information for Remediation Projects, Revised Version. EPA 542-B-98-007.

(13) Fure, A.D., J.W. Jawitz, and M.D. Annable. DNAPL source depletion: Linking architecture and flux response. *J. Contam. Hydrol*. 85, 118-140, **2006**.

(14) Glover, K.C., J. Munakata-Marr, and T.H. Illangasekare. Biologically enhanced mass transfer of tetrachloroethene from DNAPL in source zones: experimental evaluation and influence of pool morphology. *Environ. Sci. Technol*. **2007**, 41, 1384-1389.

(15) Guilbeault, M.A., B.L. Parker, and J.A. Cherry. Mass and flux distributions from DNAPL zones in sandy aquifers. *Ground Water* 43, 70-86, **2005**.

(16) Haest, P.J., D. Springael, and E. Smolders. 2010. Dechlorination kinetics of TCE at toxic TCE concentrations: Assessment of different models. Water Research 44:332-339.

(17) Harkness, M.R., A.A. Bracco, M.J. Brennan Jr., K.A. DeWeerd, and J.L. Spivack. Use of bioaugmentation to stimulate complete reductive dechlorination of trichloroethene in Dover soil columns. *Environ. Sci. Technol.* **1999**, 33, 1100-1109.

(18) Hao, L; Leaist, D.G. Binary mutual diffusion coefficients of aqueous alcohols. Methanol to 1-heptanol. J. Chem. Eng. Data 1996 41, 210-213.

(19) Interstate Technology & Regulatory Council. Overview of in situ bioremediation of chlorinated ethene DNAPL source zones. **2005**, BioDNAPL-1. Washington, D.C.

(20) Interstate Technology & Regulatory Council. In situ bioremediation of chlorinated ethene DNAPL source zones: case studies. **2007**, BioDNAPL-2. Washington, D.C.

(21) ITRC, In situ bioremediation of chlorinated ethene DNAPL source zones: Case studies. Washington, D.C., **2007**.

(22) Jardine, P.M.; Sanford, W.E.; Gwo, J.P.; Reedy, O.C.; Hicks, D.S.; Riggs, J.S.; Bailey, W.B. Quantifying diffusive mass transfer in fractured shale bedrock. Water Resour. Res. 1999 35, 2015-2030.

(23) Krug, T.A., C. Wolfe, R.D. Norris, and C.J. Winstead. 2009. Cost Analysis of In Situ Perchlorate Bioremediation Technologies. In In Situ Remediation of Perchlorate in Groundwater. H.F. Stroo and C.H. Ward, Eds. SERDP/ESTCP Environmental Remediation Technology.

(24) Lendvay, J.M., F.E. Löffler, M. Dollhopf, M.R. Aiello, G. Daniels, B.Z. Fathepure, M. Gebhard, R. Heine, R. Helton, J. Shi, R. Krajmalnik-Brown, C.L. Major, Jr., M.J. Barcelona, E. Petrovskis, R. Hickey, J.M. Tiedje, and P. Adriaens. Bioreactive barriers: a comparison of bioaugmentation and biostimulation for chlorinated solvent remediation. *Environ. Sci. Technol.* **2003**, 37, 1422-1431.

(25) Lide, D.R. (ed). CRC Handbook of Chemistry and Physics – 80th edition. 1999 CRC Press, Boca Raton, FL.

(26) Longino, B.L.; Kueper, B.H. Nonwetting phase retention and mobilization in rock fractures. Water Resour. Res. 1999 35, 2085-2093.

(27) Major, D.W., M.L. McMaster, E.E. Cox, E.A. Edwards, S.M. Dworatzek, E.R. Hendrickson, M.G. Starr, J.A. Payne, and L.W. Buonamici. Field demonstration of a successful bioaugmentation to achieve dechlorination of tetrachloroethene to ethene. *Environ. Sci. Technol.* **2002**, 36, 5106-5116.

(28) Manoli, G., J.C. Chambon, J.C., P.L. Bjerg, C. Scheutz, P.J. Binning, and M.M. Broholm. 2012. A remediation performance model for enhanced metabolic reductive dechlorination of chloroethenes in fractured clay till. Journal of Contaminant Hydrology 131:64-78.

(29) Mourzenko, V.V., F. Yousefian, B. Kolbah, J.-F. Thovert, P.M. Adler. Solute transport at fracture intersections. *Wat. Resour. Res*. **2002**, 38, 1000-1013.

(30) Novak, J.T.; Goldsmith, C.D.; Benoit, R.E.; O'Brien, J.H. Biodegradation of methanol and tertiary butyl alcohol in subsurface systems. Water Sci. Technol. 1985 17, 71-85.

(31) Parker, B.L.; Gillham, R.W.; Cherry, J.A. Diffusive disappearance of immiscible-phase organic liquids in fractured geologic media. Ground Water 1994 35, 805-820.

(32) Rodríguez, D.J.; Kueper, B.H. Specification of matrix cleanup goals in fractured porous media. Ground Water 2013 51, 58-65.

(33) Rivett, M. and S. Feenstra, "Dissolution of an emplaced source of DNAPL in a natural aquifer setting", *Environ. Sci. Technol.*, 39, 447-455, **2005**.

(34) Schaefer, C.E., A.V. Callaghan, J.D. King, and J.E. McCray. Dense nonaqueous phase liquid architecture and dissolution in discretely fractured sandstone blocks. *Environ. Sci. Technol*. **2009**, 43, 1877-1883.

(35) Schaefer, C.E., C.W. Condee, S. Vainberg, and R.J. Steffan. Bioaugmentation for chlorinated ethenes using *Dehalococcoides* sp.: comparison between batch and column experiments. *Chemosphere.* **2009**, 75, 141-148.

(36) Schaefer, C.E., D. Lippincott, and R.J. Steffan. Field scale evaluation of bioaugmentation dosage for treating chlorinated ethenes. *Ground Water Monitoring and Remediation.* **2010**, 113-124.

(37) Schaefer, C.E., R.M. Towne, S. Vainberg, J.E. McCray, and R.J. Steffan. Bioaugmentation for treatment of dense non-aqueous phase liquid in fractured sandstone blocks. *Environ. Sci. Technol*. **2010**, 44, 4958-4964.

(38) Schaefer, C.E.; Towne, R.M.; Lazouskaya, V.; Bishop, M.E.; Dong, H. Diffusive flux and pore anisotropy in sedimentary rocks. J. Contam. Hydrol. 2012, 131, 1-8.

(39) Schaefer, C.E.; Towne, R.M.; Lippincott, D.R.; Lacombe, P.; Bishop, M.E.; Dong, H. Abiotic dechlorination in rock matrices impacted by long-term exposure to TCE. Chemosphere 2015 119, 744-749.

(40) Schaefer, C.E., E.B. White, G.M. Lavorgna, and M.D. Annable. 2016. Dense nonaqueous-phase liquid architecture in fractured bedrock: implications for treatment and plume longevity. Environmental Science & Technology 50:207-213.

(41) Seyedabbasi, M.A.; Kulkarni, P.R.; McDade, J.M.; Newell, C.J.; Gandhi, D.; Gallinatti, J.D.; Cocianni, V.; Ferguson, D.J. Matrix diffusion modeling applied to long-term pump-and-treat data: 2. Results from three sites. Remediation J. 2013 23, 93-109.

(42) Torlapati, J., T.P. Clement, C.E. Schaefer, C.E., and K.K. Lee. 2012. Modeling Dehalococcoides Sp. augmented bioremediation in a single fracture system. Ground Water Monitoring and Remediation 32:75-83.

(43) United States Environmental Protection Agency. Demonstration of bioaugmentation of DNAPL through biostimulation and bioaugmentation at Launch Complex 34 Cape Canaveral Air Force station, Florida. **2004**, EPA/540/R-07/007.

(44) Wang, F.; Annable, M.D.; Schaefer, C.E.; Ault, T.D.; Cho, J.; Jawitz, J.W. Enhanced aqueous dissolution of a DNAPL source to characterize the source strength function. J. Contam. Hydrol. 2014 169, 75–89.

(45) West, M.R.; Kueper, B.H. Plume detachment and recession times in fractured rock. Ground Water 2010, 48, 416-426.

(46) Yang, Y. and P.L. McCarty. Biologically enhanced dissolution of tetrachloroethene DNAPL. *Environ. Sci. Technol.* **2005**, 34, 2979-2984.

APPENDIX A POINTS OF CONTACT

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APPENDIX B FIELD OPERATIONS SUMMARY TABLE

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Date	Duration	Day Relative to Bioaugmentation	Activity	Extraction Well 37-B12				Extraction Well 37-B13				Comments
				Pump Cycle				Pump Cycle				
				Refill (min:sec)	Discharge (min:sec)	Flowrate (mL/min)	Flow Totalizer (liters)	Refill (min:sec)	Discharge (min:sec)	Flowrate (mL/min)	Flow Totalizer (liters)	
1/10/2013	**13 days**	**-596**	**Install 37-B06, 37-B07, 37-B08, 37-B09**									**4 wells: 37-B06, 37-B07, 37-B08, 37-B09**
1/17/2013	**2 days**	**-589**	**Geophysical Testing**									**2 wells: 37-B06, 37-B09**
1/23/2013	**3 days**	**-583**	**Push-Pull Testing**									**3 intervals: 37-B06s, 37-B06d, 37-B07**
3/5/2013	**17 days**	**-542**	**Interwell Testing**									**2 wells: 37-B06, 37-B07**
12/4/2013	**13 days**	**-268**	**Install 37-B10, 37-B11, 37-B12, 37-B13**									**4 wells: 37-B10, 37-B11, 37-B12, 37-B13**
12/18/2013	**3 days**	**-254**	**Geophysical Testing**									**4 wells: 37-B07, 37-B10, 37-B12, 37-B13**
1/8/2014	**175 days**	**-233**	**STAGE 1 - Hydraulic Testing & Baseline Sampling**									
1/8/2014	1 day	-233	Short-term pump test at 37-B12									
1/9/2014	1 day	-232	Short-term pump test at 37-B13									
1/10/2014	1 day	-231	Short-term pump test at 37-B06									
1/13/2014	1 day	-228	Short-term pump test at 37-B07									
5/28/2014	**2 days**	**-93**	**Baseline Sampling Event No. 1**									**4 wells/7 intervals: 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13**
6/30/2014	2 days	-60	Groundwater Recirculation System Testing				205,495				148,626	
7/2/2014	**1 day**	-58	**Baseline Sampling Event No. 2**									**4 wells/7 intervals: 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13**
7/2/2014	**57 days**		**STAGE 2 - Groundwater Recirculation and PTT**									
7/2/2014	1 day	-58	Groundwater Recirculation System Start-up	4:30	0:30	80	205,518	4:30	0:30	80	148,637	
7/3/2014		-57	System Operating	4:30	0:30	72	205,616	4:30	0:30	36	148,716	
7/6/2014		-54	System Operating	4:30	0:30	66		4:30	0:30	18		
7/8/2014		-52	System Operating	4:30	0:30	81	206,184	4:30	0:30	31	148,993	Deflate packer in 37-B13 due to low well production
7/10/2014		-50	System Operating	4:30	0:30	82	206,415	4:30	0:30	26	149,123	
7/15/2014	**92 days**	**-45**	**Partitioning Tracer Testing**	**4:30**	**0:30**	**90**	**206,983**	**4:30**	**0:30**	**27**	**149,408**	**Multiple Sampling Rounds at 4 wells/7 intervals: 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13**
7/30/2014		-30	System Operating	4:30	0:30	100	209,236	4:30	0:30	22	150,218	
8/7/2014		-22	System Operating	4:30	0:30	98	210,445	4:30	0:30	26	150,740	
8/14/2014		-15	System Operating	4:30	0:30	98	211,501	4:30	0:30	26	151,219	
8/27/2014	**1 day**	**-2**	**Pre-Bioaugmentation Sampling Event**									**5 wells/8 intervals: 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13, 37-EW07**
8/28/2014	**264 days**	**-1**	**STAGE 3 - Bioaugmentation Treatment and Monitoring**									
8/28/2014	1 day	-1	Initial Lactate/Nutrient Pulse Injection	4:30	0:30	86	213,532	4:30	0:30	28	152,192	57 liters of lactate/nutirents (1,000 mg/L lactate, 100 mg/L DAP, 100 mg/L yeast extract) injected at approximately 400 mL/min. Begin auto amendment injection.
8/29/2014	1 day	0	Bioaugmentation Injection									19 liters of SDC-9 culture injected at approximetly 400 mL/min. Inject 38 liters of chase water containing 1,000 mg/L lactate, 100 mg/L DAP, 100 mg/L yeast extract. Increase pumping cycle time for 37-B12 from 12 mins (11:30 refill, 0:30 discharge) to decrease flow to injection well.
9/2/2014		4	System Operating	11:30	0:30	42	213,882	4:30	0:30	26	152,498	
9/9/2014	**1 day**	**11**	**Post-Bioaugmentation Sampling Event No. 1**	**11:30**	**0:30**	**42**	**214,300**	**4:30**	**0:30**	**28**	**152,874**	**5 wells/8 intervals: 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13, 37-EW07**
9/24/2014		26	System Operating	11:30	0:30	42	214,714	4:30	0:30	52	153,365	
10/2/2014	1 day	34	Redevelope 37-B06 with surge block and pumping	11:30	0:30	42	214,841	4:30	0:30	58	153,549	System down during well redevelopment activities
10/13/2014	**1 day**	**45**	**Post-Bioaugmentation Sampling Event No. 2**	**11:30**	**0:30**	**42**	**215,078**	**4:30**	**0:30**	**58**	**153,887**	**4 wells/7 intervals: 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13**

Date	Duration	Day Relative to Bioaugmentation	Activity	Extraction Well 37-B12				Extraction Well 37-B13				Comments
				Pump Cycle				Pump Cycle				
				Refill (min:sec)	Discharge (min:sec)	Flowrate (mL/min)	Flow Totalizer (liters)	Refill (min:sec)	Discharge (min:sec)	Flowrate (mL/min)	Flow Totalizer (liters)	
10/20/2014		52	System Operating	11:30	0:30	42	215,136	4:30	0:30	60	153,974	Mix new 50 gallon batch of amendments (1,000 mg/L lactate, 100 mg/L DAP, 100 mg/L yeast extract). Set chemical feed pump at 30 mL/min. Install anti-syphon valve on amendmnet injection line to stop syphoning of amendments into process stream.
11/5/2014		68	System Operating	11:30	0:30	42	215,390	4:30	0:30	60	154,355	
11/19/2014	**1 day**	**82**	**Post-Bioaugmentation Sampling Event No. 3**	**11:30**	**0:30**	**42**	**215,651**	**4:30**	**0:30**	**60**	**154,743**	**4 wells/7 intervals: 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13**
12/17/2014	**1 day**	**110**	**Post-Bioaugmentation Sampling Event No. 4**									**4 wells/7 intervals: 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13**
12/17/2014		110	System Operating	11:30	0:30	42	216,045	4:30	0:30	66	155,320	Add bicarbonate to achieve 200 mg/L in process stream. Set chemical feed pump to 2 mins ON, 118 mins OFF
1/13/2015		137	System Operating	11:30	0:30	42	216,236	4:30	0:30	75	155,608	Set chemical feed pump to 2 mins ON, 28 mins OFF
2/9/2015	4 days	164	Redevelope 37-B06 with Nu-Well products									System down during well redevelopment activities
2/13/2015		168	System Operating	11:30	0:30	42	216,462	4:30	0:30	80	155,920	Restart system, 37-B06 re-install bottom packer only, add 2 liters (in 19 liter keg) SDC-9 culture to 37-B06
2/16/2015		171	System Operating	11:30	0:30		216,639	4:30	0:30		156,112	
2/23/2015		178	System Operating	11:30	0:30	42	216,736	4:30	0:30	63	156,256	
3/5/2015	**1 day**	**188**	**Post-Bioaugmentation Sampling Event No. 5**	**11:30**	**0:30**	**42**	**216,934**	**4:30**	**0:30**	**76**	**156,513**	**4 wells/7 intervals: 37-B07s, 37-B07i, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13**
3/16/2015		199	System Operating	11:30	0:30	42	217,050	4:30	0:30	70	156,682	
3/17/2015		200	System Operating	11:30	0:30		217,068	4:30	0:30		156,707	
3/27/2015	1 day	210	Redevelope 37-B06 with surge block and wire brush									System down during well redevelopment activities
3/28/2015		211	System Operating	11:30	0:30	42	217,147	4:30	0:30	85	156,815	
4/13/2015	**1 day**	**227**	**Post-Bioaugmentation Sampling Event No. 6**	**11:30**	**0:30**	**42**	**218,327**	**4:30**	**0:30**	**22**	**157,614**	**4 wells/6 intervals: 37-B07s, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13**
4/18/2015		232	System Operating	11:30	0:30	42	218,662	4:30	0:30	20	157,858	Add 2 liters (in 19 liter keg) SDC-9 culture to 37-B06. Deflate packer in 37-B06. Mix 10 gallons of lactate/nutrients
4/21/2015		235	System Operating	11:30	0:30	42	218,868	4:30	0:30	20	158,003	Mix 40 gallons of lactate/nutrients
5/19/2015	**1 day**	**263**	**Shut-down recirculation system**	**11:30**	**0:30**	**42**	**220,419**	**4:30**	**0:30**	**40**	**159,351**	
5/19/2015	**295 days**	**263**	**STAGE 4 - Post-Treatment Monitoring and Assessment**									
5/19/2015	**1 day**	**263**	**Rebound Baseline Sampling Event**									**4 wells/6 intervals: 37-B07s, 37-B07d, 37-B11s, 37-B11d, 37-B12, 37-B13**
8/5/2015	**1 day**	**341**	**Rebound Sampling Event No. 1**									**2 wells/3 intervals: 37-B07d, 37-B11s, 37-B11d**
10/19/2015	**1 day**	**416**	**Rebound Sampling Event No. 2**									**1 well/2 intervals: 37-B11s, 37-B11d**
10/19/2015	3 days	416	Transport soil drums from staging area to site, spread soil onsite									Spreading of soil on-site approved by Base personnel
1/12/2016	**1 day**	**501**	**Rebound Sampling Event No. 3**									**1 well/2 intervals: 37-B11s, 37-B11d**
3/9/2016	**1 day**	**558**	**Rebound Sampling Event No. 4**									**1 well/2 intervals: 37-B11s, 37-B11d**
7/12/2016	1 day	683	Discharge IDW water to Base industrial sewer									Discharge approved under permit from Base
9/28/2016	**2 days**	**761**	**Post-Treatment Rock Core Collection**									**37-B14: Collect samples for VOC and ferrous iron analysis**

APPENDIX C ANALYTICAL DATA TABLES

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Appendix C - Table 1: Analytical Results Summary - Stage 2 Partitioning Tracer Test

			VOCs					Alcohols			
Sample ID	Sample Date	Sample Time	DCE (mg/L)	TCE (mg/L)	PCE (mg/L)	VC (mg/L)	Bromide (mg/L)	Methanol (mg/L)	24DMP (mg/L)	2-octanol (mg/L)	355TMH (mg/L)
37-B07s	7/15/2014	9:00	<0.1	0.6	4.8	<0.1					
37-B07s	7/15/2014	10:00	<0.1	0.5	4.5	<0.1	2.00	0	0	0	0
37-B07s	7/15/2014	14:00	<0.1	0.7	8.3	<0.1	2.02	0	0	0	0
37-B07s	7/16/2014	17:00	<0.1	1.7	12.2	<0.1	2.04	0	0	0	0
37-B07s	7/17/2014	17:00	<0.1	0.9	12.2	<0.1	2.11	0	0	0	0
37-B07s	7/18/2014	11:30					1.83	0	0	0	0
37-B07s	7/19/2014	9:00	<0.1	0.9	13.0	<0.1	1.73	0	0	0	0
37-B07s	7/21/2014	7:00	<0.1	0.9	11.8	<0.1	1.70	0	0	0	0
37-B07s	7/22/2014	7:00	<0.1	1.1	13.2	<0.1	1.63	0	0	0	0
37-B07s	7/23/2014	9:00	<0.1	1.0	12.1	<0.1	1.47	0	0	0	0
37-B07s	7/24/2014	9:00	<0.1	1.1	10.6	<0.1	1.68	0	0	0	0
37-B07s	7/25/2014	9:00	<0.1	1.0	11.2	<0.1	1.45	0	0	0	0
37-B07s	7/31/2014	10:00	<0.1	0.9	11.5	<0.1	1.58	0	0	0	0
37-B07s	8/7/2014	10:00	<0.1	0.9	9.1	<0.1	1.69	0	0	0	0
37-B07s	8/14/2014	8:35	<0.1	0.8	8.4	<0.1		0	0.05	0	0
37-B07s	8/27/2014	11:35	<0.1	0.9	9.2	<0.1	2.16	0	0.09	0	0
37-B07s	9/9/2014	9:10	<0.1	1.1	10.6	<0.1	2.10	0	0	0	0
37-B07i	7/15/2014	9:00	<0.1	0.6	5.2	<0.1					
37-B07i	7/15/2014	10:00	<0.1	0.7	8.1	<0.1	2.20	0	0	0	0
37-B07i	7/15/2014	14:00	<0.1	0.6	6	<0.1	2.01	0	0	0	0
37-B07i	7/16/2014	17:00	<0.1	0.6	5.8	<0.1	1.89	0	0	0	0
37-B07i	7/17/2014	17:00	<0.1	0.5	5.3	<0.1	1.86	0	0	0	0
37-B07i	7/18/2014	11:30		0.5	5.4		1.97	0	0	0	0
37-B07i	7/19/2014	9:00	<0.1	0.5	6.1	<0.1	1.89	0	0	0	0
37-B07i	7/21/2014	7:00	<0.1	0.5	5.9	<0.1	1.49	0	0	0	0
37-B07i	7/21/2014	17:00		0.4	5.7		1.56	0	0	0	0
37-B07i	7/22/2014	7:00	<0.1	0.5	5.4	<0.1	1.51	0	0	0	0
37-B07i	7/22/2014	17:00		0.6	9.7		1.50	0	0	0	0
37-B07i	7/23/2014	9:00	<0.1	0.6	6	<0.1	1.38	0	0	0	0
37-B07i	7/23/2014	17:00		1.4	5.3		1.50	0	0	0	0
37-B07i	7/24/2014	9:00	<0.1	0.6	7.6	<0.1	1.44	0	0	0	0
37-B07i	7/24/2014	17:00		0.4	6.5		1.47	0	0	0	0
37-B07i	7/25/2014	9:00	<0.1	0.6	7.1	<0.1	1.53	0	0	0	0
37-B07i	7/31/2014	10:00	<0.1	0.3	4.0	<0.1	1.53	0	0	0	0
37-B07i	8/7/2014	10:00	<0.1	0.4	5.0	<0.1	1.59	0	0	0	0
37-B07i	8/14/2014	9:30	<0.1	0.5	4.5	<0.1		0	0	0	0
37-B07i	8/28/2014		<0.1	0.7	9.6	<0.1		0	0	0	0
37-B07i	9/9/2014	8:40	<0.1	0.5	6.8	<0.1		0	0	0	0
37-B07d	7/15/2014	9:00	<0.1	0.6	7.5	<0.1					
37-B07d	7/15/2014	10:00	<0.1	1.1	25.6	<0.1	1.60	0	0	0	0
37-B07d	7/15/2014	14:00	<0.1	1.0	24.8	<0.1	1.42	0	0	0	0
37-B07d	7/16/2014	17:00	<0.1	1.0	24.0	<0.1	1.47	0	0	0	0
37-B07d	7/17/2014	17:00	<0.1	1.1	25.3	<0.1	1.44	0	0	0	0
37-B07d	7/18/2014	11:30		1.1	28.4		1.64	0.2	0.2	0.0	0
37-B07d	7/19/2014	9:00	<0.1	1.1	28.1	<0.1	1.86	0.5	0.4	0.0	
37-B07d	7/21/2014	7:00	<0.1	1.1	27.0	<0.1	2.58	1.0	1.0	0.1	
37-B07d	7/21/2014	17:00		0.8	30.5		2.98	1.4	1.1	0.1	
37-B07d	7/22/2014	7:00	<0.1	1.4	34.1	<0.1	3.19	1.6	1.4	0.1	
37-B07d	7/22/2014	17:00		1.4	36.3		3.66	1.9	1.6	0.1	
37-B07d	7/23/2014	9:00	<0.1	1.2	30.7	<0.1	4.04	2.2	2.2	0.2	
37-B07d	7/23/2014	17:00		1.2	32.9		4.52	2.5	2.0	0.2	
37-B07d	7/24/2014	9:00	<0.1	1.4	35.3	<0.1	4.74	2.8	2.2	0.2	
37-B07d	7/24/2014	17:00		1.4	36.8		4.88	3.1	2.6	0.3	
37-B07d	7/25/2014	9:00	<0.1	1.4	34.3	<0.1	5.18	3.3	2.7	0.2	
37-B07d	7/31/2014	10:00	<0.1	1.1	27.4	<0.1	5.60	3.2	3.1	0.2	0.1
37-B07d	8/7/2014	10:00	<0.1	1.3	25.7	<0.1	6.29	2.2	3.8	0.0	0.0
37-B07d	8/14/2014	7:30	<0.1	1.4	32.2	<0.1		1.95	4.32	0.15	0.05
37-B07d	8/27/2014	12:40	<0.1	1.9	45.6	<0.1	5.65	1.00	4.00	0.15	0.07
37-B07d	9/9/2014	8:30	<0.1	2.3	68.7	<0.1	4.10	0.11	3.52	0.00	0.00

Appendix C - Table 1: Analytical Results Summary - Stage 2 Partitioning Tracer Test

			VOCs					Alcohols			
Sample ID	Sample Date	Sample Time	DCE (mg/L)	TCE (mg/L)	PCE (mg/L)	VC (mg/L)	Bromide (mg/L)	Methanol (mg/L)	24DMP (mg/L)	2-octanol (mg/L)	355TMH (mg/L)
37-B11s	7/15/2014	9:00	<0.1	0.0	2.6	<0.1					
37-B11s	7/15/2014	10:00	<0.1	2.6	43.4	<0.1	1.09	0	0	0	0
37-B11s	7/15/2014	12:00		0.6	7.3		1.75	0	0	0	0
37-B11s	7/15/2014	14:00	<0.1	2.6	44.6	<0.1	1.08	0.3	0.1	0.0	0.0
37-B11s	7/15/2014	17:00		2.6	41.5		8.44	22.4	11.7	3.7	2.0
37-B11s	7/16/2014	7:00		2.0	20.8		33.46	90.0	43.9	13.3	8.1
37-B11s	7/16/2014	12:00		1.7	25.6		187.85	532.7	246.3	79.1	46.7
37-B11s	7/16/2014	17:00	<0.1	1.4	22.6	<0.1	235.57	582.3	292.5	94.3	57.4
37-B11s	7/17/2014	7:00		2.3	36.8		84.44	212.0	103.8	32.7	20.1
37-B11s	7/17/2014	11:30		2.7	39.9		61.33	160.9	73.1	22.4	13.8
37-B11s	7/17/2014	17:00	<0.1	3.0	43.3	<0.1	43.99	116.5	55.4	16.6	10.0
37-B11s	7/18/2014	7:00		3.3	46.3		30.93	79.8	36.7	10.4	6.3
37-B11s	7/18/2014	11:30		3.3	46.8		25.50	62.5	29.8	8.5	5.2
37-B11s	7/18/2014	17:00		3.5	49.0		23.89	56.3	26.8	6.9	4.5
37-B11s	7/19/2014	9:00	<0.1	3.5	52.6	<0.1	18.50	45.1	20.2	5.7	3.7
37-B11s	7/20/2014	9:00		3.6	52.3		14.61	39.1	17.9	4.7	3.0
37-B11s	7/21/2014	7:00	<0.1	3.6	54.6	<0.1	9.50	23.6	11.0	2.7	1.9
37-B11s	7/21/2014	17:00		3.8	61.5		7.91	21.0	10.1	2.4	1.6
37-B11s	7/22/2014	7:00	<0.1	2.8	57.8	<0.1	6.65	16.8	8.6	1.8	1.3
37-B11s	7/22/2014	17:00		3.4	58.5		6.14	14.3	7.3	1.6	1.1
37-B11s	7/23/2014	9:00	<0.1	3.8	62.3	<0.1	5.58	10.3	6.6	1.1	1.0
37-B11s	7/23/2014	17:00		3.5	58.5		4.88	8.5	5.2	1.0	1.0
37-B11s	7/24/2014	9:00	<0.1	3.8	66.7	<0.1	3.95	5.8	4.2	0.8	0.7
37-B11s	7/25/2014	9:00	<0.1	3.7	60.0	<0.1	2.99	2.6	3.2	0.4	0.4
37-B11s	7/31/2014	10:00	<0.1	4.1	70.7	<0.1	1.50	0.0	1.0	0.1	0.03
37-B11s	8/7/2014	10:00	<0.1	4.5	70.7	<0.1	1.01	0.0	0.6	0.0	0.0
37-B11s	8/14/2014	7:50	<0.1	3.9	59.7	<0.1		0.00	0.22	0.00	0.00
37-B11s	8/27/2014	10:30	<0.1	4.6	81.0	<0.1	1.04	0.02	0.09	0.00	0.00
37-B11s	9/9/2014	10:30					1.73	0.00	0.00	0.00	0.00
37-B11d	7/15/2014	9:00	<0.1	0.7	13.8	<0.1					
37-B11d	7/15/2014	10:00	<0.1	0.9	16.6	<0.1	1.52	0	0	0	0
37-B11d	7/15/2014	12:00	<0.1	1.2	19.1	<0.1	1.21	0	0	0	0
37-B11d	7/15/2014	14:00	<0.1	1.3	20.6	<0.1	1.36	0	0	0	0
37-B11d	7/15/2014	17:00	<0.1	1.3	21.2	<0.1	1.76	0	0	0	0
37-B11d	7/16/2014	7:00	<0.1	1.4	22.5	<0.1	2.95	5.1	2.6	0.7	0.3
37-B11d	7/16/2014	12:00	<0.1	1.3	21.8	<0.1	13.21	20.8	10.6	3.1	1.9
37-B11d	7/16/2014	17:00	<0.1	1.4	21.9	<0.1	11.97	17.9	9.2	2.6	1.4
37-B11d	7/17/2014	7:00	<0.1	1.2	19.9	<0.1	7.52	14.7	7.7	1.7	1.0
37-B11d	7/17/2014	11:30	<0.1	1.4	22.0	<0.1	15.06	44.2	24.1	6.7	3.8
37-B11d	7/17/2014	17:00	<0.1	1.5	25.7	<0.1	112.00	321.2	153.2	46.8	28.4
37-B11d	7/18/2014	7:00	<0.1	1.9	26.4	<0.1	116.79	341.4	163.0	49.1	30.0
37-B11d	7/18/2014	11:30	<0.1	1.9	28.4	<0.1	121.37	284.6	136.0	44.3	26.5
37-B11d	7/18/2014	17:00	<0.1	1.8	26.8	<0.1	40.23	98.1	50.1	14.6	8.6
37-B11d	7/19/2014	9:00	<0.1	1.6	22.5	<0.1	38.14	97.1	44.8	13.0	7.9
37-B11d	7/20/2014	9:00	<0.1	1.9	26.6	<0.1	34.63	84.0	41.0	10.4	6.4
37-B11d	7/21/2014	7:00	<0.1	2.0	32.1	<0.1	32.75	81.5	38.0	9.1	5.1
37-B11d	7/21/2014	17:00	<0.1	2.1	31.5	<0.1	30.20	73.9	37.6	7.9	4.5
37-B11d	7/22/2014	7:00	<0.1	2.1	25.8	<0.1	31.31	72.4	36.2	7.0	4.2
37-B11d	7/22/2014	17:00	<0.1	2.3	32.2	<0.1	27.85	64.6	33.4	6.8	4.0
37-B11d	7/23/2014	9:00	<0.1	2.3	32.3	<0.1	26.45	60.6	31.7	6.5	3.8
37-B11d	7/23/2014	17:00	<0.1	2.5	34.0	<0.1	25.66	61.8	30.8	6.1	3.5
37-B11d	7/24/2014	9:00	<0.1	2.6	29.0	<0.1	24.97	58.8	29.6	5.6	3.4
37-B11d	7/25/2014	9:00	<0.1	2.6	37.7	<0.1	22.94	54.7	27.3	5.6	3.1
37-B11d	7/31/2014	10:00	<0.1	2.9	40.0	<0.1	16.57	37.9	19.5	3.8	1.8
37-B11d	8/7/2014	10:00	<0.1	3.3	45.8	<0.1	11.48	27.4	14.0	2.5	1.4
37-B11d	8/14/2014	8:15	<0.1	3.9	43.9	<0.1		17.3	8.8	0.6	0.0
37-B11d	8/27/2014	11:00	<0.1	4.6	54.7	<0.1	4.91	7.4	4.6	0.2	0.0
37-B11d	9/9/2014	10:15					2.65				

Appendix C - Table 1: Analytical Results Summary - Stage 2 Partitioning Tracer Test

			VOCs					Alcohols			
Sample ID	Sample Date	Sample Time	DCE (mg/L)	TCE (mg/L)	PCE (mg/L)	VC (mg/L)	Bromide (mg/L)	Methanol (mg/L)	24DMP (mg/L)	2-octanol (mg/L)	355TMH (mg/L)
37-B12	7/15/2014	9:00	<0.1	2.7	30.1	<0.1					
37-B12	7/15/2014	10:00	<0.1	4.3	109	<0.1	1.27	0	0	0	0
37-B12	7/15/2014	14:00	<0.1	5.0	117.8	<0.1	1.14	0	0	0	0
37-B12	7/16/2014	17:00	<0.1	5.4	113.3	<0.1	0.89	0	0	0	0
37-B12	7/17/2014	17:00	<0.1	5.2	110.0	<0.1	0.93	0	0	0	0
37-B12	7/18/2014	11:30	<0.1	4.7	104.4	<0.1	0.64	0	0	0	0
37-B12	7/19/2014	9:00	<0.1	5.5	117.3	<0.1	0.79	0	0	0	0
37-B12	7/21/2014	7:00	<0.1	5.4	119.3	<0.1	0.96	0	0	0	0
37-B12	7/22/2014	7:00	<0.1	5.4	129.6	<0.1	1.04	0	0	0	0
37-B12	7/23/2014	9:00	<0.1	4.8	125.4	<0.1	1.07	0	0	0	0
37-B12	7/24/2014	9:00	<0.1	4.4	129.3	<0.1	1.05	0	0	0	0
37-B12	7/25/2014	9:00	<0.1	4.4	119.7	<0.1	0.96	0	0	0	0
37-B12	7/31/2014	10:00	<0.1	6.2	157.5	<0.1	0.93	0	0	0	0
37-B12	8/7/2014	10:00	<0.1	5.1	121.5	<0.1	0.88	0	0	0	0
37-B12	8/14/2014	7:00	<0.1	5.6	121.4	<0.1		0	0	0	0
37-B12	8/27/2014	15:35	<0.1	6.8	150.0	<0.1	0.12	0	0	0	0
37-B12	9/9/2014		<0.1	8.6	173.6	<0.1		0	0	0	0
37-B13	7/15/2014	9:00	<0.1	0.1	15.6	<0.1					
37-B13	7/15/2014	10:00	<0.1	0.4	35.5	<0.1	1.12	0	0	0	0
37-B13	7/15/2014	14:00	<0.1	0.3	31.0	<0.1	1.23	0	0	0	0
37-B13	7/16/2014	17:00	<0.1	0.4	32.1	<0.1	1.03	0	0	0	0
37-B13	7/17/2014	17:00	<0.1	0.3	30.6	<0.1	1.10	0	0	0	0
37-B13	7/18/2014	11:30	<0.1	0.4	38.1	<0.1	1.03	0	0	0	0
37-B13	7/19/2014	9:00	<0.1	0.4	38.2	<0.1	0.95	0	0	0	0
37-B13	7/21/2014	7:00	<0.1	0.4	43.2	<0.1	0.56	0	0	0	0
37-B13	7/22/2014	7:00	<0.1	0.4	43.1	<0.1	0.78	0	0	0	0
37-B13	7/23/2014	9:00	<0.1	0.4	41.0	<0.1	0.51	0	0	0	0
37-B13	7/24/2014	9:00	<0.1	0.5	44.3	<0.1	0.51	0	0	0	0
37-B13	7/25/2014	9:00	<0.1	0.5	49.0	<0.1	0.56	0	0	0	0
37-B13	7/31/2014	10:00	<0.1	0.5	56.8	<0.1	0.54	0	0	0	0
37-B13	8/7/2014	10:00	<0.1	0.5	61.7	<0.1		0	0	0	0
37-B13	8/14/2014	7:05	<0.1	0.6	62.0	<0.1		0	0	0	0
37-B13	8/27/2014	14:42	<0.1	0.5	54.3	<0.1	1.02	0	0	0	0
37-B13	9/9/2014		<0.1	0.6	77.5	<0.1		0	0	0	0

Appendix C - Table 2: Analytical Results Summary - Bioaugmentation and Rebound Assessment

			VOCs				VFAs										Anions						Reduced Gases				Dechlorinating bacteria			
Sample ID	Sample Date	Sample Time	DCE (mg/L)	TCE (mg/L)	PCE (mg/L)	VC (mg/L)	Lactic	Acetic	Propionic	Formic (mg/L)	Butyric	Pyruvic	Valeric	Dissolved Hydrogen (ug/L)	Total Iron (ug/L)	Dissolved Iron (ug/L)	Chloride (mg/L)	Nitrite (mg/L)	Sulfate (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Bromide (mg/L)	Methane (mg/L)	Ethane (mg/L)	Ethene (mg/L)	Propane (mg/L)	DHC (cells/mL)	TCE (cells/mL)	BVC (cells/mL)	VCR (cells/mL)
37-B07s	5/29/2014	10:30	<0.4	1.3	42.2	<0.4											776	1.98	590	11.7	0.2	1.65	<0.002	<0.004	<0.005	<0.006				
37-B07s	7/2/2014	12:15	<0.1	0.8	5.1	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.013	681	140	822	5.85	606	7.44	0.2	1.38					<10	<5.00E-01	<5.00E-01	<5.00E-01
37-B07s	8/27/2014	11:35	<0.1	0.9	9.2	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.008			685	0.2	471	18.3	0.2	2.16					<10			
37-B07s	9/9/2014	9:10	<0.1	1.1	10.6	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				790	0.2	540	17.5	0.2	2.10					18			
37-B07s	10/13/2014	8:25	<0.1	0.7	9.6	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0		28.9	12.6	807	0.2	585	17.3	0.2	1.23	<0.002	<0.004	<0.005	<0.006	258			
37-B07s	11/19/2014	8:25	<0.1	0.7	8.6	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.0042			795	0.2	607	17.1	0.2	1.69	<0.002	<0.004	<0.005	<0.006	114			
37-B07s	12/17/2014	10:30	<0.1	0.5	6.5	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				718	0.2	575	20.1	0.2	1.97	<0.002	<0.004	<0.005	<0.006	18.7			
37-B07s	3/5/2015	9:06	<0.1	0.6	7.6	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				386	0.2	298	9.02	0.2	0.86	<0.002	<0.004	<0.005	<0.006	3480			
37-B07s	4/13/2015	10:45	<0.1	0.5	8.3	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0		57.9	16.3	408	0.2	283	9.42	0.2	0.75	<0.002	<0.004	<0.005	<0.006				
37-B07s	5/19/2015	11:15	<0.1	0.4	7.3	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0		107	63.1	445	0.2	318	7.92	0.2	0.67	<0.002	<0.004	<0.005	<0.006				
37-B07i	7/2/2014	10:40	<0.1	0.8	5.6	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				818	5.83	602	7.25	0.2	1.40								
37-B07i	8/28/2014		<0.1	0.7	9.6	<0.1																								
37-B07i	9/9/2014	8:40	<0.1	0.5	6.8	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0																	
37-B07i	10/13/2014	11:15	<0.1	0.5	4.9	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				826	0.2	584	10.6	0.2	0.93	<0.002	<0.004	<0.005	<0.006				
37-B07i	11/19/2014	11:40					<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				880	1.21	616	6.86	0.2	1.76	<0.002	<0.004	<0.005	<0.006				
37-B07i	12/17/2014	8:30	<0.1	0.5	11.3	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				891	1.49	641	5.69	0.2	1.43	<0.002	<0.004	<0.005	<0.006				
37-B07i	3/5/2015	8:05	<0.1	0.7	14.4	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				847	1.76	607	3.15	0.2	1.22	0.0034	0.00345	0.00773	<0.006				
37-B07d	1/18/2013		<0.25	0.6	34	<0.25																								
37-B07d	3/5/2013		<0.1	1.2	25	<0.1																								
37-B07d	1/13/2014		<0.4	1.1	11.5	<0.4																								
37-B07d	5/29/2014	10:30	<0.1	1.5	46.0	<0.1											767	2.34	583	11.3	0.2	1.62	<0.002	<0.004	<0.005	<0.006				
37-B07d	7/2/2014	10:05	<0.1	1.0	8.4	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.212	3190	1790	777	5.34	582	7.54	0.2	1.42					53	<5.00E-01	<5.00E-01	<5.00E-01
37-B07d	8/27/2014	12:40	<0.1	1.9	45.6	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.201			434	0.13	420	0.15	0.2	5.65					10			
37-B07d	9/9/2014	8:30	<0.1	2.3	68.7	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				379	0.12	363	0.18	0.2	4.10					10			
37-B07d	10/13/2014	10:45	<0.1	1.6	41.5	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.78	5010	853	399	0.2	387	0.24	0.2	2.63	<0.002	<0.004	<0.005	<0.006	239			
37-B07d	11/19/2014	9:20	<0.1	1.6	39	<0.1	1.06	1.45	4.93	<1.0	<1.0	<1.0	<1.0	2.29			471	0.2	467	0.2	0.2	3.81	<0.002	<0.004	<0.005	<0.006	106			
37-B07d	12/17/2014	8:50	<0.1	1.2	29.3	<0.1	<1.0	60.3	59.7	<1.0	<1.0	<1.0	<1.0				486	0.2	477	0.2	0.33	3.28	<0.002	<0.004	<0.005	<0.006	6.3			
37-B07d	3/5/2015	8:35	0.83	1.67	38	<0.1	<1.0	83.9	57.8	<1.0	<1.0	<1.0	<1.0				472	0.2	426	0.2	0.54	2.32	0.00443	0.00328	0.00552	0.00439	1450			
37-B07d	4/13/2015	9:45	3.0	2.0	38.6	<0.1	<1.0	<1.0	199	65.6	<1.0	<1.0	<1.0	0.0399	3710	3630	369	0.2	273	0.2	0.51	2.4	0.00183	<0.004	<0.005	<0.006	1680			
37-B07d	5/19/2015	11:55	2.0	1.3	22.8	<0.1	<1.0	66.6	10.5	<1.0	<1.0	<1.0	<1.0		6580	6460	504	0.2	386	0.2	0.2	0.2	0.00157	<0.004	0.00308	<0.006				
37-B07d	8/5/2015	7:05	2.3	1.4	27.8	<0.1	<1.0	75.5	<1.0	<1.0	<1.0	<1.0	<1.0		2140	1910	314	0.2	219	0.2	0.2	4.93	<0.002	<0.004	0.00332	<0.006				
37-B11s	5/28/2014	10:30	<0.1	0.3	5.2	<0.1											261	2.26	341	6.75	0.2	1.15	<0.002	<0.004	<0.005	<0.006				
37-B11s	7/2/2014	8:15	<0.1	0.6	2.9	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.0066			263	2.87	331	5.62	0.2	1.02					10			
37-B11s	8/27/2014	10:30	<0.1	4.6	81.0	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	1.72	<12.5	<12.5	411	0.22	455	2.09	0.2	1.04					10			
37-B11s	9/9/2014	10:30					233	<1.0	9.29	<1.0	<1.0	<1.0	<1.0				402	0.2	379	0.2	1.9	1.73					996			
37-B11s	10/13/2014	11:45	0.4	2.8	5.42	2.2	19400	1230	1860	20.0	383	20.0	20.0	213			508	0.2	434	0.2	218	3.42	<0.002	<0.004	<0.005	<0.006	11600			
37-B11s	11/19/2014	10:25	104	5.9	6	<0.1	<1.0	546	655	<1.0	114	<1.0	59.7	0.0056			650	0.2	365	0.2	22.6	0.73	<0.002	<0.004	<0.005	<0.006	1810			
37-B11s	12/17/2014	10:50	26.8	2.5	8.7	<0.1	3.13	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				46.2	0.6	107	1.39	7.11	0.83	<0.002	<0.004	<0.005	<0.006	196			
37-B11s	3/5/2015	9:30	18.8	4.8	9.8	0.04	<1.0	1797	2564	131	<1.0	31.9	<1.0				529	0.2	142	0.2	216	2.68	<0.002	<0.004	<0.005	0.00253	662000			
37-B11s	4/13/2015	11:05	60.3	0.5	0.8	0.1	<1.0	2040	2650	<1.0	315	13.1	42.5	<0.0042	<12.5	622	500	0.2	7.84	0.2	139	0.69	0.399	<0.004	<0.005	<0.006	1130000	32700	<3.6	25100
37-B11s	5/19/2015	10:10	55.3	<0.1	<0.1	0.2	<1.0	1780	2050	<1.0	232	<1.0	49.8		2250	1740	517	0.2	0.88	0.2	46	0.76	<0.002	<0.004	0.0127	<0.006				
37-B11s	8/5/2015	7:50	7.0	<0.1	<0.1	8.3	<1.0	1960	2300	<1.0	164	<1.0	53.6		11500	10100	252	0.2	0.2	0.2	10.6	0.51	0.00251	<0.004	1.29	<0.006				
37-B11s	10/19/2015	7:55	0.415	0.013	0.12	0.047	<1.0	<20.0	<1.0	<1.0	<1.0	<1.0	<1.0				27.1	0.2	77	0.2	53.6	0.52	0.00759	<0.004	0.234	<0.006	1260000			
37-B11s	1/12/2016	13:15	0.043	0.0057	0.05	<0.1	2.39	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0		5270	673	50	1.26	53.7	0.2	3.71	0.19	1.57	<0.004	0.762	<0.006	3720000			
37-B11s	3/9/2016	8:05	0.064	0.011	0.024	<0.1	<1.0	1.02	<1.0	<1.0	<1.0	<1.0	<1.0				13.3	0.2	28.6	0.2	10.4	0.23	0.482	<0.004	0.575	<0.006				
37-B11d	5/28/2014	10:30	<0.1	0.8	27.3	<0.1											315	1.1	345	6.06	0.2	1.92	<0.002	<0.004	<0.005	<0.006				
37-B11d	7/2/2014	9:15	<0.1	0.5	14.1	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.0035			278	1.55	330	6.34	0.2	1.02					10			
37-B11d	8/27/2014	11:00	<0.1	4.6	54.7	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.005	13.7	<12.5	424	0.2	433	0.2	0.2	4.91					10			
37-B11d	9/9/2014	10:15					134	<1.0	5.22	<1.0	<1.0	<1.0	<1.0				354	0.2	350	0.2	0.41	2.65					2650			
37-B11d	10/13/2014	12:30	26.3	2.5	5.2	2.1	409	783	1390	<1.0	119	<1.0	7.6	7.42			448	0.2	328	0.2	19.4	1.37	<0.002	<0.004	<0.005	<0.006	12700			
37-B11d	11/19/2014	11:15	38	1.4	5.7	<0.1	<1.0	1430	2870	<1.0	359	<1.0	36.9	0.0022			554	0.2	347	0.2	22.7	1.42	<0.002	<0.004	<0.005	<0.006	107000			
37-B11d	12/17/2014	11:25	35	1.3	2.1	<0.1	<1.0	1390	2650	<1.0	362	<1.0	56.1				555	0.49	377	0.2	19.4	1.59	<0.002	<0.004	<0.005	<0.006	331			
37-B11d	3/5/2015	10:15	45.7	0.2	1.1	0.04	<1.0	843	860	<1.0	<1.0	11.1	<1.0				425	0.2	0.13	0.2	38.8	0.93	0.0036	<0.004	0.0035	<0.006	33900			
37-B11d	4/13/2015	12:15	36.4	<0.1	<0.1	0.9	<1.0	1460	1850	<1.0	237	42.5	37.8	0.0018	<12.5	5270	451	0.2	0.22	0.2	89.2	0.89	<0.002	<0.004	<0.005	<0.006	2140000	49700	<50	118000
37-B11d	5/19/2015	10:50	42.3	<0.1	<0.1	1.5	<1.0	1530	1920	<1.0	225	<1.0	42.4		4470	2940	431	0.2	0.2	0.2	63.9	0.83	0.00268	<0.004	0.0636	<0.006				
37-B11d	8/5/2015	8:25	16.3	<0.1	<0.1	10.9	<1.0	1770	2200	<1.0	139	<1.0	50.7		6580	6790	159	0.2	0.2	0.2	16.4	1.02	0.00285	<0.004	0.439	<0.006				
37-B11d	10/19/2015	9:15	0.054	0.012	0.038	0.04	215	1860	2310	<1.0	135	<1.0	57.7				555	0.2	0.2	0.2	19.2	1.35	0.013	<0.004	1.54	<0.006	6640000			
37-B11d	1/12/2016	13:55	0.031	0.007	0.043	<0.1	<20	11.8	429	<20	22.1	14.6	175		77	6850	356	0.2	0.2	0.2	13.9	0.64	0.342	<0.004	1.64	<0.006	3150000			
37-B11d	3/9/2016	8:30	0.015	0.004	<0.1	<0.1	<1.0	877	847	<1.0	5.78	<1.0	16.2				380	0.2	0.2	0.2	0.18	0.92	0.817	<0.004	3.25	<0.006				
37-B12	1/8/2014		<2.1	3.5	84	<2.1																								
37-B12	5/28/2014	10:30	<0.1	3.7	86.4	<0.1											489	1.19	253	2.18	0.2	1.09	<0.002	<0.004	<0.005	<0.006				
37-B12	7/2/2014	12:55	<0.1	1.4	17.8	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.012	101	<25.0	565	0.2	273	2.42	0.2	0.88					12	1.00E-01	<5.00E-01	<5.00E-01
37-B12	8/27/2014	15:35	<0.1	6.8	150.0	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.006	174	25.6	421	0.2	447	1.63	0.2	0.12					3.6			
37-B12	9/9/2014		<0.1	8.6	173.6	<0.1																								
37-B12	10/13/2014	8:50	<0.1	6.7	127.8	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.004	14.3	<12.5	655	0.2	263	2.82	0.2	1.00	<0.002	<0.004	<0.005	<0.006	391			
37-B12	11/19/2014	7:30	<0.1	6.6	119	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.0092			683	0.84	295	2.50	0.2	1.03	<0.002	<0.004	<0.005	<0.006	10			
37-B12	12/17/2014	10:05	<0.1	6.1	108	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				795	1.7	359	2.94	0.2	1.19	<0.002	<0.004	<0.005	<0.006				
37-B12	3/5/2015	11:00	<0.1	4.0	50.8	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				737	0.98	305	2.68	0.2	0.93	<0.002	<0.004	<0.005	<0.006				
37-B12	4/13/2015	8:05	<0.1	5.9	110	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.0756	31.6	30.7	535	0.2	319	2.12	0.2	0.56	<0.002	<0.004	<0.005	<0.006	6.6	60	<50	<50
37-B12	5/19/2015	13:30	<0.1	5.2	82	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0		31.5	24.8	607	0.2	292	2.09	0.2	0.89	<0.002	<0.004	<0.005	<0.006				

Appendix C - Table 2: Analytical Results Summary - Bioaugmentation and Rebound Assessment

			VOCs				VFAs										Anions						Reduced Gases				Dechlorinating bacteria			
Sample ID	Sample Date	Sample Time	DCE (mg/L)	TCE (mg/L)	PCE (mg/L)	VC (mg/L)	Lactic	Acetic	Propionic	Formic (mg/L)	Butyric	Pyruvic	Valeric	Dissolved Hydrogen (ug/L)	Total Iron (ug/L)	Dissolved Iron (ug/L)	Chloride (mg/L)	Nitrite (mg/L)	Sulfate (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Bromide (mg/L)	Methane (mg/L)	Ethane (mg/L)	Ethene (mg/L)	Propane (mg/L)	DHC (cells/mL)	TCE (cells/mL)	BVC (cells/mL)	VCR (cells/mL)
37-B13	1/7/2014		<2.1	<2.1	58	<2.1																								
37-B13	1/9/2014		<2.1	<2.1	50	<2.1																								
37-B13	5/29/2014	10:30	<0.1	0.3	69.3	<0.1											471	4.2	499	0.55	0.2	0.95	<0.002	<0.004	<0.005	<0.006				
37-B13	7/2/2014	13:20	<0.1	0.5	15.1	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.65	6570	6650	460	2.72	489	1.03	0.2	0.67					7.70E+00	<5.00E-01	<5.00E-01	<5.00E-01
37-B13	8/27/2014	14:42	<0.1	0.5	54.3	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.006	955	102	455	0.37	499	4.6	0.2	1.02					5.3			
37-B13	9/9/2014		<0.1	0.6	77.5	<0.1																								
37-B13	10/13/2014	8:45	<0.1	0.5	86.7	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.022	1030	58.7	387	0.2	428	4.68	0.2	0.62	<0.002	<0.004	<0.005	<0.006	144			
37-B13	11/19/2014	7:40	<0.1	0.4	78	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.0035			412	0.78	466	4.57	0.2	0.60	<0.002	<0.004	<0.005	<0.006	10			
37-B13	12/17/2014	9:55	<0.1	0.3	80.4	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				479	1.29	548	5.03	0.2	1.09	<0.002	<0.004	<0.005	<0.006				
37-B13	3/5/2015	11:30	<0.1	0.4	61.3	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0				419	0.97	471	4.71	0.2	0.62	<0.002	<0.004	<0.005	<0.006				
37-B13	4/13/2015	7:50	<0.1	0.6	69.4	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	0.0064	232	162	355	0.2	428	4.3	0.2	0.4	<0.002	<0.004	<0.005	<0.006				
37-B13	5/19/2015	12:30	<0.1	0.3	38.4	<0.1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0		174	27	366	2.2	453	5.29	0.2	0.2	<0.002	<0.004	<0.005	<0.006				
37-EW07	8/27/2014	13:30															42.7	1.07	174	13.6	0.2						200			
37-EW07	9/9/2014	9:50															27.3	0.46	131	9.57	0.2									

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